Lowering Hinders for Maritime Biofuels

Identifying means to increase the use of biofuels in the marine sector

IEA Bioenergy Task 39

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Identifying means to increase the use of biofuels in the marine sector

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EXECUTIVE SUMMARY

The International Maritime Organization's (IMO's) Fourth GHG study 2020 (IMO, 2021) reported that in 2018, global shipping energy demand accounted for nearly 11 exajoules (EJ), resulting in around 1 billion tonnes of carbon dioxide (CO_{2e}) emissions. Further, part of the short sea shipping and all inland shipping is excluded from that figure. Since the previous IEA Bioenergy Task 39 report on marine biofuels (Simonsen et al, 2021), reporting on the barriers to increased uptake of biomass based fuels for shipping, the production and use of maritime biofuels have grown substantially. The maritime shipping sector is coming under increasing pressure to reduce its greenhouse gas (GHG) emissions. Policies, roadmaps and industrial initiatives for decarbonizing the shipping sector have been presented and are under development. For example, the port of Singapore alone have bunkered a 660 Mt of B24 this year (2024) and biofuel blends have been delivered to ships on all continents. The bunkered biofuel volume only amounts to half a percent for 2024, but the market is growing. This is driven by IMO regulation heeded in several Emission Control Areas and by major ports worldwide, and by regional regulatory measures in e.g. EU, USA and Singapore.

While biofuels are uniquely positioned to answer the call to decarbonize shipping, there are a number of barriers to introduction in larger quantities. This report aims at identifying and demonstrating methods to overcome barriers that were identified in Simonsen et al (2021), in order to accelerate the transition.

For this report, 17 interviews were conducted with key stakeholders in the biofuel and e-fuel value chains involved with the marine freight transportation sector, including fuel producers, ports, regulators, shipping companies and research institutions. The interviews indicate that initial activities along the value chain for biofuel production, distribution and use are underway, but that cost, regulatory and resource constraints have prohibited uptake beyond the first few percent. However, investments in biofuel production as well as biofuel compatible bunkering capability and ships are going ahead in a way which suggests market uptake, especially along specially assigned "green corridors" where biofuel use is supported technically and economically.

Maritime shipping is varied as to types of goods transported, transport modes and fuel and vessel types. In general, this study focuses on means to achieve production and use of substantial biofuel volumes, bunkering infrastructure and adaptation of standards regarding deep sea shipping. However, some near-shore and inland waterways fuel options and technology have been studied. It is shown that the main factors that affect the pace and impact of a transition includes the strength of climate policies (e.g. the cost of carbon) and economic growth.

Barriers to the introduction of biofuels include the cost of biofuel production (in relation to fossil fuels), cost of scaling production, lack of international standards/specifications and lack of infrastructure, lack of fuel supply (e.g. green methanol and drop-in biofuels), concerns regarding the compatibility of engine/fuel blends and the stability of drop-in biofuels as well as the management and bunkering of blends, and general enforcement of current regulation are among the listed barriers. Further examples of barriers include lack of economic incentives, uncertainty in the cost for biofuel feedstocks, criteria for sustainability approval and regulatory barriers to include renewable feedstocks in marine fuels.

Methods to overcome the mentioned barriers include the incorporation of additional feedstocks according to RED III, especially urban waste and forest product processing residues. To facilitate the uptake of new feedstocks, the principle of Book and Claim should be regulated and introduced across markets. By better understanding the Total Cost of Ownership for biofuel users, cost increases may be absorbed by the end users. To contribute to the transition, stakeholders would be well advised to approach either of the Green Corridors that are developing, where a sustainable value chain can be held together and expand. R&D&D on suitable engines (e.g. for ethanol and ammonia) and related infrastructure must be supported. Blending mandates and carbon taxation are important drivers for sustainable production and distribution.

FOREWORD

Global shipping has been a reality since millennia. The world's first steam-powered ship was the Pyroscaphe built in France in 1783 by Marquis Claude de Jouffroy and his colleagues. This marked the beginning of the motorized shipping era, accelerating development of global trade and transport. The next milestone came in 1903 when the French canal barge "Petit Pierre" made waves on the Marne-Rhine canal. This marked the first recorded use of a diesel engine for marine propulsion.

The voyage of commercial marine diesel engines then began in 1908 when the Swedish engine manufacturer A.B. Motorer supplied reversible engines for the cargo ships Rapp and Schnapp in the Baltic and North Sea. More than one hundred years later, we see a global transition from conventional fossil diesel-powered large ships to a multitude of energy solutions for lower emissions transportation of the seas. Ships running on unconventional fuels like methanol, biogas, biodiesel, ammonia, hydrogen and electricity. In addition, use of suction sails, wind rotors and also regular sails. A long comeback for wind-powered propulsion.

In 2023 the world's first methanol-powered container ship, the Laura Maersk, started its maiden journey - on green methanol. The global shipping company A.P. Møller – Maersk aims to reach net-zero greenhouse gas emissions by 2040 and works actively with ports to reduce the carbon footprint for sustainable logistics solutions. This marks the start for a global change in world-wide shipping operations.

Global shipping consumes over 300 million tonnes of oil per year and emits around 1 billion tonnes of carbon dioxide. The International Maritime Organization (IMO) has a GHG Strategy with net-zero by 2050. There is thus ample need to identify and lower hinders for increased use of maritime biofuels. A number of barriers were identified in a previous Task 39 report (Progress towards biofuels for marine shipping - Status and identification of barriers for utilization of advanced biofuels in the marine sector). To find low-hanging fruits to lower the emissions in shipping and establish needed stable policy framework for sustainable fuels to replace fossil fuels, these research questions were addressed:

- *How can the industry extend the use of biofuels for the marine transport sector? What are the current trends of push and pull mechanisms in the market?*
- *What are the main barriers and hinders for the deployment of use of maritime biofuels? What is needed to realize the potential?*

The main scope of work has been to assess the promising potential routes to accelerate the transition to a carbon neutral shipping sector with maritime biofuels, to evaluate technical, regulatory, legal and economic barriers to success and define mitigation strategies for the identified barriers by developing a sustainable fuel roadmap for the maritime industry.

The work in this report has been validated by researchers and other project partners from Ireland, Sweden, Denmark, The Netherlands, New Zealand, Canada, Japan and USA. Project leader and main contact for project lead has been Tom Walsh, Ireland with first author David Bauner of Renetech. We thank all companies who participated, for example Maersk, Stena, St1, Liquid Wind, and the Port of Singapore. In addition, the organizations of IMO and the Methanol Institute have helped with information, perspectives and analysis.

It is the hope of the authors and team that the report will serve as scientific input for laying out policy framework in coming years, to be based on facts and stakeholder views on how and what could be the most successful implementation for sustainable shipping.

Tomas Ekbom

Tomas Ekbom, IEA Bioenergy Task 39 Leader

> ***"Never regard study as a duty but as an enviable opportunity to learn to know the liberating influence of beauty in the realm of the spirit for your own personal joy and to the profit of the community to which your later works belong".***
>
> ***Albert Einstein***

List of acronyms

AEGL - Acute Exposure Guideline Levels
ASTM International - American Society for Testing and Materials International
BAU - Business as usual
Cat-HTR - Catalytic Hydrothermal Reactor
CCS - Carbon Capture and Storage/Sequestration
CCU – Carbon Capture and Use
CCUS - Carbon Capture, Utilization, and Storage
CFS - Clean Fuel Standard
CII - Carbon Intensity Indicator
COP21 - 21th Conference of the Parties of the United Nations (on Climate Change)
CORSIA - Carbon Offsetting and Reduction Scheme for International Aviation
CRI - Carbon Recycling International
CTD - Crude Tall Diesel
CTO - Crude Tall Oil
CVO - Cracked Vegetable Oil
DBFZ - *Deutsches Biomasseforschungszentrum* (German Biomass Research Center)
DCS – (Fuel Oil Consumption) Data Collection System
DoE - Department of Energy
ECA - Emission Control Area
EEDI - Energy Efficiency Design Index
EEOI - Energy Efficiency Operational Indicator
EEXI - Energy Efficiency Existing Ship Index
EISA - Energy Independence and Security Act
EMSA - The European Maritime Safety Agency
EPA - Environmental Protection Agency
ESG - Environmental, Social, Governance
ETD - Energy Taxation Directive
FAME - Fatty Acid Methyl Ester
FCC - Fluid Catalytic Cracking
FLL – Fuel Lifecycle Label
FRL - Fuel Readiness Levels
FT – Fischer-Tropsch
GDP - Gross Domestic Production
GHG - Greenhouse Gas
HDPO – Hydrotreated Pyrolysis Oil
HDRD - Hydrogenation Derived Renewable Diesel
HEFA – Hydro-processed Esters and Fatty Acids (same as HVO)
HVO - Hydrotreated Vegetable Oil
HFO – Heavy Fuel Oil
ICAO - International Civil Aviation Organization
ICMS - Tax on Circulation of Goods and Services (Brazil)
IETS - Innovation and Energy Technology Sector
IMO – International Maritime Organization
IMRB - International Maritime Research and Development Board

ISSC - International Sustainability & Carbon Certification
LBG - Liquified Biogas
LCFS - Low-Carbon Fuel Standard
LCIF - Low Carbon Innovation Fund
LPG - Liquified propane gas
MARPOL - International Convention for the Prevention of Pollution from Ships
MGO – Marine Gas Oil
MS - Member State
MSW - Municipal Solid Waste
MT – metric tons
NDC - Nationally Determined Contribution
OECD - Organisation for Economic Co-operation and Development
PERD - Program of Energy Research and Development
PtG - Power-to-gaseous (fuel)
PtL - Power-to-liquid (fuel)
PtX - Power-to-X
RD&D - Research, Development and Demonstration
RFS - Renewable Fuels Standard
RIN - Renewable Identification Number
RME - Rapeseed Methyl Esters
RNFBO - Renewable Liquid and Gaseous Fuels of Non-Biological Origin
SAF – Sustainable Aviation Fuel
SEEMP - Ship Energy Efficiency Management Plan
SDGs - Sustainable Development Goals
SDS - Sustainable Development Scenario
SRD - Solvolytic Reactive Distillation
TEU - Twenty-foot Equivalent Unit
TCR - Thermo-Catalytic Reforming
TTW - Tank-to-Wake
UN - United Nations
USDA - US Department of Agriculture
USDOE - US Department of Energy
VGO - Vacuum gas oil
WTT - Well-to-Tank

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1 Background

1.1 Introduction

This is the report for **Project T39-T3** of the Technology Collaboration programme **Bioenergy for Transport** of the International Energy Agency (IEA), named **Task 39** in its 2022-2024 triennium.

IEA Technology Collaboration Programmes (TCPs) are organized under the auspices of the International Energy Agency (IEA) but are functionally and legally autonomous. The IEA TCP Task 39 pertains to the Bioenergy Technology Collaboration Programme (TCP), a Programme of Research, Development and Demonstration on Bioenergy (IEA Bioenergy), which functions within a Framework created by the International Energy Agency (IEA). Members of the Task are Austria, Belgium, Brazil, Canada, China, Denmark, the European Commission, Germany, Ireland, Japan, New Zealand, South Korea, Sweden, The Netherlands and the United States of America. Additional Limited Sponsor is US Grains Council.

Task 39 is further divided into Technology and Commercialization Projects, and Sustainability, Policy, Markets and Implementation Projects. Project T39-T3 is in the Technology and Commercialization category, focusing on overcoming barriers for increased use of biofuels in the maritime sector.

1.2 Objective and Goals

This report sets out to assess the potential for lowering hinders to the introduction of sustainable biofuels into the shipping sector.

The objectives are to identify and describe means to overcome hinders for the scaling up of sustainable biofuels for the shipping sector. Some of these hinders were identified in a previous IEA TCP report (Simonsen et al, 2021) and are described further in section 1.3.2.

The goal is to validate and demonstrate the means to effectively increase the amount of biofuels used in shipping – leading to reduced use of fuel of fossil origin in shipping.

Target groups for this report include the stakeholders along the value chains, including authorities and (other) regulators, who are (or are becoming) involved in the transition.

1.3 Methodology

1.3.1 Introduction

The methodology used for the project to prepare this report included an (initial) literature study, resulting in a description of the state of the art of biofuel in maritime shipping. Based on an initial understanding of the challenges at hand, a reference group was formed where the focus of the study was discussed. The state of the art is presented as chapter 2 of this report.

Based on the chosen preliminary focus areas, a number of interviews were carried out. Based on interview results, the main areas for analysis were defined. These focus areas were distributed among a number of authors for topical contributions – mainly elements of the biofuel value chain. These contributions, as adapted and updated during the project period, constitute Chapter 3 of this report.

Finally, the main conclusions as well as an account of important contemporary roadmap results are presented. This is presented in Chapter 4 of this report.

1.3.2 Literature study

This report builds on the previous report of Task 39); *Progress towards biofuels for marine shipping; Status and identification of barriers for utilization of advanced biofuels in the marine sector*, by Simonsen, Weiss, van Dyk, van Thuijl, and Thomsen (2021).[1]

A literature review was carried out to assess development after 2021, primarily in order to inform chapter 2, including significant input was from the recently published report from Task 60, the IEA TCP on Advanced Motor Fuels); *Progress of Advanced Marine Fuels* by Winther, Anli, Rosenblatt, Weisser, Wang, Aakko-Saksa, Woo, Lindblom and Sauperl (2023)[2].

The Simonsen *et al* (2021) study identified barriers to utilization of advanced biofuels in the marine sector, e.g. the lack of economic incentives. Biofuels were identified as the most promising short- to mid-term solution for both reducing carbon emissions and meeting sulphur regulations. Müller-Casseres et al. (2024), shows that "Drop-in biofuels (e.g., FAME-biodiesel, SVO and HVO-diesel) and renewable alcohols (e.g., ethanol and methanol) seem the most promising short-term alternative fuels". Among the candidate alternative fuels, biofuels and natural gas appear as the unique options without significant or major barriers related to production maturity, applicability, energy density, safety and toxicity. The Winther *et al* (2023) study identified a potential for development, *inter alia* that marine engines can use a wide range of renewable fuels, and that the market for flexible fuel marine engines is growing.

1.3.3 Establishment of a reference group

During the first half of the project period, a reference group was established. The group consists of representatives of maritime (biofuels) related organizations, who have contributed with early input, highlighting current areas of work, of interest and important remaining challenges, thereby strongly contributed to designing the structure and content of the report.

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[1] ISBN 978-1-910154-86-1

[2] AMF Task 60, October 2023

Table 1. Project reference group

Name	Affiliation
Sune Tjalfe Thomsen	University of Copenhagen
Ali Hedayati	IVL Svenska Miljöinstitutet
Dinis Reis Oliveira	Stena Teknik (Stena Rederi AB)
Fredrik Törnqvist	Colabit
Henrik Brodin	Södra
Roberta Cenni	Maersk Mc-Kinney Møller Center for Zero Carbon Shipping
Steve Rogers (former manager)	Licella
Wolter Rautelin, Riikka-Mari Haara	Neste
Marco Buffi	European Commission, Joint Research Centre (JRC)

Any remaining errors are the responsibility of the respective authors of the report.

1.3.4 Interviews

During the project year, around a dozen interviews with experts in this field along the different parts of the value chains – some from the reference group - were carried out to assess the discourse for the present report. The results of the interviews were initially used to structure the report and later on in the project year to solidify and to source information as content in the different sections. The list of interviewees can be found in Annex 1. Some of the interviewees have also been generous enough to co-author and review this report.

1.3.5 Analysis

Analysis of technical, financial, environmental and market related information was carried out based on written sources and interviews. Results, depending on type, have been presented in the pertinent sections of this report. The barriers and the state of the art along the value chains are identified and described in chapter 2. Describing means to overcome barriers to the proliferation of biofuels in maritime shipping, together with prospective topical analysis follows in chapter 3. The building blocks of the main sustainable biofuel value chains (bioethanol, biomethanol, biodiesel, biomethane) for shipping is discussed regarding regulation, research, investment, fuel production and innovation.

Section 3.2 includes scenarios for different development pathways going forward. To illustrate the intricacies of specific innovations and areas under development, case studies have been added. These are presented as separate boxes in the running text. Further, section 3.7 may be seen as a case study on the New Zealand potential for lignocellulosic pyrolysis marine fuels. Section 3.8 is an interview with the Port of Singapore regarding its work with biofuels as part of decarbonization.

The present report integrates these results and the current developments into its assessment, focusing on selected areas for development with a large potential. Scenarios by DNV, IEA and IMO, based on imminent regulation and assumptions made by the respective organization, are presented. The scenarios can be seen as roadmaps where biofuels play a decisive role in the decarbonization of marine shipping.

1.4 Acknowledgements

This report is the product of collaboration on several levels. Our first thank you goes to the Member States for funding the work on this report. We are most grateful to the IEA TCP Secretariat for the publishing, and for managing the December 3, 2024 webinar. We would like to thank the authors of the previous IEA TCP publications, Simonsen et al (2021) and Hsieh & Felby (2017). We thank the Reference Group for your help in setting the direction and outline for the work. We would also like to thank the following external reviewers for valuable contributions, as well as for identifying and correcting numerous errors in previous versions of this report:

Glaucia Mendes Souza, with participation of BIOEN and Agroicone colleagues
Liane WONG, Hafiz RAHMAT and Nikesh RADHAKRISHNAN and Elke van Thuijl.

Any remaining errors are the responsibility of the respective authors of the report.

1.5 Shipping industry - history and current role

As accounted for in Simonsen et al (2021), the first sea-going ships in history probably date back to around 3,000 B.C. and led to the colonization of almost half of our planet. The first big merchant hull ships were built after 1,200 BC. These were able to carry a relatively significant amount of cargo and could be steered. Sails remained the dominant propulsion technology until the invention of the steam engine in the 19th century, which contributed to a huge increase in international trade. In the beginning of the 20th century the British Royal Navy introduced diesel engines, which soon after led commercial ship operators to transition to the use of fuel oil made from liquid petroleum and to some extent from coal.

From the mid-20th century, new ships have almost exclusively been constructed with diesel engines, with only some military or specialized vessels using steam turbines. To date all large merchant ships are propelled by a two- or four-stroke diesel engine. However, as we will see later in this report, dual-fuel and gas engines are now entering the market.

Maritime transport today accounts for about 70 percent of global trade by value and about 80 percent by volume (IMO). There are five main categories of vessels: 1) liquid bulk; 2) dry bulk; 3) general cargo; 4) container, and; 5) other vessels. The latter category may include roll on/roll off (RORO), cruise ships, ferries and other types of passenger transport as well as research ships and military vessels. Many ferries combine passenger transport and RORO transport.

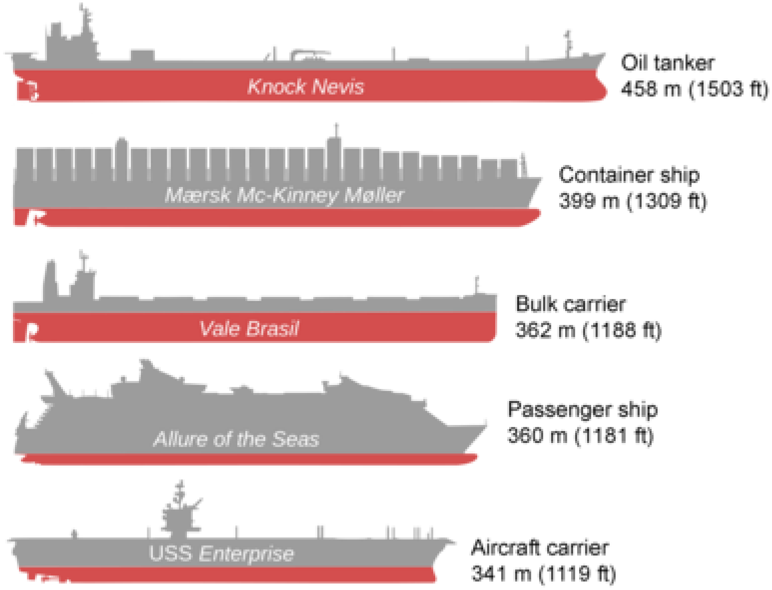

Figure 1. Examples of ship sizes

Sizes of deep-sea shipping vessels are sometimes guided by certain routes which limit their size. “Suezmax” vessels, able to pass the Suez Canal, may have a capacity of between 100,000 and 160,000 dwt, thus typically found on routes to and from West Africa and in the Mediterranean. Aframax vessels, subscribing to the Average Freight Rate Assessment rating system, typically have a size of 70,000 to 100,000 dwt, mostly oil tankers sized to fit most European ports. Panamax vessels, able to pass the locks of the Panama Canal, are typically 40,000 to 70,000 dwt. Last and definitely not least, the Very Large Crude Carriers (VLCCs) and the Ultra-Large Crude Carriers (ULCCs) such as the Knock Nevis pictured above (Figure 1). The latter category – crude carriers in excess of 400 m length – is no longer being built.

In shipping globally, approximately 12.2 billion tons of cargo are handled each year (2023) and 80-90 percent of all international freight transport is done by sea. At the same time, shipping accounts for approximately 3 percent of global emissions of carbon dioxide (equivalents). In 2017, the global emissions from shipping amounted to 7.8 million tonnes of carbon dioxide equivalents - 15 percent more than the year before and 246 percent more compared to 1990. Below (Figure 2) is a graph showing carbon emissions per vessel type for the past decade. It can be noted that CO_2 emissions in absolute numbers predominantly come from ocean-going vessels – tankers, bulk carriers and container ships.

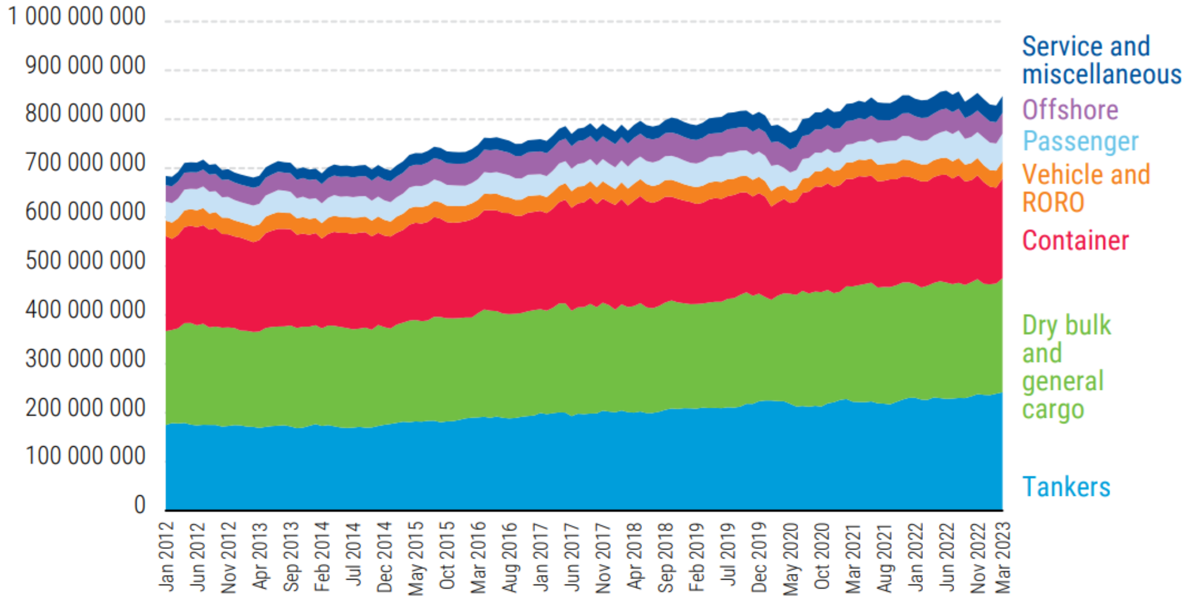

Figure 2. Total CO_2 emissions by vessel type, tons, January 2012 - March 2023. Source: UNCTAD, based on data provided by Marine Benchmark, july 2023.

While shipping is thus generally very energy-efficient per ton-km, it is historically strongly increasing. A report from the European Environment Agency (EEA, 2017) shows that global shipping could come to account for as much as 17 percent of the world's carbon dioxide emissions in 2050 if no measures are taken.

As of 1 January 2023, the world merchant fleet comprised 150 493 vessels over 100 gross tonnage (UNCTAD, 2023). There are over 50 000 merchant ships trading internationally and transporting all kinds of goods on all major seas - the International Chamber of Shipping claims there are in excess of 50,000 container ships alone currently (2024) operating on the high seas.

The age of the global fleet is increasing. At the beginning of 2023, the average age of commercial ships reached 22.2 years, higher than the previous year. Over the past decade, the fleet has aged by an average of two years, with more than half of the vessels now being over 15 years old. As a consequence, many ships are either too old to retrofit or too young to scrap (UNCTAD, 2023). The renewal of the current fleet and the retrofitting existing vessels to adapt to new technologies are challenging, requiring significant investment and considerable time.

The World Navy is registered in over 150 nations and is manned by over a million sailors. Today's ships are technologically sophisticated, high-value assets (larger, high-tech ships can cost over $200 million to build), and the operation of merchant ships generates an estimated annual income of over 450 billion Euro in freight rates.

The largest vessel categories by number are work and service vessels, fishing vessels and general cargo ships in the small to medium size category. While numerous, these are in minority as to tonnage. Vessel subcategories also include different type of freight vessels, barges, ferries, coastal tankers and tugs. Regarding tonnage, tankers, cargo ships and container ships constitute the absolute majority.

Apart from the ships themselves, a number of support functions are instrumental for the operations of the industry. These include ports, ship builders, engine makers, service companies, regulators, fuel producers and fuel distributors, pilots and many more. The industry, ultimately, depends on its clients for survival. For the purpose of this report we will focus on the stakeholders related to biofuels – fuel producers, distributors (including ports), engine makers, ship owners, cargo transport buyers and regulators.

Shipbuilding is dominated by Asian stakeholders. Major companies in shipbuilding include Mitsubishi Heavy Industries, China Shipbuilding Industry Corp., China State Shipbuilding Corp., STX Offshore & Shipbuilding, DSME, Samsung Heavy Industries, Sumitomo Heavy Industries and Fincantieri. The latter is from Italy.

Major companies operating in the marine propulsion engine market include Caterpillar Marine (MaK), Hyundai Heavy Industries Ltd., Yanmar Co. Ltd., MAN Energy Solutions SE and Wärtsilä Corporation. The Wärtsilä subsidiary developing low speed two stroke marine engines in 2015 merged with Winterthur Gas & Diesel and are now manufactured under the name WinGD. WinGD is fully owned by China State Shipbuilding Corporation.

Major companies in marine shipping include A.P. Møller-Mærsk A/S, China Ocean Shipping Company Ltd, Cargill Inc., CMA CGM S.A. Hapag-Lloyd AG, Nippon Yusen, Evergreen Marin Corp., K-line, Hyundai Merchant Marine Co. Ltd and Kuehne+Nagel International AG.

Significant companies in the field of bunkering include Bomin Bunker Oil Corp., Lukoil-Bunker LLC, Monjasa, Aegean Marine Petroleum Network, Inc., Chemoil Energy Limited, BP PLC, World Fuel Services Corp., Bunker Holding A/S, Gazpromneft Marine Bunker LLC, GAC Bunker Fuels Ltd., Royal Dutch Shell Plc, Exxon Mobil Corporation and KPI Bridge Oil A/S.

Beyond the global fleet subject to regulation and enforcement through IMO regulation, there are so called shadow vessels, temporarily registered under targeted flags or not registered at all. According to some sources (e.g. Atlantic Council, 2024) these shadow vessels form a global fleet of some 1400 ships, transporting all kinds of goods to and from Russia, Venezuela, Iran and North Korea and carry out 10-20% of maritime transport work. Of these, as many as 1000 “dark” or “grey” tankers may be transporting Russian crude oil. These vessels lack Western insurance and are unlikely to play a constructive role in the decarbonization of shipping. The shadow fleet is not further discussed in this report.

1.6 Marine fuel use today

Conventional liquid fossil marine fuels, such as Heavy Fuel Oil and Marine Gasoil constitute the absolute majority of fuels for marine shipping. Around 6.5% of the fossil fuel (by energy content) used are in the form of liquefied natural gas and liquefied petroleum gas.

Depending on whether the fuel was produced through distillation or accrued as a residue in the oil refinery, fossil fuel oil is classified as a *distillate* (or “distillate fuel” according to the standard) or a *residual* fuel.

Smaller ships usually use lighter marine fuels such as **distillate fuels** and less viscous residual fuel oils. These are often called Marine Gasoil (MGO). Distillate fuels are divided into four classes: DMX, DMA, DMB and DMZ[3]. In practice, mixtures of distillate fuels and residual fuels are mostly used, i.e. intermediate fuel oils (IFO). IFO 380 and IFO 180 (RMG) are the fuels most commonly used in shipping.

In accordance with ISO 8217, **residual fuels**, called Fuel Oils or heavy fuel oils, are divided into six fuel types depending on their viscosity (kinematic viscosity) – RMA, RMB, RMD, RME, RMG and RMK – in combination with their maximum kinematic viscosity limit value (at 50°C). The viscosity is given in square millimeters per second (mm^2/s). Large values such as 700 describe very viscous residue fuels. The lower the kinematic viscosity value, the thinner the fuel.

Residual fuels are used in large, medium to slow-speed marine engines. Provided that the ship is not in a zone with special emissions restrictions (Emission Control Area, or ECA), this will usually be an intermediate fuel oil (IFO) 380 marine fuel type with the ISO 8217 designation RMG 380 or RMK 380. There is also a low sulphur quality residual oil available in two qualities; ultra-low sulphur fuel oil (ULSFO), with max 0.10% S, and very low sulphur fuel oil (VLSFO), with max 0.50% S.

The volumes of marine fuel consumed by the world fleet were around 257 million tonnes of oil per year in 2014, down to 203 million in 2020 (IMO,2021) and up again to 212 million tonnes in 2021 and 213 million tonnes of fuel in 2022 (IMO, MEPC81, 2024). It can be noted that the figure for 2022 is reported from 800 more ships than for 2021 (around 29 000 ships). The substantial fall observed in 2020, is most probably due to the COVID-19 pandemic, with restrictions put in place worldwide. Estimates including unregistered sales amount to around 300 million tonnes. Unregistered sales and distribution may be increasing (Atlantic Council, 2024).

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[3] DMX is a distillate that is used only in smaller engines (lifeboats/emergency units) and is intended for use outside the engine room. DMA and DMB differ mainly in that DMB may contain traces of residual fuel.

of fuel reported has no indication of substantial increase year on year at present. Figure 3 indicates that the dominating categories as to fuel consumption are bulk carriers, tankers and container ships.

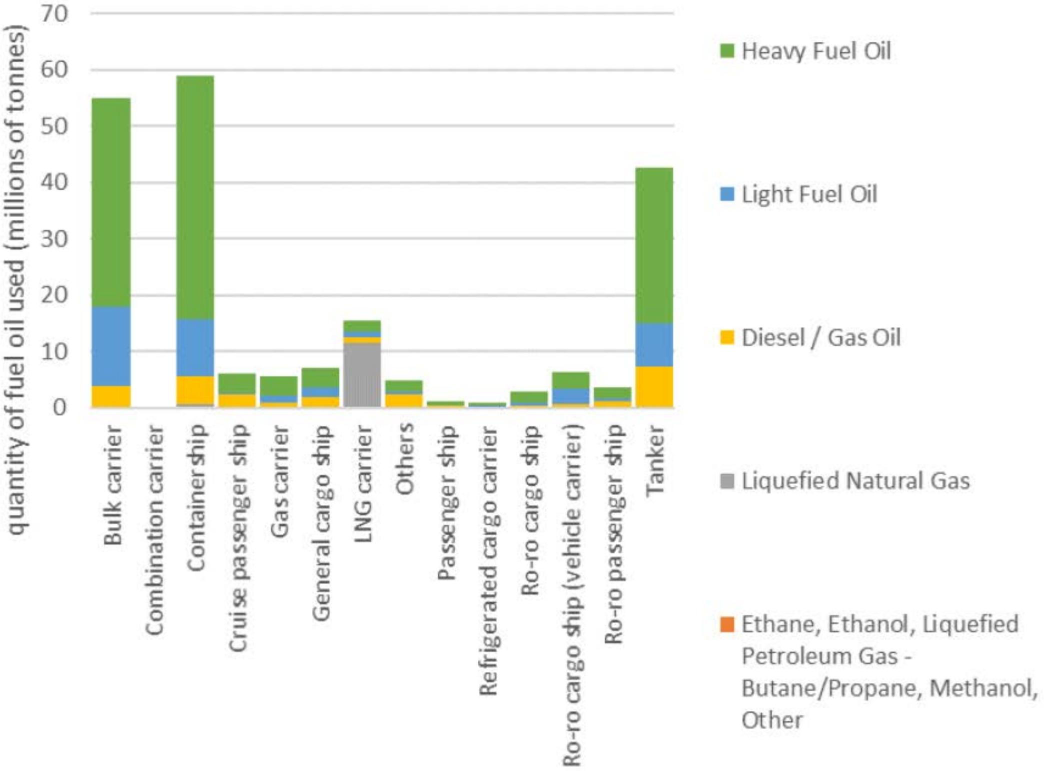

Figure 3. Aggregated annual amount of each type of fuel oil consumed for ships of 5,000 GT and above by EEDI ship type, 2023. Source: IMO DCS, 2024

The data collected by IMO DCS is limited to commercial transport ships of 5,000 gross tonnes (GT) and above, which produce approximately 85% of the total CO_2 emissions from international shipping, thus excluding military, submarine, oil rigs and other marine vessel categories. Furthermore, the unregulated fleet, the so called grey or dark vessels, which for wet bulk may constitute between 10 and 20% of global capacity (Atlantic Council, 2024), is not included, or further discussed here. Estimates of total fuel consumption globally, including unregistered sales, amount to around 300 million tonnes.

Looking at the different regions of the world, Shanghai, the world's largest container port with 49 million TEU (a measure to indicate how much cargo that pass the harbour per year, here corresponding to the transport capacity of 49M twenty-foot containers) sold around 3 million tons of bunker fuel (i.e. fuel used to propel the ships). The port of Singapore, a global shipping hub strategically located between China and India, is the world's biggest port as regards delivered bunker fuel, amounting to over 50 million ton of fuel. The port of Singapore is discussed in its market role in section 2.4.1, and Port administrators are interviewed on current work in section 3.8.

The Baltic Sea and the North Sea are trafficked by around 10,000 ships each year. The scope of sea traffic has grown and today there are always around 2,000 ships in the Baltic Sea at the same time. There are at least around 1,000 container ships that consume an average of

10,000 tons of marine diesel per year, making that market alone more than 10 million tons of fuel. Notably, Poland have doubled its port activity in the ten-year period 2012-2022 according to official EU statistics.

Significant companies in the field of bunkering include Bomin Bunker Oil Corp., Lukoil-Bunker LLC, Monjasa, Aegean Marine Petroleum Network, Inc., Chemoil Energy Limited, BP PLC, World Fuel Services Corp., Bunker Holding A/S, Gazpromneft Marine Bunker LLC, GAC Bunker Fuels Ltd., Royal Dutch Shell Plc, Exxon Mobil Corporation and KPI Bridge Oil A/S.

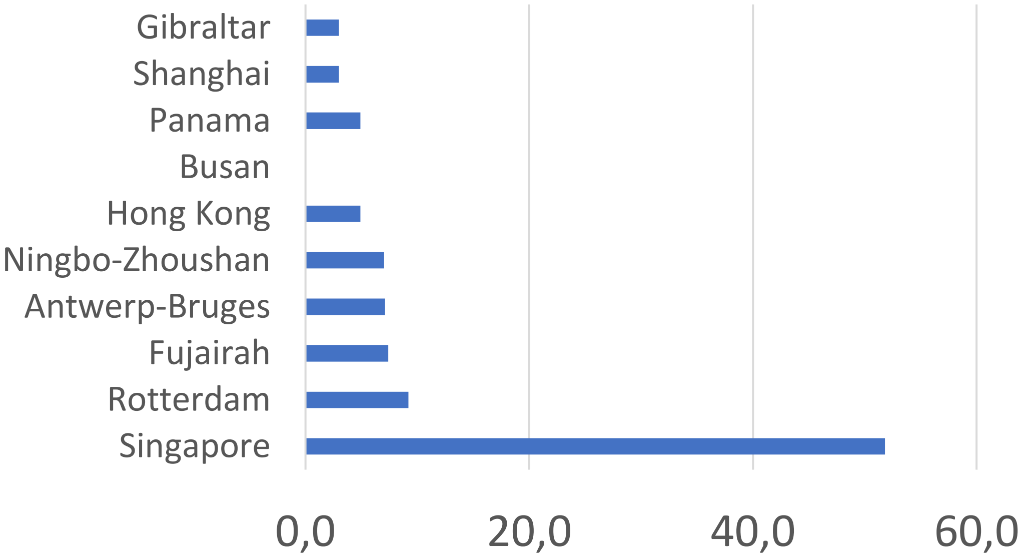

Figure 4. World's largest bunkering ports 2023 (million tons). Source: Information from the respective ports.

Other factors than fuel type affect emissions from shipping. According to a report from Inverto (2024), hundreds of vessels since mid-December 2023 sailing around South Africa's Cape of Good Hope instead of going through the Suez Canal and the Bay of Aden. Shipping from South Asia to Northern Europe thus have increased fuel use for the distance considerably, emitting 13, 6 million ton CO_2 extra from going around Cape of Good Hope up to April 2024. According to a report from Xeneta (2024), CO_2 emissions from container ships from Asia to the Mediterranean in Q1 2024 increased 63% compared to Q4 2023. Part of this emissions increase are due to ships sailing at higher speeds to make up for the extra distance.

Severe drought in 2023 and early 2024 reduced water levels in the Panama Canal, resulting in reduced traffic from the Americas to Asia. Rates on Europe-to-South America routes dropped by 36%, while Africa-to-South America routes saw a 20% increase. This volatility has been fueled by geopolitical shifts, including Egypt's decision to source grain from Brazil and the U.S. instead of from Ukraine (UNCTAD, 2024).

1.7 The concept of maritime biofuels and potential benefits

The maritime sector is characterized by significantly high levels of committed greenhouse gas (GHG) emissions (Bullock et al., 2020). The core benefit of replacing fossil fuels with sustainable maritime biofuels, either as drop-in (direct replacement in existing engines) fuels or using fuels that would require adjustments in the value chain regarding infrastructure, bunkering and ships, is that these fuels would reduce the carbon footprint of the transport relation, while sustainable supply can be expected over time. Increasing the fraction of sustainable biofuels for global shipping entails a number of potential benefits. These include:

- Reducing CO_2 emission from fuel use
- Enabling regional production, which reduces the need for global fuel transport and can create local employment
- Reducing emissions and other environmental impact from fossil fuel production at the point of origin, and also onboard (SO_x and NO_x reduction possible)
- Creation of local employment and income generation, whether in the agricultural phase, contributing to rural communities' development, or in the industrial stage.
- Enhancing energy security by diversifying sources, and offers developing countries, especially those with suitable soils and climates, an opportunity to play an active role in the global energy transition.

Biofuels are not cracked from fossil crudes, and thus are low in cat fines and sediments. In addition, biofuels generally have lower sulphur levels, fulfilling the sulphur emissions regulation and are secure in terms of safety and toxicity. Some examples of value chains for the production of deep-sea maritime fuels are the following:

- Cellulosic waste -> bio-oils -> drop-in HFO or MGO (->bunkering > use)
- Oil crops (soy, palm) -> HVO
- Sugarcane juice -> ethanol
- Sugarcane straw -> HDPO
- Sugarcane straw -> NH_3
- Forest residues -> HDPO
- Forest residues -> NH_3
- Organic Waste -> biogas > methane -> liquefied methane

Biomethane can also be further refined to biomethanol

- Organic Waste -> biogas > methane -> methanol (->bunkering > use)

The value chains introduced above are further explored in chapter 2. Means to overcome barriers to expanded use of the biofuels is discussed section 3.4.

If the use of biofuels is incentivized and/or regulated and demand increases, a number of potential issues must be addressed, depending on type of sourcing;

- Environmental (negative) impact. Including loss of biodiversity
- Availability
- Infrastructure requirements (ports)
- Adulteration and use of non-certified fuel components and feedstocks
- Falsified records on supply

Shipping is cost driven, and biofuels for several reasons are typically more costly compared with the marine fuels used today, leading to increased OPEX/CAPEX with shipping companies, and thus potentially implying slow development of the market for sustainable maritime biofuels. While biofuels are the most cost-effective non-fossil fuel option (IRENA, 2024), institutional support along the various value chains for development of production and use of sustainable biofuels for the shipping sector is thus necessary to ensure mitigation of risks and bridging the price gap.

A secondary benefit, which may reduce cost, is regional production of each fuel quality which meets demand. Regionalization of fuel production and supply has a large potential of reducing the amount of fuel which is shipped, and will thus also reduce demand for shipping of crudes and refined fuels. At the same time, large scale production where this is most efficient is also needed to achieve the cost benefits and volume to enact the transition.

Biofuels represent a key pathway in the short, medium and long-term for maritime transport sector decarbonization (i.e. defossiliazation). IMO's targets are ambitious, and few mature technologies are available. The rate of introduction of new technologies and the speed of fleet renewal are serious challenges to achieving the sector's decarbonization targets. However, biofuel sourcing and production are in many cases mature, making them readily available for immediate use as blends or direct replacement fuels, with minimal to no need for adjustments in operational or infrastructure terms (IRENA, 2024). Additionally, biofuels has also the potential to act a source of biogenic carbon for producing e-fuels. The possibility to couple biofuels production with new technologies such as carbon capture can potentially lead to negative GHG emissions values[4]. As to target markets, it can be noted from Figure 3 that any global strategy for decarbonization of maritime shipping must include bulk, container and tanker vessels. If the transition is to precede fleet renewal in these categories, then also renewable Heavy Fuel Oil must be included in the strategy.

There are several options for innovation and scaling up regarding biofuel production. Green methanol production may be cheaper using CO_2 from fermentation and H_2 from bagasse gasification, coupled with process facilities of typical sugarcane ethanol plants. This is suitable both in terms of economic assessment and life cycle analysis. Bio-oil from eucalyptus is already a reality that needs to be upgraded for diesel engines, an easier process for maritime applications. Bio-crude from pyrolysis may serve as an intermediate feedstock for maritime and other application biofuels. Ethanol may also be used as maritime fuel when methanol is the option.

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[4] According to the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines), any carbon in the fuel derived from biomass should be reported as an information item and not included in the sectoral or national totals to avoid double counting, since the net emissions from biomass are already accounted for in the Agriculture Forestry and Other Land Use (AFOLU) sector at a national level.

Beyond sustainable biofuels, maritime shipping may be executed sustainably by electric propulsion and by means of so-called e-fuels, where renewable hydrogen from solar and wind power reacts with e.g. biogenic process residual carbon dioxide to form green e-methanol or other fuels. Since electric propulsion generally has higher system efficiency than combustion engines, this is an attractive option as long as energy for the electric motors can be stored, generated or otherwise be made available on board. Another route for reducing carbon emissions would be carbon capture onboard the ship for subsequent offloading of the CO_2 at port and final storage (see section 2.6.8). Finally, energy efficiency increases and other means to reduce on-board fuel demand may serve to facilitate the decarbonization of the marine shipping sector.

2 Developing the market for sustainable marine fuels

2.1 Introduction

This section provides an outline of the state of the art of biofuels for maritime shipping, focused on the value chains from supply to use and impact. The chapter is concluded with a section regarding enhancing energy efficiency of ship propulsion, which would reduce the fuel demand per ton-km and thus increase the willingness to pay for sustainable fuels.

It should be noted that “marine biofuels” in the “market” has different connotations depending on the role of the stakeholder. For the supplier of feedstocks, biomass supplied is either a byproduct or dedicated crop for which the supplier wants compensation. The biofuel producer is typically a technical specialist and/or an entrepreneur who needs stable offtake contracts to plan production and to facilitate investment. Distributors and bunker ports need steady availability and standards to facilitate sales in order to maintain their role in their respective regions with reasonable prices. Users (shipping companies) want to comply with regulations while reducing costs for investment and operations. For them, biofuels must be vessel compatible and available, often translating to a B24 blend, CBG/CNG blend or sustainable methanol quality. Transport buyers finally (typically) want low environmental impact and reasonable and predictable transport pricing. However, since the marketplace has a lot of volatility as to transport demand, availability of biofuel and relevant infrastructure, predictability in supply and demand may be low if the fuel is not a commodity. At this point in time, green corridors (see section 3.4.5), where biofuels are made available and in demand, is an important stepping stone towards commodity markets for different sustainable fuel types. Here, regulators and other institutions can facilitate market growth by supporting the corridors which foster future markets.

2.2 Biomass sourcing

Biomass is poised to become an important source for the production of sustainable fuels for maritime shipping. However, here are increasing and competing demands for using biomass for bio-based products in sectors such as construction, energy, transport, furniture and textile industries, while also reserving it for restoration of agricultural soils, nature conservation and carbon sequestration. Regarding fuels, biomass is projected to play an increasing role for supply of feedstocks to other sectors such as aviation, road transport and for power production.

If we limit the perspectives to energy, the projected global contributions of biomass to the global energy supply in 2050 (and beyond) range between 100–400 EJ which would correspond to about 10–30% of the total projected global future energy demand. This contribution is comparable to today's biomass share (of which a considerable part is non-commercial biomass use, such as cooking fuel) to an extent that makes biomass a pillar of the future world's energy supply, similar to the role mineral oil has today (Faaij, 2022). These ranges have been subject to considerable debate and analysis, implying that the amount of biomass which in total can be made available for the production of maritime shipping fuels in a given period cannot be easily defined. Studies vary substantially in results regarding biomass potentials since they use different frameworks, how one thinks the future world will develop, and assumptions. The results of global studies in 2015, of which some are contradictory, are illustrated in the following diagram (Figure 5).

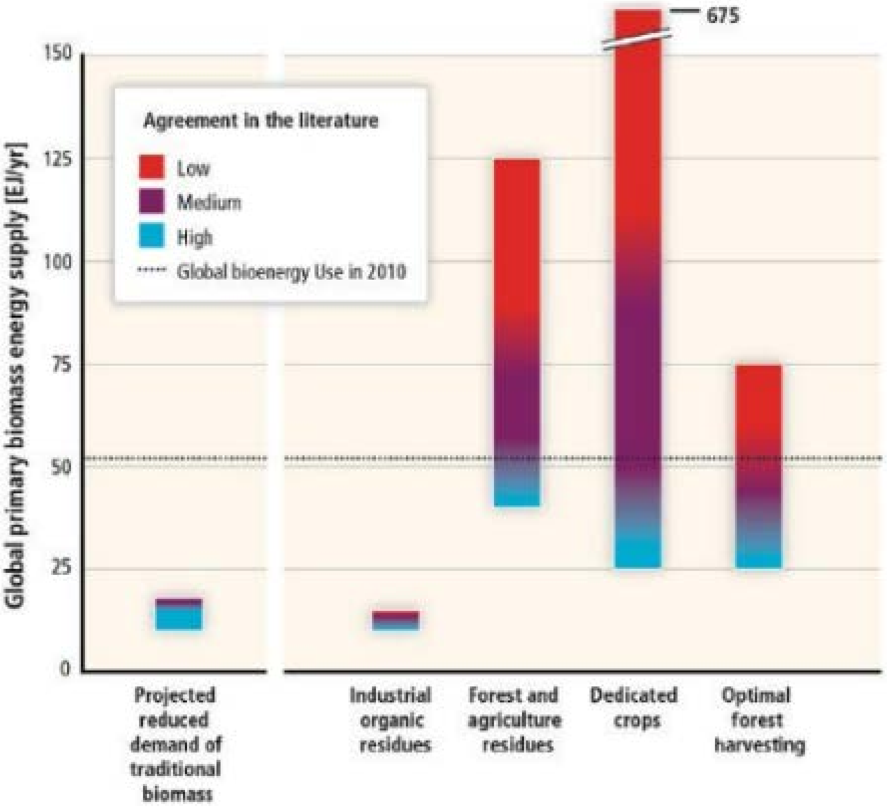

Figure 5. Global available biomass energy supply. Source: Creutzig et al, 2015.

2.2.1 Regional supply of feedstocks

To be renewable and sustainable, fuels cannot be sourced from fossil sources such as mineral oil, natural gas, petroleum gas (LPG, includes butane), or coal. There are many diverse options for biomass feedstocks - different types of virgin and recycled solid or suspended (liquid) biomass - including, but not limited to, those listed in Annex IX of the EU RED. Biogenic synthetic fuels or e-fuels can also be sourced from e.g. biogenic CO_2 and renewable power production such as PV (solar) wind and hydropower. A third type of source is non-biogenic origin waste from products such as used tyres made with fossil fuels. As we will see, a central difference between sourcing of fossil feedstocks (crude oil and natural gas) and sourcing of biogenic material is that the potential for regional sourcing increases.

The main feedstock categories to consider are listed in Table 2.

The pathways described in Table 2 are essentially the same as presented in van Dyk and Saddler (2024) concerning SAF, with the addition of feedstocks for anaerobic digestion (AD). Fats are efficient feedstocks for AD production of methane-rich biogas as well as for diesel type biofuel production through esterification (transesterification) and hydrogenation. These types of biomass and their aptitude for different types of processing and use is described by DBFZ[19] in Figure 6. In addition, resources for e-fuels; electricity, water and carbon, are shown.

Table 2. Biomass sourcing categories for biofuel production

Type of biomass	Example of biomass source	Processing technology and product examples
Biomass rich in oil and fat	Oilseeds, used cooking oil, animal fats	Esterification -> biodiesel Hydrogenation -> HVO
Biomass rich in Volatile organic compounds (VOCs)	Organic fraction of municipal solid waste	Anaerobic digestion (AD) -> liquefaction -> LBG
Biomass rich in sugar and starch	Sugar beets, sugarcane, cereals, corn	Fermentation -> ethanol
Lignocellulosic biomass	Wood, agri-waste, garden waste	Pyrolysis ->bio-oils->diesel Gasification →syngas → F/T diesel

Feedstocks like cornstover, wheat straw, sugarcane straw, and rice straw, or agro-industrial residues like saw mill waste, sugarcane bagasse, corn cobs, or pulping liquors and other non-food biomass are examples of feedstocks for what is called ‘second generation’ biofuels or Advanced biofuels. These feedstocks have the benefit of not using fossil inputs directly for the production of biofuels, but also by reducing the risk that feedstock demand does results in land use change which may increase emissions. However, there are also drawbacks in their use as feedstock since supply chains and conversion routes are not as mature and cost competitive (Cantarella et al., 2023) as e.g. first generation ethanol from corn.

A Global Biomass Resource Assessment[5], a multi-country (29 members and 21 participants, mostly sovereign states), government-led initiative dedicated to advancing the global transition to a sustainable, bio-based economy, has been carried out by the Clean Energy Ministerial[6] (CEM) Biofuture Platform Initiative. The assessment shares data assembled from citable sources around the globe, as reported for current biomass production. As an example of results, it was found that while second generation ethanol has become a reality, its availability and as well as potential future production is related to production of first generation ethanol, which generates residues for the second generation ethanol production. Data was compiled from 2018 to 2024.

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[5] https://bioenergykdf.ornl.gov/international-feedstocks
[6] https://www.cleanenergyministerial.org

Sourcing feedstocks for production of marine biofuels compete with sourcing for other fuel categories: road vehicle and aviation fuel, chemical processes and manufacturing, as well as “carbon sinks”, and biochar production for agricultural application as well as for production of “green steel”. As decarbonization progresses across sectors, markets and continents, this competition will likely increase and each sector will have to accommodate with its competitive advantages and specific demand.

The different production processes for biofuels allow for different types of feedstocks to be used, and it is essential to be technologically neutral and feedstock agnostic in developing demand and international markets to accelerate energy transitions, particularly in hard-to-abate sectors. While local production of biofuels is important, the establishment of global supply through trade agreements and certification schemes will remain important to create stable and acceptable prices for biofuels, since biomass sourcing and biofuel production is more suitable in some countries than others. This notion may however be counteracted by the recent international (China, USA, EU) shift towards domestic resilience and self-sufficiency, particularly in energy transition products and sectors (UNCTAD, 2024).

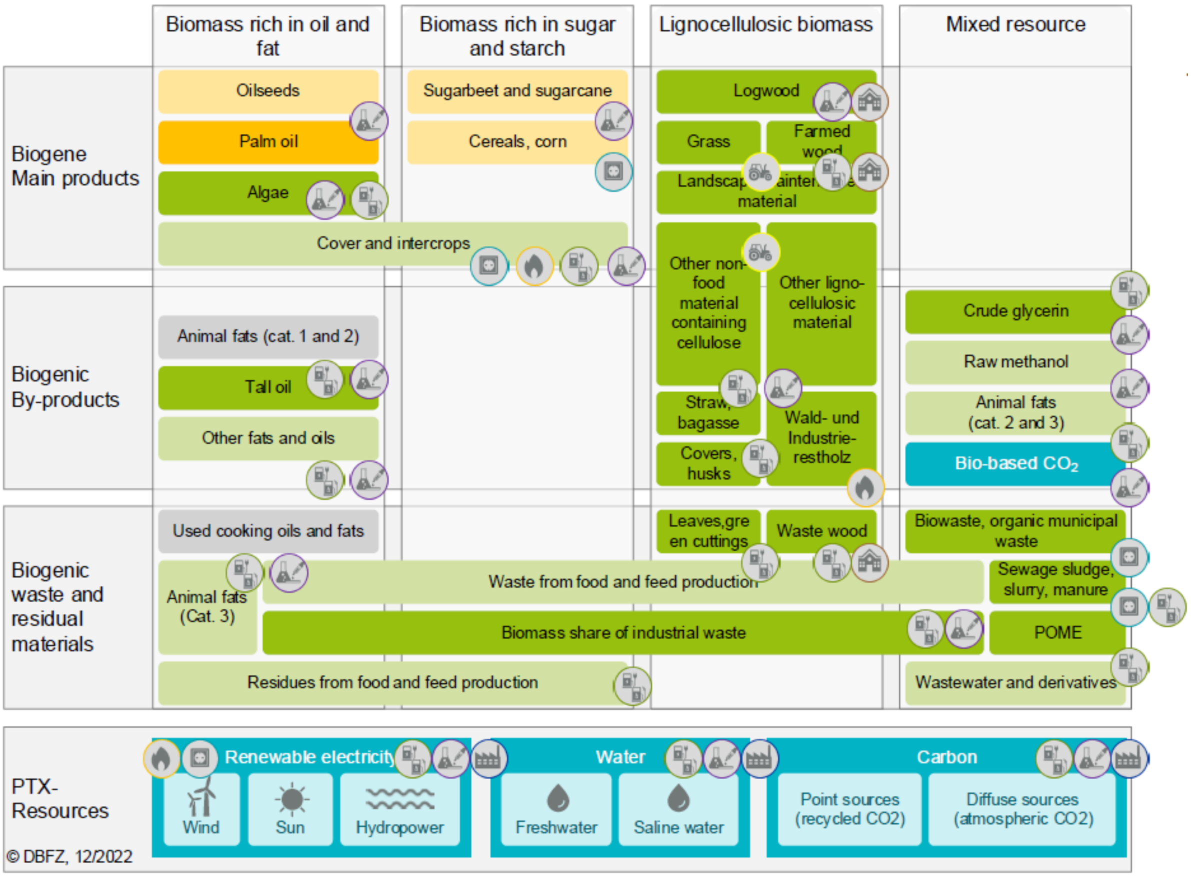

Figure 6. Feedstock types matrix (Source: DBFZ)

Feedstock supply potential vary across continents. For example, biomass for advanced biofuel production in North America has been researched and trialed extensively. As indicated in Table 6.2 in Simonsen et al (2021), a number of facilities produce biofuels using agricultural, forest and animal residues, animal fats and MSW, albeit not necessarily aimed at marine use. While cost remains a barrier, the availability of feedstocks is not.

An example of potential sourcing of biomass is the development of an (international) market for pyrolysis oils which are easy to transport and could be further processed, e g by hydrotreatment, to bio-MGO and bio-HFO[7]. The pyrolysis cluster Moerdijk have identified several feedstock options, e.g. grass, lignin, waste wood, “green RDF” and others.

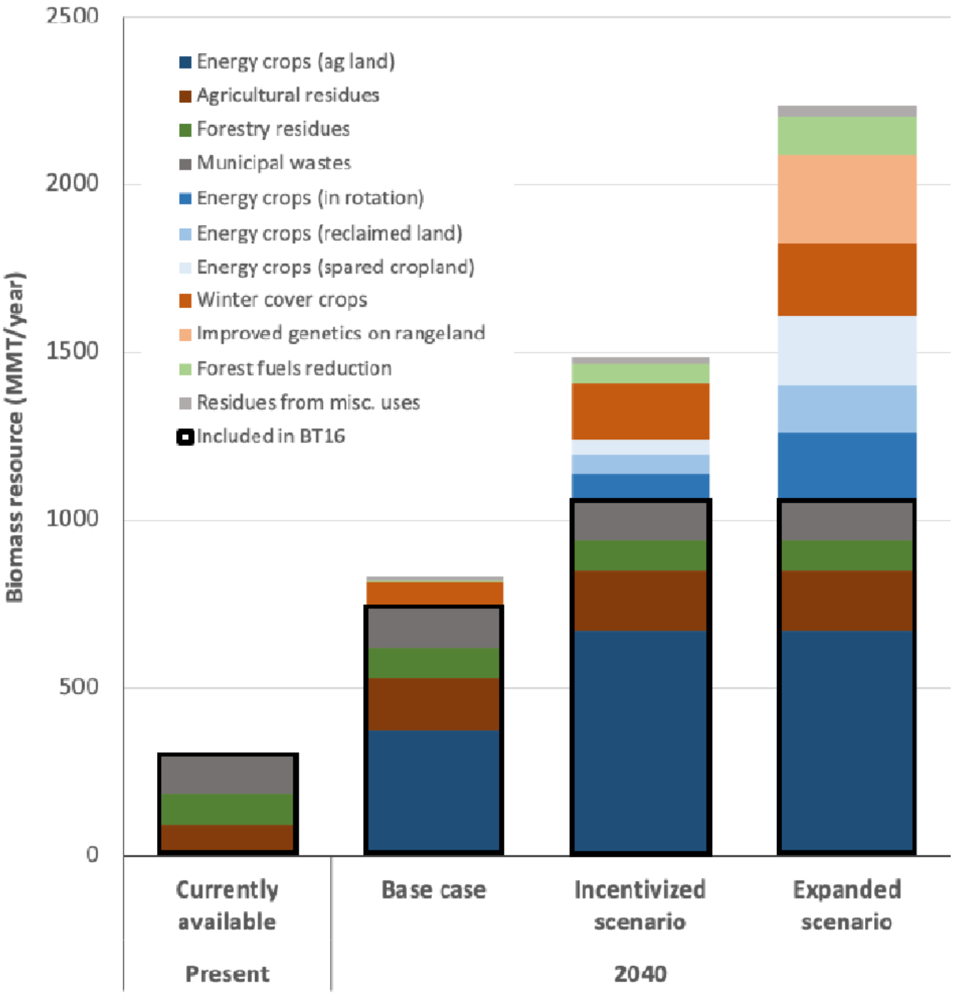

Figure 7. Biomass supply potentials in the contiguous United States from specified sources, present and in 2040. Field et al, 2023

South America, particularly Brazil, produces biofuels in a large scale, predominantly from locally sourced sugar cane and vegetable oil. Argentina, Brazil, Colombia and Guatemala provide 24% of the global biodiesel supply using soy and palm (Canabarro et al., 2023).

Asian countries such as Indonesia, Malaysia, and Thailand has used palm oil as the main feedstocks for biodiesel production, suggesting the need for other alternative resources. (Syafiuddin et al, 2020). In Australia, biodiesel production is limited and mainly based on tallow and vegetable oil. For increased production, a scenario as proposed in the case study for New Zealand in section 3.7 may be considered.

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[7] *Potential for Pyrolysis in the Marine Marke*’, presentation by Sjors Geraeddts, GoodFuels, World Bioenergy Association Webinar, January 2017

As the world weans itself off fossil fuels and recognizes issues with deforestation and degraded soils, a competition for resources is likely to ensue. Beginning with biomass residues from forestry and agriculture, there is a dichotomy between using these residues for energy purposes, refining the residues to e.g. biochar and reinserting it into the ground, or simply plowing stalks into the ground or leaving branches in the forest after felling. There are also calls for slowing down the harvesting of biomass such as forests to create “carbon sinks” and reducing the amount of CO_2 emissions from combustion or other processing.

In some regions it is common to create new farmland by “slash-and-burn”. Demand for the different residues differ between regions, where in the northern regions co-generation of district heating and power is common, while in the south e g residual bagasse from sugar production may be used for power generation. Some consider it a dichotomy between biofuel production and the production of food, feed, and fibre, especially for developing economies, while others challenge the notion of inherent food-energy competition (Galembeck et al., 2018) - crops that serve both food and bioenergy needs, such as soybeans and corn, can reduce trade-offs (Kline et al., 2016). FAO recognizes that:

> ”Through good governance, sustainable bioenergy addresses the risks related to the land and resources used for its production and the potential impacts on food security” [8].

The willingness to pay may be higher for biomass for power production and the production of sustainable aviation fuel (SAF) than for renewable marine fuels. However, it may also be that feedstock requirements are differentiated so that certain feedstocks may serve better for e g bio-HFO than for SAF production.

2.2.2 Regulation and incentives

Regulation that limits the sourcing of sustainable (and other) biomass is generally not global. While it is important that all sourcing is limited to sustainable and renewable sources, the potential for regionalization lies in that different regions of the world engage in securing virgin and waste feedstocks that can be produced and harvested sustainably.

According to the IMO resolution MEPC 391(81) which presents the LCA Guidelines with what has been agreed so far for the classification of marine fuels as sustainable, there is no mention of different “generations” of biofuels. It is important to understand the limitations on the feedstock for a given type of fuel. In some policy frameworks, such as the RED III Directive (Europe), some feedstocks are not eligible to qualify as a second generation biofuel source. Other markets are feedstock agnostic and focus on verifying that the biofuel has low-carbon intensity (US, Brazil). However, Canadas Clean Fuel Regulations (CFR) and British Columbia’s Low Carbon Fuel Standard introduce a carbon price indirectly through a credit market where compliance credits can be traded. Both mandates establish carbon intensities for each pathway – that is, each type of biofuel and feedstock – through life-cycle analyses.

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[8] https://www.fao.org/climate-change/news/news-detail/sustainable-bioenergy-for-climate-and-development-goals/en

To the extent that supply and demand would be regionalized as part of a transition to advanced/sustainable fuels, the local availability of the different types of feedstocks is also important. Notably, the facility of sourcing biomass rich in sugar and starch or oil and fat varies considerably across climate zones.

For the European Union, the Renewable Energy Directive (RED III) in its Annex IX lists approved feedstocks for conversion to renewable energy/fuels. It is limited to feedstocks for the production of biogas for transport and advanced biofuels; algae[9], the biomass fraction of mixed municipal waste[10], biowaste from private households[11], the biomass fraction of industrial waste[12], straw, animal manure and sewage sludge, palm oil mill effluent and empty palm fruit bunches, tall oil pitch, crude glycerine, bagasse, grape marcs and wine lees, nut shells, husks, (corn) cobs[13], biomass fraction of wastes and residues from forestry and forest-based industries[14], other non-food cellulosic material and other ligno-cellulosic material except saw logs and veneer logs. This is similar to what is regulated in ISO 8217:2024. For biofuels that are not considered as “advanced”, used cooking oil (UCO) and animal fats[15] can be also be considered towards the minimum share as established in the first subparagraph of Article 25(1), with limited use. Europe has set steeper goals than what is currently proposed for IMO regulation regarding sourcing of biofuels, but IMO regulation is still under development.

The Brazilian biofuel policy RenovaBio (see for example Canabarro et al, 2023) allows biofuel producers to voluntarily certify their production and receive, as a result, energy-environmental sufficiency scores. These notes are multiplied by the volume of biofuel traded, resulting in the decarbonization credit (CBIO) that a producer can commercialize.

USA Department of Energy in December 2024 launched an action plan[16] for maritime energy and emissions innovation. Given that large ocean-going vessels represent 66% of energy consumption in the U.S. maritime sector from fuels bunkered in the United States, and that combustion from heavy fuel oil also contributes to emissions and air pollutants, the action plan includes a transition to low-GHG fuels, including green ammonia and methanol for ocean-going vessels; support development of sustainable drop-in fuels; and adopt vessel electrification and hydrogen fuel cell technology. Goals of the action plan include production of 700 million gallons of heavy fuel oil (2.5 million m^3) equivalent of sustainable maritime fuel and 80 million gallons (30,000 m^3) equivalent of marine biogasoline annually by 2030.

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[9] if cultivated on land in ponds or photobioreactors

[10] but not separated household waste, subject to recycling targets as specified

[11] as defined

[12] not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry, and excluding feedstocks listed in part B

[13] cleaned of kernels of corn

[14] Namely: bark, branches, precommercial thinnings, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil

[15] classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009

[16] https://www.transportation.gov/priorities/climate-and-sustainability/action-plan-maritime-energy-and-emissions-innovation

Asian biofuel production, dominated by palm oil based biodiesel in countries such as Malaysia and Indonesia, receives subsidies for biodiesel blending in fossil diesel. New initiatives includes certification for sourcing for SAF production. Six ASEAN member states have developed specific biofuel policies, fostering local production[17].

2.3 Marine Biofuel production

2.3.1 Introduction

The following biofuels are considered in this section (2.3), selected from a combination of projected production volumes and the suitability for shipping:

- Bio-HFO and F-T biodiesel from biocrudes
- Lignocellulosic (F-T/pulping/solvolysis/pyrolysis) fuels (HDPO, Hydrotreated Pyrolysis Oil)
- Biodiesel (FAME or HEFA) – Bio -MGO
- Hydrogenated Vegetable Oils (HVO)
- Alcohols; Bio-methanol and Bio-ethanol
- Biomethane (LBG/CBG)
- Dimethyl Ether (DME)
- Ammonia (NH_3) (from sustainable biogenic sources only)
- E-methanol, can source CO_2 from biogenic sources.

Based on the feedstock types, these can be categorized as pertaining to one of these value-chains or pathways.

Table 3. Production pathways for biofuels

Feedstock	Process, intermediate carrier	Final fuel
Cellulosic byproducts (e.g. Sugarcane straw and/or forest residues)	bio-oils , pyrolysis, fractionation	drop-in bio-HFO or bio-MGO
Residual oils and fats ->	Transesterification	Biodiesel (FAME/HEFA)
Oil crops (soy, palm)	Hydrotreatment	HVO
Sugarcane juice	Fermentation	ethanol
Sugarcane straw and/or forest residue	Haber-Bosch	ammonia
Organic waste	biogas > methane	liquefied biomethane (LBG)
Organic waste	biogas > methane	biomethanol
Biogenic CO2, electricity	Hydrolysis	e-methanol

Among many other implications, this suggests that certain value chains for the production of maritime biofuels (a k a biobunker fuels) will only materialize in certain climates and thus in certain locations, dubbed “hotspots”. According to Carvalho et al (2021), Brazil is the country (“region”) with highest biobunker potential. However, FuelEU Maritime may restrict food and feed crops based biofuels for use in the EU market.

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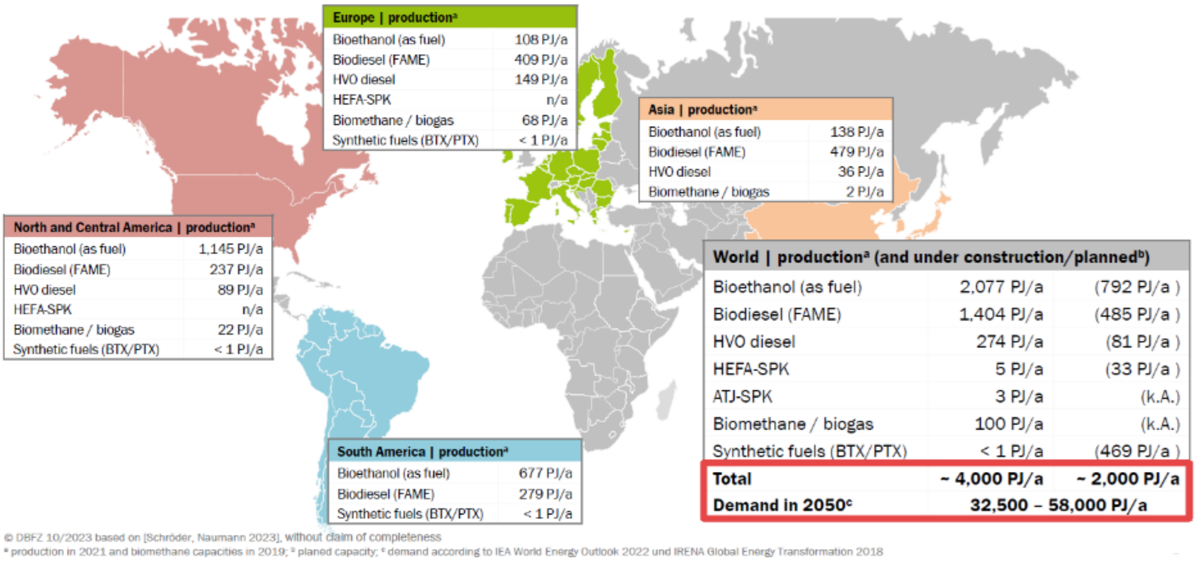
[17] *Sustainable feedstock assessment for sustainable aviation fuel production in Southeast Asia*. Roundtable on Sustainable Biomaterials, September 2024. www.rsb.org

2.3.2 Current production and expected demand

Each region of the world manages its own strategy as to producing marine fuel. To balance supply and demand, global wet bulk shipping plays an instrumental role. In the fossil era, this translated for the most part to subject local ports to global trade. However, with the advent of decarbonization, a potential to bring production home has led to initiatives and incentives across the globe. USA in January 2023 released its federal strategy, “U.S. National Blueprint for Transportation Decarbonization”, with the goal to meet the goal of net-zero GHG emissions economy-wide by 2050. A Maritime Decarbonization Action Plan will be presented in 2024 to outline multiple decarbonization pathways in fuels, energies, and technologies across vessel types and operational profiles. The EU has presented its FuelEU Maritime regulations to increase the share of renewable and low-carbon fuels in the fuel mix of international maritime transport within the EU. As an example on the demand side, The First Movers Coalition[18] has gathered stakeholders in maritime shipping (as one of eight sectors) to master zero-carbon shipping across several vessel types by 2030.

Sourcing of biofuel feedstocks and biofuel production is carried out with a view to supply different types of transport; road vehicles, aviation, maritime vessels etc. In addition to this, the same feedstocks are sourced for production of bioplastics and chemicals. Road vehicles (rolling stock) and aviation (both operational planes using drop-in SAF and future engine designs adapted to new fuels) are thus contenders for the use of biobased fuels and other chemicals. Due to this, DBFZ (2023) estimates demand to be increased 15 times compared to today’s supply, and tenfold compared to existing and planned production, until 2050.



Europe | production[a]	
Bioethanol (as fuel)	108 PJ/a
Biodiesel (FAME)	409 PJ/a
HVO diesel	149 PJ/a
HEFA-SPK	n/a
Biomethane / biogas	68 PJ/a
Synthetic fuels (BTX/PTX)	< 1 PJ/a

Asia | production[a]	
Bioethanol (as fuel)	138 PJ/a
Biodiesel (FAME)	479 PJ/a
HVO diesel	36 PJ/a
Biomethane / biogas	2 PJ/a

North and Central America | production[a]	
Bioethanol (as fuel)	1,145 PJ/a
Biodiesel (FAME)	237 PJ/a
HVO diesel	89 PJ/a
HEFA-SPK	n/a
Biomethane / biogas	22 PJ/a
Synthetic fuels (BTX/PTX)	< 1 PJ/a

World | production[a] (and under construction/planned[b])		
Bioethanol (as fuel)	2,077 PJ/a	(792 PJ/a)
Biodiesel (FAME)	1,404 PJ/a	(485 PJ/a)
HVO diesel	274 PJ/a	(81 PJ/a)
HEFA-SPK	5 PJ/a	(33 PJ/a)
ATJ-SPK	3 PJ/a	(k.A.)
Biomethane / biogas	100 PJ/a	(k.A.)
Synthetic fuels (BTX/PTX)	< 1 PJ/a	(469 PJ/a)
Total	**~ 4,000 PJ/a**	**~ 2,000 PJ/a**
Demand in 2050[c]	**32,500 – 58,000 PJ/a**	

South America | production[a]	
Bioethanol (as fuel)	677 PJ/a
Biodiesel (FAME)	279 PJ/a
Synthetic fuels (BTX/PTX)	< 1 PJ/a

© DBFZ 10/2023 based on [Schröder, Naumann 2023], without claim of completeness

[a] production in 2021 and biomethane capacities in 2019; [b] planed capacity; [c] demand according to IEA World Energy Outlook 2022 und IRENA Global Energy Transformation 2018

Figure 8. Renewable fuel in the international market[19]

The potential for additional sourcing lies with expanding waste utilization, increasing sourcing to the present producers, and also involve improved waste management in

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[18] https://initiatives.weforum.org/first-movers-coalition/home

[19] *Perspective on renewable fuels for sustainable mobility* Müller-Langer, F.; Schröder, J.; Naumann, K. DBFZ presentation, International expert workshop "Ten times more renewable fuels", Leipzig, Oct 24, 2023

emerging economies e.g. in Africa and Asia. An analysis of biofuels implementation[20] in emerging markets of Africa, Asia, and Latin America shows that meeting 25% blending targets requires only 1–7.8% of their total land area, achieving substantial GHG reductions. Especially India, Indonesia and South Africa would benefit from increased local biofuel production given the anticipated low carbon intensity of production in these countries.

Biofuel production technologies, funding, and flexibility towards different user categories and specifications is an ecosystem in its own right. As we can see in the figure above, a tenfold increase in production would not only excise a toll on feedstocks and possibly risk indirect effects on feedstock sustainability, but could lead to negative impacts from feedstock competition for food, feed and fuel production.

Production of alternative fuels – notably biofuels and e-fuels – is a moving field. The Future Fuels and Technology Project (FFT Project), a partnership project between the International Maritime Organization (IMO) and the Republic of Korea, in April 2024 launched a website with the aim to provide information on zero and near-zero marine fuels and technologies. The **futurefuels.imo.org** website includes sections on:

- Current data on alternative fuels and supply, up-to-date indicative prices, information on the IMO Data Collection System (DCS),
- Insight on the readiness, scalability and sustainability of new marine fuels and technologies, including fuel price forecasts, R&D and demonstration projects, as well as information on relevant initiatives in the shipping and energy industries,
- Selected global news, information resources (including reports and journal papers), and information on IMO events related to GHG emissions reduction in international shipping,
- Training materials and useful tools on alternative fuels, energy efficiency technologies and other GHG reduction measures.

Further, with its Alternative Fuels Insight initiative, DNV provides the maritime industry with an open platform for evaluating the uptake of alternative fuels and technologies.

2.3.3 Oleo-chemical derived diesel fuels

Biomass based Diesel type fuels can – if specifications otherwise match that of the engine – serve as drop-in fuels, reducing the need to adapt the infrastructure and engine in order to accelerate the transition. This means that Bio-HFO and bio-MGO can compete at higher prices than e.g. biobased ammonia and methanol, given that the cost for adaptation is lower or nil.

Pyrolysis and gasification has a potential for bio-oil production. For example, Pyrolysis based on Ensyn’s Technology (https://www.ensyn.com/) has been used to produce biocrudes which serve as intermediate feedstocks for biofuel production. Feedstocks may be forest and agricultural residues - straw, rice straw, wheat straw, peanut shells, corncobs, vegetable leaves, bean straw (etc), waste wood, yard waste, and energy crops.

The gasification process for a given plant is designed based on a specific feedstock, which impacts the feedstock preparation, type of gasification reactor, the syngas cleanup process

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[20] IEA Task 39, July 2024 https://www.ieabioenergy.com/blog/publications/biofuels-in-emerging-markets-of-africa-and-asia-an-overview-of-costs-and-greenhouse-gas-savings/

and (regarding volumes) downstream F-T processing of the syngas to marine fuel. While the Fischer-Tropsch process is fully commercial, the preceding processing steps, as well as the overall integration of the process, have yet to be fully commercialized. Both bio-HFO and bio-MGO may be produced.

Bio-DME (Di-Methyl-Ether) is typically produced by biomass gasification, followed by methanol synthesis and dehydration. DME is non-toxic and gaseous in ambient conditions. It requires a pressure of about 5 bar to stay liquid but do not require cryogenic storage. Volumetrically, DME is a little over half the energy content of diesel. See section 3.3.1 for a discussion on the need for research for developing DME as a marine fuel.

2.3.4 Bioalcohols

Methanol is the simplest alcohol with a chemical formula CH_3OH. It is a light, volatile, colourless, flammable liquid with a specific alcohol odor; it is highly toxic and unfit for consumption. Methanol has many uses and is versatile as a fuel source with an energy value of 16MJ/l or 20GJ/t.

As shown in Figure 9, there are several pathways to produce more or less renewable methanol. Gasification/reforming of biomass or reacting biogenic CO2 with H2 from electrolysis are the two main pathways for renewable production, in addition to AD/Methanization and the conventional Fermentation/Distillation.

Methanol is seeing current investment along the value chain. Renewable methanol is today produced in a few locations. Examples include production using pulp mill residue in Sweden, waste in Canada, and from CO_2 emissions at a small commercial plant in Iceland.

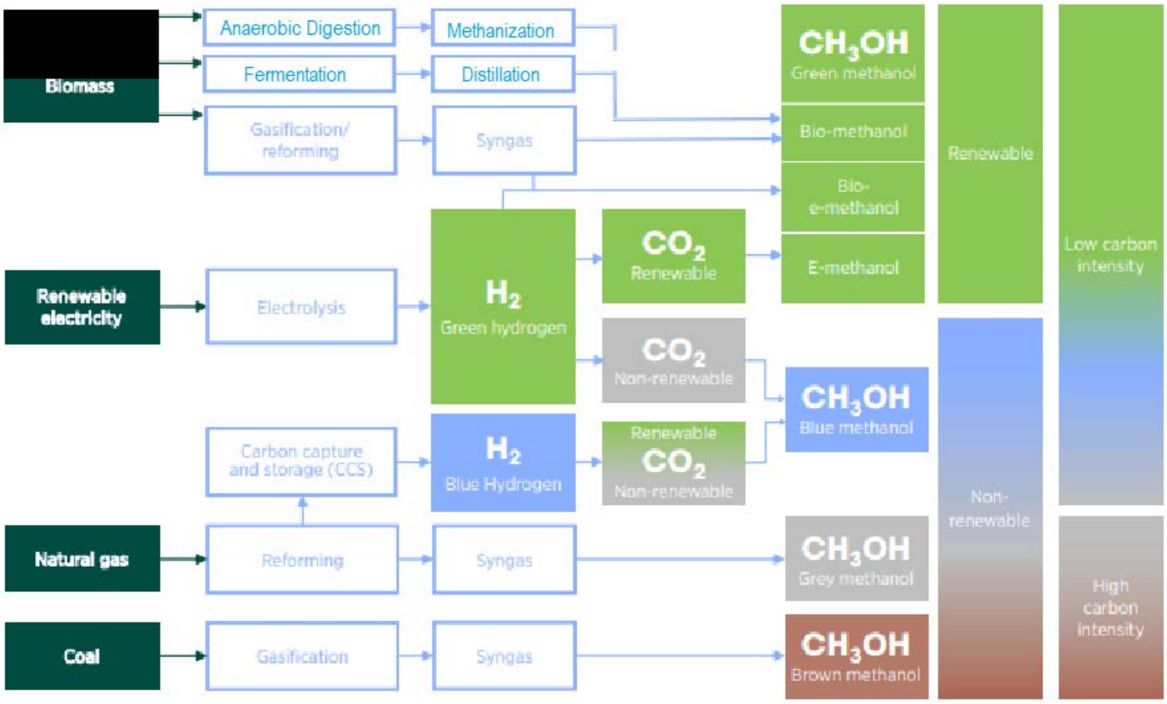


Figure 9. Methanol production pathways. Modified from IRENA and Methanol Institute (2021)

Bioethanol is the main biofuel commodity globally, produced with fermentation and distillation of sugary feedstocks, and produced with or without natural gas as process energy input depending on market.

Lignocellulosic residues (LC) of different origin is an alternative pathway to increase feedstock availability without the investment in additional land area. Ideally, any residue containing cellulose or hemicellulose may be a suitable feedstock, e.g., forestry remains, food waste, crops and their remains, leaves, straw, paper and garden residues. Moreover, it is compatible with circular economy principles, as this eliminates concerns around water and food security.

However, the higher cost for processing lignocellulosic residues to ethanol have prevented large scale production of ethanol from such feedstocks. Further, ethanol would require modifications in vessels and infrastructure to serve, for example, instead of methanol as ship fuel. There are investigations underway to assess its potential under current regulations e.g. in the EU. This is also discussed further in section 3.3.1.

2.3.5 Drop-in biofuels (pyrolysis- and synthetic biofuels)

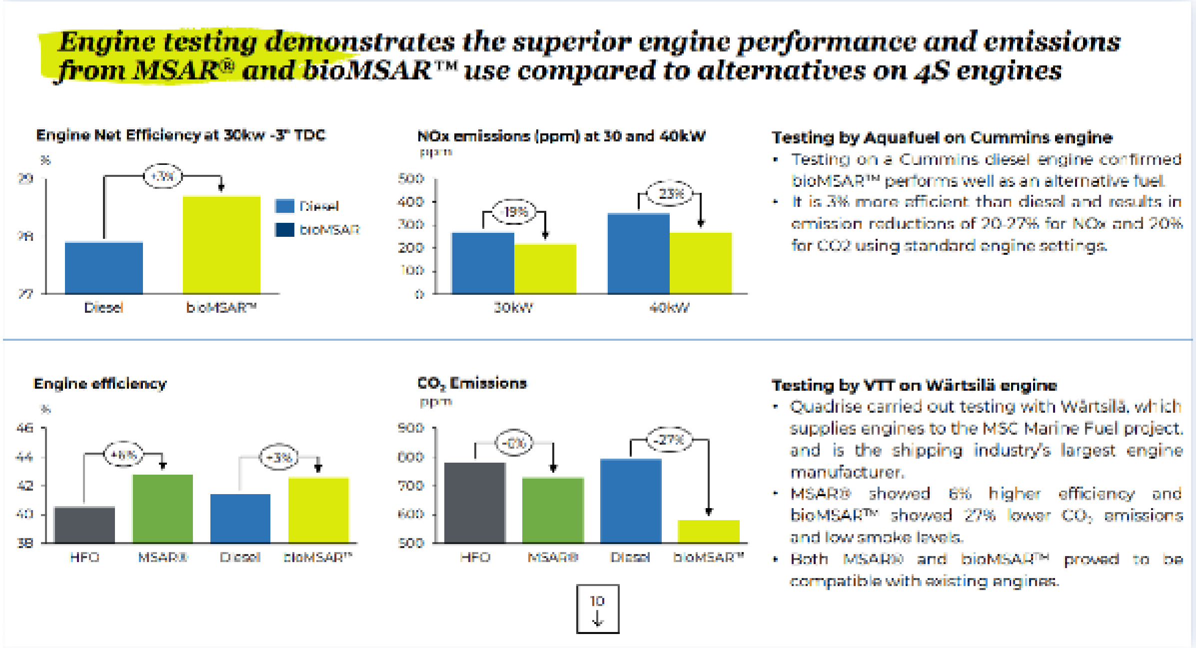
Including biocrude from pyrolysis and hydrothermal liquefaction. Drop in marine biofuels mimic the characteristics of its fossil predecessors to an extent that their compatibility with fossil marine fuels facilitates the introduction and blending.

This is further discussed in section 3.5.1.

2.3.6 Lignin solvolysis and emulsion fuels

As one means to dissolving lignin and produce a combustable fuel, solvolysis involves the fragmentation of lignin molecules into lower molecular weight products. It occurs at moderate temperatures, in acidic or a basic condition. If the process uses water as the solvent, it may also be referred to as hydrolysis. An emulsion fuel combines two immiscible phases, oil and water, to create a stable fuel blend using small quantities of surfactants.

The company Quadrise, based in the UK, develops “QED” fuels branded MSAR and bioMSAR as an alternative to marine fuel oil. The emulsion fuel technology offers superfine dispersion of oil-in-water which entails compete combustion at lower temperatures. See Annex A2.



Engine testing demonstrates the superior engine performance and emissions from MSAR® and bioMSAR™ use compared to alternatives on 4S engines

Testing by Aquafuel on Cummins engine

- Testing on a Cummins diesel engine confirmed bioMSAR™ performs well as an alternative fuel.
- It is 3% more efficient than diesel and results in emission reductions of 20-27% for NOx and 20% for CO2 using standard engine settings.

Testing by VTT on Wärtsilä engine

- Quadrise carried out testing with Wärtsilä, which supplies engines to the MSC Marine Fuel project, and is the shipping industry's largest engine manufacturer.
- MSAR® showed 6% higher efficiency and bioMSAR™ showed 27% lower CO_2 emissions and low smoke levels.
- Both MSAR® and bioMSAR™ proved to be compatible with existing engines.

BioMSAR has a water content of only 10%, offering up to 90% biofuel components. Testing is carried out together with MSC.

2.3.7 Renewable methane

Methane – the molecule of natural gas and biogas – can replace or be blended with fossil methane either in compressed (CBG) or liquefied (LBG) form. Anaerobic digestion of biomass feedstocks to produce biomethane is an established technology and can use a variety of feedstocks. Biomethane can serve as drop-in fuels, replacing LNG or CNG, reducing the need to adapt the infrastructure and engine in order to accelerate the transition.

Methane used as shipping fuel was extensively described in section 5.1.6 in Thomsen et al (2021). Compressed and liquefied biomethane can generally be used interchangeably with compressed and liquiefied natural gas, respectively. See sections 2.4.2.

Biomethane can also be processed to methanol. See section 3.5.4 for more information.

2.3.8 E-fuels and hydrogen derived fuels

Other types of fuels may complement biofuels for certain regions and vessel/engine combinations.

Green ammonia (NH_3) is a carbon–neutral alternative to traditional ammonia, made using renewable energy sources such as solar or wind power which can breakdown water into hydrogen and oxygen. Ammonia has been identified by IEA as a potential candidate for decarbonizing marine fuels in part due to expected cost competitiveness with other alternative fuels. While sustainable ammonia has a very low carbon footprint, to sustain demand for any quantities for this fuel would require significant increase in the production of hydrogen from renewable sources adjacent to any production facility. Further, the issue of safety is primordial as regards the handling of ammonia. Aspects relating to distribution and use of ammonia are further discussed in section 2.4.2.

Today (2024), almost half of H_2 is consumed in NH_3 plants, and H_2 is mostly extracted from coal and natural gas, which emit approximately 420 million tons of CO_2 yearly. Renewable ammonia production would use Bio-H_2 from H_2-electrolysis and N_2-separated from the atmosphere. A typical process of green-NH_3 production is shown in Figure 10. NH_3 is used as an H_2 carrier or directly in a dual-fuel compression ignition engine, or in fuel cells.

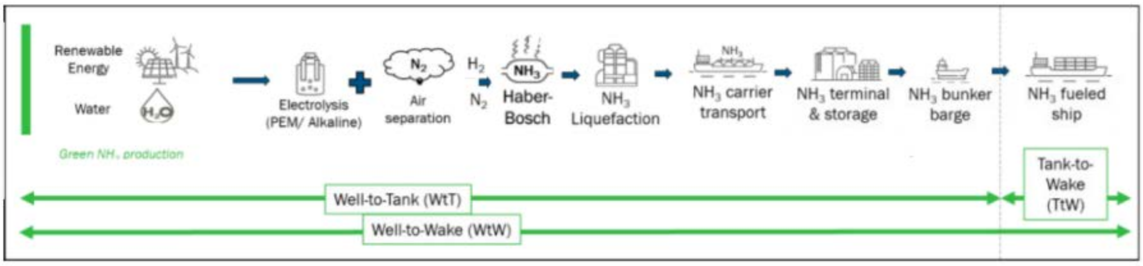


Figure 10. System boundaries for green hydrogen. Modified from Sphera (2024).

Stakeholders in biofuel and e-fuel production include biofuel producers, suppliers of biomass feedstock, regulators and suppliers of equipment to production plants. Biofuel producers include Oil majors as well as independent companies. An example is the First Movers Coalition (FMC) of the World Economic Forum. Under the FMC, 16 companies within shipping have committed to having 5% of their deep-sea shipping powered by zero-emission fuels by 2030 or to move at least 10% of the volume of their goods on such vessels by 2030, increasing to 100% by 2040. Fuels include renewable ammonia and methanol.

See also section 3.4.4 regarding the IMO Future Fuels and Technology Project.

2.4 Distribution and bunkering

2.4.1 Market structure

Major bunkering ports today include Rotterdam and Singapore (see Figure 4 above). Singapore, the world's largest bunkering hub and busiest transshipment port, bunkers over 50 million tons of fuel a year, and has together with Rotterdam sourced around one million ton of biofuel already in the first half of 2024, to a large extent by virtue of the requirements of the IMO regulations. The Maritime and Port Authority (MPA) of Singapore targets to reduce absolute emissions from port terminals by at least 60% from 2005 levels by 2030, and to achieve net zero by 2050. MPA have developed frameworks to allow licensed bunkers suppliers to supply biofuel within the port to vessels.

The unique high bunkering volumes in the Port of Singapore arises from its strategic location between China and India/Africa/Europe, its role as a global bunkering hub with the infrastructure to harbor a large number of ocean-going vessels of all types, and offering competitive fuel prices. It is therefore also a key player in any effort to introduce sustainable marine fuels in a larger scale on the market. See section 3.8 for more information.

The Port of Singapore collaborates with several domestic and international institutions regarding development in this area. The Nanyang Technological University (NTU) Maritime Energy & Sustainable Development Centre of Excellence[21] (MESD), launched in October 2017, is working to enable the use of biofuels in Singapore e.g. biofuel compatibility studies and sea trials for harbour craft. The Global Centre for Maritime Decarbonisation[22] (GCMD), was launched on August 1, 2021. GCMD is a non-profit organisation that supports the decarbonisation of the maritime sector as a sort pf proving ground through pilots and trials, assessing diverse items such as the carbon reduction potential and quantity of drop-in green fuels, ammonia as a maritime fuel and biofuel certification.

GCMD are currently managing global trials on biofuel blending and bunkering, comprising four supply chain trials involving three major ports – Singapore, Vlissingen and Rotterdam, and bunkering of seven vessels across several segments including container, tankers and gas carriers. The trials deploy existing biofuel blends, such as HVO and UCOME, blended with either VLSFO, HSFO or MGO in blends up to 30% biofuels (B30). Different tracing techniques, including the use of physical tracers, carbon dating, and chemical fingerprinting are included in the trials. A lock-and-seal methodology to track sustainable biofuels from their production

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[21] https://www.ntu.edu.sg/mesd-coe/publications
[22] https://www.gcformd.org

facilities to their consumption on-board vessels is also evaluated. One goal with the trials is to use the results to form the basis of an assurance framework for drop-in green fuels. Such a framework could provide emissions abatement assurance to ship-owners and charterers who are paying a premium to deploy green fuels over fossil fuels.

The port of Rotterdam sells around 10 million tons of bunker fuel annually. Sales of bunker LNG fuel is increasing in Rotterdam, now at around 100 000 m^3 per year. As to the quality of oil bunkered, LSFO or better is required in all ports under IMO regulation, with the exception of ships equipped with scrubber filters. Requirements for such equipment is now increasingly installed in ships, which has led to an increase in an increasing demand for the cheaper HSFO fuel. For example, the market share of high-sulphur bunkers in Fujairah (UAE) increased to 24% in 2023 compared with 20% in 2022[23]. The same trend may be seen for e.g. the Antwerp-Bruges port.

The development of supply, capacity of bunkering and capability of blending is very likely not going to be a straight line. The port of Rotterdam reports that the sales of bunker fuel and biofuel blend marine fuels declined by 26 % in 2023 compared to 2022 (Argus media, 2024). While not concerning marine fuels primarily, it may be noted that Shell Nederland Raffinaderij in July of 2024 announced that it paused its construction work at a biofuels production facility at the Shell Energy and Chemicals Park. The plant had been expected to start production in 2024 with a capacity of 820 tonnes a year of Sustainable Aviation Fuel and renewable diesel, using waste feedstock and certified sustainable vegetable oils.

It can be expected that the ports which participate in Green Corridor initiatives (see section 3.4.5) will lead the transition to low-GHG fuels. As an example on the Pacific Rim, the Ports of Los Angeles and Long Beach (USA) have signed green shipping corridors agreements with ports in Asia to deploy ships with full life cycle low or even zero carbon emission capabilities in this corridor. Since the announcement of ZEERO (Zero Emissions, Energy Resilient Operation) commitment, the Port of Long Beach has invested $300 million in establishing a green fuel hub to cut carbon emissions by 91% since 2005. Examples of current development in Singapore are presented in section 3.8.

Cost as a barrier (and driver) concerns both investment in supply infrastructure as well as fuel cost. It can be noted that supply of new sustainable fuels to remote locations with lower demand and a local fleet of smaller vessels may pose a greater challenge as to the decarbonization process. Incentives vary across markets, and include requirements from clients and final users. Enhanced environmental performance may represent increasing value for clients.

2.4.2 Development of bunker capacity for alternative fuels

Bunker capacity for blends and neat biofuel qualities develops as availability meets demand, initially predominantly developed along Green Corridors as discussed in section 3.5.6. Initial requirements for scaling up include investment, and regulation and enforcement governing safety when blending fuel and fuelling vessels.

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[23] Source: Reuters, Jan 17, 2024.

Several ports and markets already have storage capability for methanol and other alternative fuels, but the availability of green methanol or biomethanol is limited.

On 22 February 2024, a total of 510 tonnes of B30 marine biofuels was supplied to the Cargill operated dry bulk carrier, Infinity Sky, in the port of Callao, Peru by global bunker fuel supplier Monjasa. This marks the first supply operation of biofuel to Peru. The B30 biofuel blend consisted of 30% Fatty Acid Methyl Ester (FAME) and 70% Very Low Sulphur Fuel Oil (VLSFO). (Source: Monjasa)

Most biofuels require similar safety and handling concerns as their conventional “counterpart” (see for example Table 3 below). However, depending on the type of alternative fuel, different levels of safeguards are required.

As regards safety precautions for handling of alternative fuel, drop-in fuels such as bio-MGO and bio-HFO, and blends such as B24 and B30 have similar requirements as their fossil counterparts. However, ammonia stands out. A major concern with using ammonia as a marine fuel is its safe handling. Ammonia is toxic and can be lethal upon a 30 min exposure to 1600 ppm concentration (AEGL 3). It is also corrosive when exposed to ambient moisture.

Bulk shipping of ammonia is well developed. However, what is often left out of the equation when discussing the potential for ammonia as a marine fuel is that the majority of the shipped form is cut 50/50 with water which leaves it useful for fertilizer but useless for fuel. The 50% cut also exponentially reduces the risks.

Ammonia is also shipped and used in anhydrous (pure) form. However, in anhydrous form it is one of the most difficult and dangerous chemicals to handle. It will eat any component made with brass or copper, it melts flesh on contact, and forms a white ground hugging – and lethal if inhaled - gas at atmospheric pressure. Any development involving pure ammonia would thus have to establish and maintain very strict – and therefore more demanding – protocols along the value chain from production to use, including on-board management.

Regarding biogas, Infrastructure for distribution in ports can benefit from increasing availability of liquefied biogas and e-biogas, as well as local fossil gas grids to enhance security of supply. Transport is currently (for example in the Nordic port of Göteborg) carried out by tanker with a storage capacity of approx. 20-25 tonnes per transport by road from producer or terminal to filling station. The cistern at the gas station where LBG is stored usually has a storage capacity of about 50-70 tonnes (Grahn et al, 2024). To enable faster bunkering, bunker ships and barges could be included as shown in Figure 22.

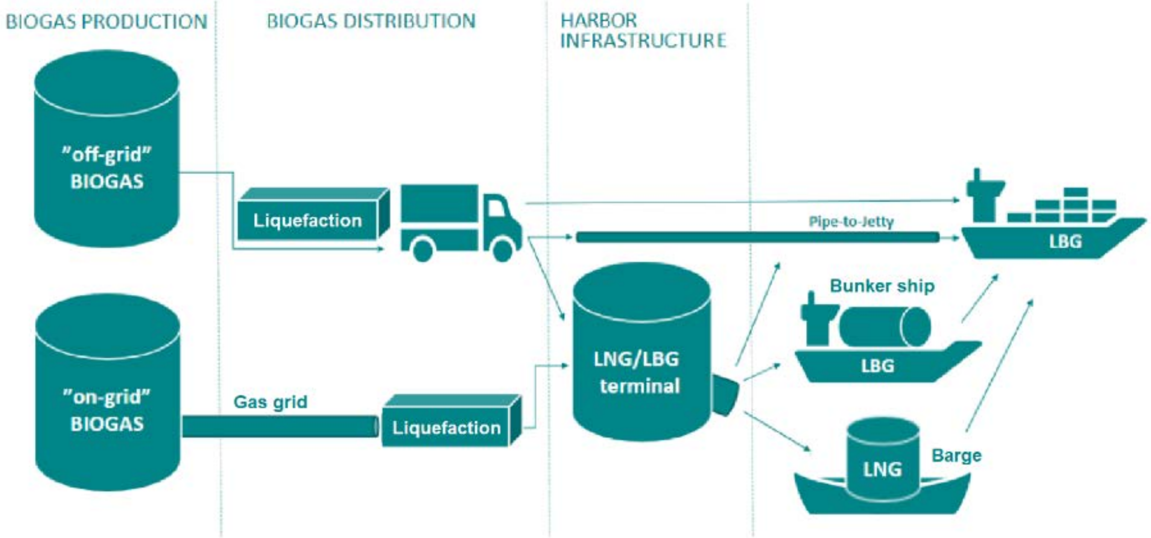

Figure 11. Fuelling infrastructure for biomethane (modified from Grahn et al, 2024)

Bunkering of DME, dimethyl ether, does not imply high risks for safety. DME is gaseous at ambient pressure but can be stored and shipped with equipment similar to what is used for shipping LPG.

Different biofuels are offered to blend with or replace fossil fuel products as indicated in Table 4.

Table 4. Biofuel replacement products

Fossil product	Biofuel blend or replacement product
Low Sulphur Fuel Oil (LSFO) Marine Diesel Fuel (MDO) Marine Gasoil Fuel (MGO) Marine Fuel Oil (MFO) Intermediate Fuel Oil (IFO) Heavy Fuel Oil (HFO)	Biodiesel (FAME) HVO F-T diesel
LNG	LBG
Methanol	Biomethanol
Ammonia	
DME	

Biofuels or biofuel blends characteristics must be tailored to serve as replacement for the respective type of fossil fuel depending on infrastructure and engine specifications etc. Specifications for biofuels is further discussed in sections 3.3.3 and 3.5.5.

2.5 Biofuel use

2.5.1 Introduction

As we have seen, there are several means to replace fossil fuel with biofuel in ships.

- Drop-in biofuel – blended or neat used in existing ship engines
- Engine conversions to adapt to new biofuels, and to biofuel blends bringing new fuel characteristics

- New fuels with engines, tanks and exhaust management adapted or developed to accommodate new types of biofuel
- Dual-fuel systems, where engines and exhaust management are controlled to accommodate one of two (or more) fuels or fuel types.

Drop–in fuels

Drop-in fuels have the advantage of minimal investment on the distribution and ship level. Drop-in fuels also enable blending. Blends are also the fastest, easiest and often the least costly means to increase the use of biofuels in shipping, using existing ships and distribution systems, with additions such as emulsifiers for blending.

New vessels may be equipped with engines approved for biofuel blends, and/or dual fuel systems with e.g. HFO and methanol or MGO/LNG.

Independent of the fuel of a certain vessel, fuel management remains important when using blends and neat biofuels since specifications may vary from one bunker to the next.

Different engine types are capable of using different fuels. Table 3 shows the capability of each type. The categories HFO MGO and VLSO are valid regarding fossil fuels as well as for biofuels and blends of the two categories.

Table 5. Fuel compatibility (modified from Simonsen et al, 2021)

Engine	HFO	MGO	LSFO	Gasoline	Methanol	Ethanol	Methane
Compression ignition (Diesel principle)							
2-stroke (slow speed)	🟩	🟩	🟩				
4-stroke (medium speed)	🟩	🟩	🟩		🟩	🟩	🟩
Spark ignition (Otto principle)							
4-stroke				🟩	🟩	🟩	🟩
Non-Reciprocating engines							
Steam turbine	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Gas turbine	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Liquefied biomethane

Ships fueled by LNG, or liquefied natural gas, effectively run on liquefied methane which may be of fossil or renewable origin. LNG demand has grown around eight times the rate of overall natural gas consumption over the past five years, meaning that production of ships carrying LNG has increased considerably. Given the lower carbon emissions of LNG fuelled ships, both conversions to LNG (e.g. dual fuel with diesel) and production of new LNG fuelled vessels have increased. In most cases, the most economical option for a conversion is to convert the existing engines of a vessel, but installation of new dual fuel engines is in some cases a feasible option as well. Also the fuel gas handling system needs to be installed including the bunkering station, LNG tanks and related process equipment as well as the control and monitoring system. Conversions can be carried out from MGO and even for HFO fuelled vessels.

Biomethanol
Methanol is a liquid at ambient temperature and pressure, making it a favourable marine fuel in terms of storage and handling. Methanol has the lowest carbon content and highest hydrogen content of any liquid fuel. For a given level of autonomy, methanol requires double the size tanks as diesel fuel. Even so, dual-fuel two- and four-stroke methanol engines are commercially available and operational. The industry has also gained operational experience of these engines on board different ship types in the past decade. Methanol dual-fuel engines are now being developed and commercialized for a wide range of vessels.

An example of successful conversions was the SPIRETH project (Ellis et al, 2014). The project had two main testing and development streams, DME and methanol. A methanol-to-DME conversion process plant for shipboard operation was developed, testing the plant and the DME fuel mix onboard an existing ship, using an adapted diesel auxiliary engine. Methanol would be loaded and stored on the ship, and converted using the Haldor Topsøe OBATETM (On board alcohol to ether) process. Further, a full scale marine diesel engine was converted to run efficiently on methanol with pilot fuel ignition, and undergoing performance testing in a laboratory. SSPA Sweden AB, ScandiNAOS, Stena Rederi, Haldor Topsøe, Lloyds Register EMEA and Wärtsilä carried out the project, which was funded by Norden Energy & Transport, the Swedish Energy Agency, Baltic Sea Action Plan Facility Fund (Nordic Investment Bank), the Nordic Council of Ministers' Energy & Transport Programme, and the Danish Maritime Fund. The project led to the world's first methanol conversion of main engines on a passenger ferry, the Stena Germanica in 2015, funded in part by the EU TEN-T program.

Bioethanol
Since 2023, the engine producer Wärtsila has been testing the use of only ethanol (and also combinations of bioethanol and biodiesel) in some engines (Wärtsila famy 32, W7L32M, HY 3xDG). The availability of the fuel, with major production in Brazil and USA and a well-established production process from sugary feedstocks has sparked discussion and evaluation on a possible role also in maritime shipping[24].

(Green) ammonia
Combusting green ammonia is one means to achieve zero carbon shipping. See section 2.3.8 for further discussion on green ammonia.

The major risk connected with ammonia may not lie with Western flagged vessels crewed by highly trained officers and men, refuelling in well-regulated ports, with every part of the system from ship to holding tank monitored and inspected. In the other end of the spectrum, ships may be crewed and maintained by the lowest cost personnel the shipping company can pass off, on convenience flagged vessels, and refuelled at the lowest cost refuelling dock, potentially with less than ideal regard for safety and environmental concerns. Adding ammonia fuel to that scenario may pose a risk to sailors, dock workers, and civilians.

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[24] https://www.ajot.com/news/raizen-and-waertsilae-test-ethanol-as-an-alternative-maritime-fuel

Fuel conversions can be done by modifying the engine or by adding fuel processing equipment on-board.

Section 2.4.2 discusses ammonia distribution and bunkering.

2.5.2 Marine engines for biofuels

The production of marine engines is adapting to the demand for compatibility with biofuels and e-fuels. Installation, conversions and service must adapt to the new fuels and requirements. Major engine producers include MAN, Wärtsilä, Cummins, Mitsui, Perkins, Doosan, WinGD, MTU and others. As to the adaptation to advanced motor fuels, Winther et al (2023) noted that

- Ultra-low-sulfur marine fuel is now available in adequate quantities around the globe, contributing significantly to a reduction in marine sulfur emissions. Further, liquefied natural gas (LNG) as a fuel has seen a big surge in both number of ships and total amount of LNG used for shipping, reducing both sulfur and black carbon emissions.
- Scrubber installations have also increased rapidly since the limitations on sulfur was introduced by IMO in 2020. Open-loop scrubbers are prohibited in China.
- Emissions of black carbon, not always captured by scrubbers, can be effectively mitigated by using advanced fuels such as methane, ammonia, hydrogen, or methanol.

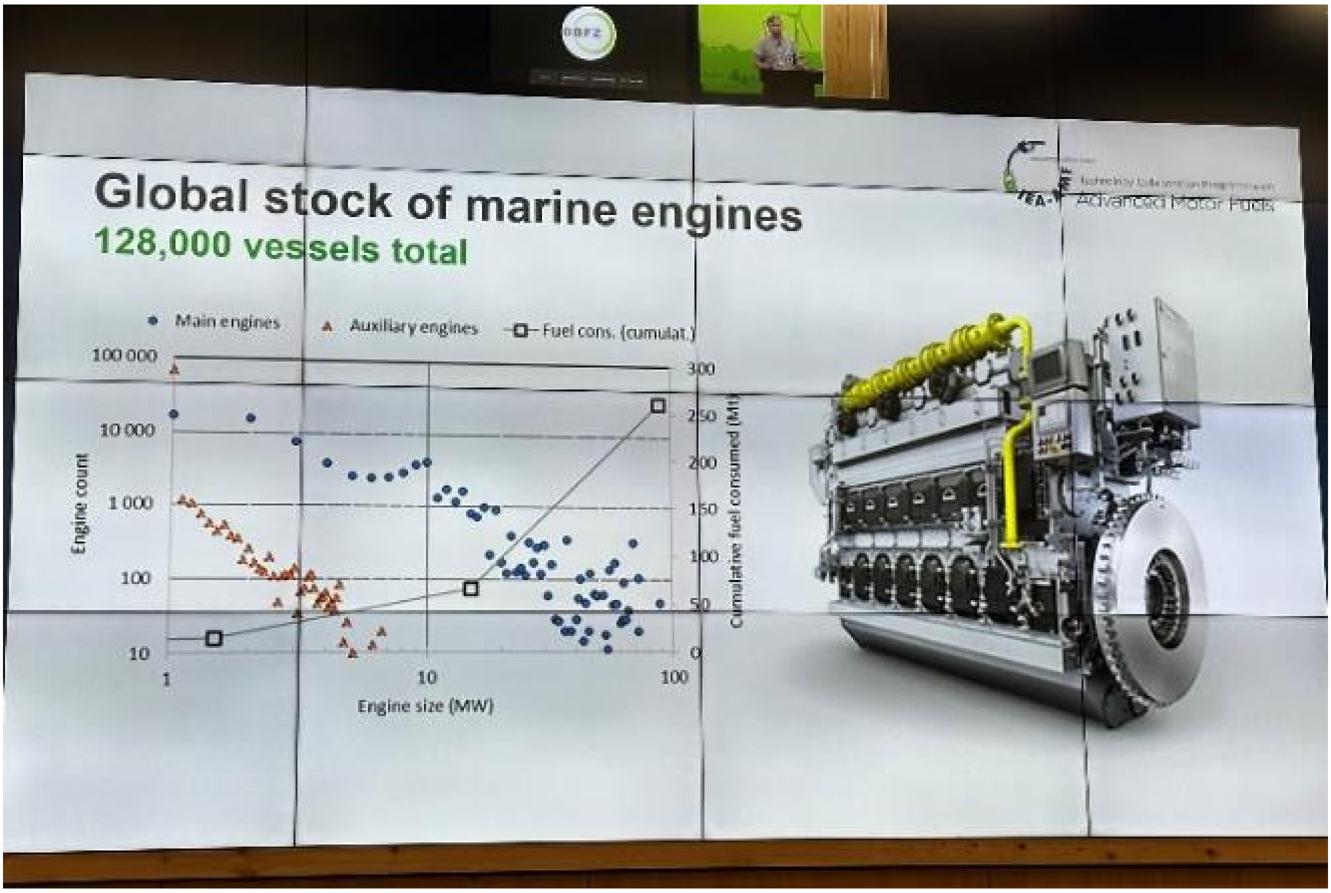
Regarding fuel consumption, marine slow speed two-stroke engines, operating without a gearbox with the propeller on the engine shaft, can reach an energy efficiency of over 50%, which is nearly double that of 4-stroke gasoline engines. There are thus considerable benefits with developing sustainable biofuels for this engine category.

Biofuels – e.g. biomethane, bioethanol, biomethanol and HVO, are effective both in reducing sulfur emissions as well as reducing net carbon emissions compared to fossil fuels. Methanol dual-fuel engines are becoming an accepted option for new ships. Wärtsilä and ethanol producer Raizen are evaluating ethanol as marine fuel[20].

Hydrogen propulsion systems, either as ICEs or fuel cell/battery hybrids, are still new to the market. Engines for ammonia are still in the research and development phase, and storage of ammonia is also a challenging area.

Electrification may be the best option for decarbonization regarding ferries and short sea shipping. It remains to be seen to which extent the higher efficiency will spark innovation and investment in this area.

It may be noted that the amount of marine engines in operation at a given time are a fraction of the number of engines operating in on- and offroad vehicles. The global shipping fleet is limited to around 128 000 vessels, with less than 1000 engines with a size above approximately 50 MW (Source: IEA TCP AMF). However, ships in circulation have a long lifetime. Thus, changes in regulation for marine fuel, unless adapted to this lifecycle, or allowing regular HFO or MGO engines using drop-in fuels to be used, will be slow and not evidently be at net zero in 2050 in line with IMO guidelines and ambition.



Global stock of marine engines

128,000 vessels total

Figure 12. Source: IEA TCP Task 60 AMF

Two examples of recent development for alternative fuel use are the two Nordic LNG-fueled ferries Viking Glory and Viking Grace, which only used liquefied biomethane (bioLNG) as fuel[25] from August 29 to September 4, 2024, as part of operations in a new green corridor (see section 3.5.6).

For smaller craft, electric motors, running on battery, gensets, or even fuel cells are an alternative. Such “hybrid” drivetrains are common for tug boats and ice breakers where propulsion may need to be directed in different directions. Electrification of local ferries and other vessels on shorter routes is expected to accelerate.

A contract was signed August 26, 2024, between Technology group Wärtsilä and Norwegian ship-owner Eidesvik to supply the equipment for the conversion of an offshore platform supply vessel (PSV) to operate with ammonia fuel.

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[25] https://bioenergyinternational.com/baltic-seas-first-green-corridor-culminates-in-an-historic-week/

The vessel, Viking Energy, which is on contract to energy major Equinor, is scheduled for conversion in early 2026 and is expected to start operating on ammonia in the first half of 2026, becoming the world’s first ammonia-fueled in-service ship.

Equinor will charter the vessel and contributes with financing for the conversion. Wärtsilä will then supply the engine and complete fuel gas supply system and exhaust aftertreatment needed for the conversion, making it also the first vessel to use Wärtsilä’s recently released ammonia solution.

In addition to the Wärtsilä 25 Ammonia engine, Wärtsilä will supply the complete ammonia solution, including its AmmoniaPac Fuel Gas Supply System, the Wärtsilä Ammonia Release Mitigation System (WARMS), and a selective catalytic reduction (SCR) system designed for ammonia[26].

2.5.3 Maritime fuel standards

The seventh version of the ISO 8217 standard named **Products from petroleum, synthetic and renewable sources — Fuels (class F) — Specifications of marine fuels** was published by ISO in May of 2024. It responds to an increased focus on environmental concerns and legislation to address them is leading to a transition in the nature of marine fuels, taking into account a shift away from marine fuels supplied from traditional oil products derived from the processing of petroleum crude, and a shift towards oil products derived from synthetic

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[26] Source: https://www.manifoldtimes.com/news/wartsila-eidesvik-to-convert-psv-to-run-on-ammonia-bunker-fuel/

and renewable, recycled or alternative sources. The new version incorporates a number of categories of distillate and residual fuels. While the new version facilitates the transition, it should be noted that sustainability aspects and accounting are not within the scope. The categories of fuel in this new version have been classified according to ISO 8216-1 and include the distillate fuel categories DMX, DMA, DMB, DMZ, DFA, DFB, DFZ and the residual fuel categories RMA, RME, RMG, RMK and RF. (see section 1.6 for a discussion on the fuel classes).

Standards for methanol marine biofuels are different since methanol is an alcohol with properties and test methods diverging for that of diesel fuels. Its use as a marine fuel is specified in ISO 6583:2024 (methanol as a fuel for marine applications). Further, the flashpoints of methanol and ethanol are both below the minimum flashpoint for marine fuels specified in the International Maritime Organizations (IMO) Safety of Life at Sea Convention (SOLAS). Criteria for their use may be found in the International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code) established by IMO. Currently (October 2024) only available in its 2016 edition, the code is about to be updated. IMO has adopted MSC.1/Circ.1621, Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel in November 2020. Further, the American Bureau of Shipping has issued its Requirements for Methanol and Ethanol fuels vessels (where the IGF code is included) in July 2024.

Standards for upgraded pyrolysis oil, synthetic biofuels and biocrudes are discussed in section 2.3.5.

Biofuel bunkering requires ISCC EU certification by the seller and Proof and Sustainability (PoS) documentation for the shipment of biofuel to be valid in the port of Singapore and other major ports. The PoS cannot be issued along with the delivery if the feedstock is not compliant with RED II.

Current fuel oil specifications may be a barrier for biofuel uptake. Specifications were based on fossil fuel which are not always reflective of biofuel components. Eg TAN for bio-oils does not reflect the low corrosivity of the bio-oil. Bio-oils contain a lot of weak acids (phenols) that are not corrosive but show up in the TAN measurement. Thus, spot test results on compatibility are not reliable for biooils.

2.5.4 Regulation

The International Maritime Organization (IMO) is a specialized agency of the United Nations responsible for the global regulative framework surrounding international shipping. The IMO regulates all aspects of safety, environmental concerns, legal matters, technical cooperation, maritime security, and efficiency within shipping. The work leading up to its strategy work on carbon emissions is further described in IEA (2021). Its implications are discussed further in this report as regards energy efficiency in section 2.6.2, and broader regarding GHG in section 3.4.3.

In 2018, the IMO adopted its Initial IMO GHG Strategy, aiming to reduce absolute GHG emissions by at least 50 percent by 2050 as compared to 2008 levels. Although the IMO participated in the 2015 United Nations Climate Change Conference in Paris, the IMO was not part of the Paris agreement on climate change and must self-regulate on issues like GHG emissions. Although accused of inaction after the Paris agreement, the IMO Marine Environment has initiated a comprehensive roadmap regarding decarbonization of shipping to (near) 2050.

In its pursuit of addressing GHG emissions and achieving its initial GHG strategy, IMO has established a comprehensive regulatory framework, encompassing the following components:

1. Energy Efficiency Design Index (EEDI): New ships must be designed and constructed with a focus on enhanced energy efficiency.
2. Ship Energy Efficiency Management Plan (SEEMP): Ship-owners use this practical tool to manage environmental performance and enhance operational efficiency.
3. Energy Efficiency Existing Ship Index (EEXI): Came into effect 1st January 2023, EEXI enforces similar design standards as EEDI, with adjustments for situations where design data may be limited.
4. Fuel Oil Consumption Data Collection System (DCS): It requires annual reporting of CO_2 emissions, activity data, and ship particulars for vessels exceeding 5,000 gross tons.
5. Carbon Intensity Indicator (CII): Rates ships above 5,000 gross tons on an A to E scale, measuring their annual performance in terms of CO_2 emissions per deadweight tonnage and distance travelled.

In 2023, this strategy was updated at the 80th session of the Marine Environment Protection Committee (MEPC 80), the IMO also introduced interim checkpoint objectives for 2030 and 2040). Including the reduction of carbon intensity of ships through improvement of their energy efficiency by at least 40% by 2030, compared to 2008.

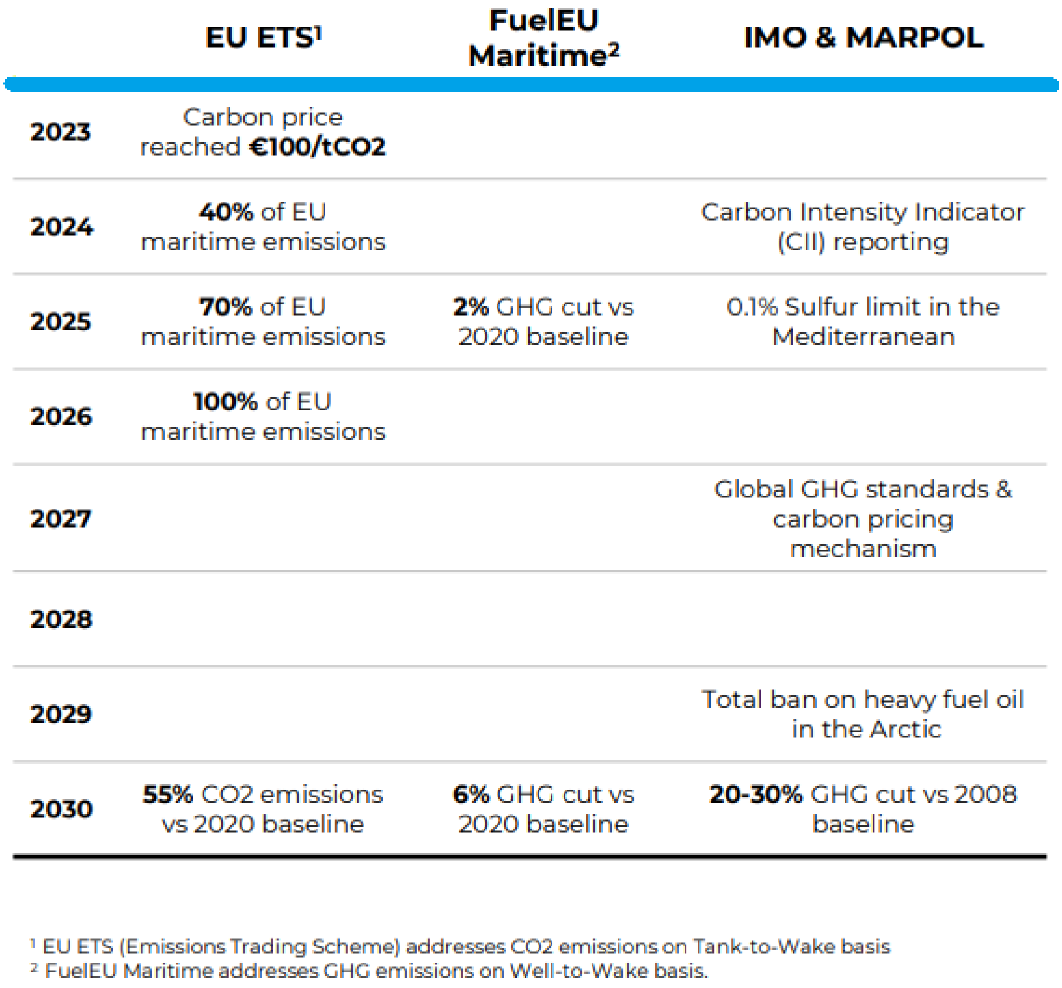
The revised strategy places a clear emphasis on fostering technological innovation and ensuring the availability of zero or nearly zero emissions technologies, fuels, and energy sources within the shipping sector. To this end, the strategy sets an interim target of 5% uptake of alternative fuels (with an aspirational target of 10%) of the energy employed by international shipping by 2030. Achieving these milestones necessitates the implementation of robust technical, operational, and economic measures on a large scale, with their effective execution taking several years. To attain net-zero GHG emissions, indicative milestones have been established, each with specific targets for each new decade. By 2030, the objective is to reduce total annual GHG emissions by a minimum of 20% (with an ambitious target of 30%) in comparison to 2008 levels. This is followed by a more substantial reduction of at least 70% (with a striving goal of 80%) by 2040, also relative to 2008 levels (IMO, 2023). These benchmarks underscore the maritime industry's unwavering commitment to alleviating its environmental footprint and actively contributing to global endeavours aimed at countering climate change.

The carbon emissions from biofuels use, or from any other fuel, cannot be directly measured but must be assessed for the whole value chain. As to the assessment of life cycle emissions from different types of renewable fuels, Carvalho et al (2023) points to that fuels that have low or zero tank-to-wake (TTW) emissions can have substantial upstream (production and distribution) emissions that are not counted when assessing only TTW emissions. Though upstream or indirect effects are uncertain and may vary between supplier and distributor, they might be large enough to greatly affect the estimated GHG savings of some fuel pathways. This must be taken into account when developing policy. For example, methane slip occurring along the value chain for CBG/LBG fuels may compromise the low emissions from renewable methane fuel. Since methane slip also occurs from fossil fuel combustion in marine engines, methane slip is the focus of several initiatives such as the UNs Oil and Gas Methane Partnership and the Methane Abatement in Maritime Innovation Initiative.

In addition to the IMO regulation on carbon emissions, there are also regulations regarding local emissions such as sulfur.

As shown in Table 6, the European Union has also developed incentives and regulation to accelerate the transition for EU maritime shipping. This is further discussed in section 3.4.

Table 6. Regulatory measures in the EU and by IMO



	EU ETS[1]	FuelEU Maritime[2]	IMO & MARPOL
2023	Carbon price reached **€100/tCO2**		
2024	**40%** of EU maritime emissions		Carbon Intensity Indicator (CII) reporting
2025	**70%** of EU maritime emissions	**2%** GHG cut vs 2020 baseline	0.1% Sulfur limit in the Mediterranean
2026	**100%** of EU maritime emissions		
2027			Global GHG standards & carbon pricing mechanism
2028			
2029			Total ban on heavy fuel oil in the Arctic
2030	**55%** CO2 emissions vs 2020 baseline	**6%** GHG cut vs 2020 baseline	**20-30%** GHG cut vs 2008 baseline

[1] EU ETS (Emissions Trading Scheme) addresses CO2 emissions on Tank-to-Wake basis
[2] FuelEU Maritime addresses GHG emissions on Well-to-Wake basis.

2.5.5 Markets and stakeholders

Several types of stakeholders have a role in the use of the fuel – shipbuilders, engine producers, shipping companies/fleet owners and not the least the transport buyers.

Transport buyers may have an important role in decarbonization of shipping in that it is with them – and their clients in turn – that the power to require fossil free transport lies. Initiatives such as the Zero Emission Maritime Buyers Alliance[27] (ZEMBA) and the First Movers Coalition[28] mean cargo owners with different business models can unite to create demand and take advantage of economies of scale. The ZEMBA alliance now comprises 40 companies, with a tender for zero-carbon shipping services through requiring e-fuels for primary propulsion set to launch in January 2025.

Operators, ports, fuel suppliers and other stakeholders have also joined forces setting targets and operational goals for given transport relations, known as Green Corridors. These are discussed in section 3.4.5.

Shipping companies are diversifying their fleet towards renewable fuels. As an example, Maersk announced in August 2024 its orders of 20 new dual fuel vessels, totalling 300 000 TEU capacity[29].

Initiatives to support the global implementation of IMO regulations include Green Voyage 2050 and the Maritime Technology Cooperation Centres. Both these initiatives could serve to enhance a dialogue on the opportunities for using sustainable marine biofuels as a means to decarbonize shipping.

To strengthen the MARPOL Annex VI convention (implementing the IMO GHG strategy to reach net-zero GHG emissions from ships by or around 2050) compliance, IMO in 2019 launched the GreenVoyage2050[30] initiative. Partnering countries are supported in assessing maritime emissions in the national context, drafting (and enacting) legislation implementing MARPOL Annex VI into national law, and developing demonstrations and innovations to support low carbon shipping. The list of partnering countries at this time includes Belize, China, Cook Islands, Georgia, India, Kenya, Malaysia, Solomon Islands and South Africa. Funding to date comes from five European states.

IMO and European Union (EU) in December 2015 agreed to establish Maritime Technology Cooperation Centres[31] (MTCCs) in five regions, i.e. Asia, Africa, Latin America, Caribbean and Pacific. The overall objective is to enhance capacity building in mitigating climate change through the effective adoption of global efficient energy measures by way of technical mentorship, professional training, data collection, regional coordination in adhering to international regulations on energy efficiency of ships. In December 2016, Shanghai Maritime University (SMU) entered into an agreement with IMO as the host Institution of MTCC-Asia, which was then inaugurated in 15th May 2017.

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[27] http://www.shipzemba.org/
[28] https://www.weforum.org/first-movers-coalition
[29] https://www.maersk.com/news/articles/2024/12/02/maersk-completes-order-of-20-dual-fuel-vessels
[30] Greenvoyage2050.imo.org
[31] https://gmn.imo.org/mtcc/

2.6 Energy efficiency

2.6.1 Introduction

Initiatives and incentives to reduce the amount of energy used per per ton-km of a given type of shipping is an important part of the work to facilitate the uptake of sustainable fuels. More efficient ships mean lower consumption and thus an increased willingness and ability to pay. A number of methods are relevant in order to reduce fuel consumption per ton-km. Which method, or combination of methods, that is relevant depends on the type of vessel and transport relation, and may include slow steaming, hull cleaning, sails and hydrofoil. Since the transport of shipping fuel itself is an important driver of demand for marine shipping, the decarbonization may affect demand since regionalization of supply of some fuel types, e.g. biogenic e-fuels, may reduce the need for transporting these fuels across markets.

Energy efficiency measures are described below. The impact from such measures are further discussed in section 3.5.7.

2.6.2 IMO Regulation on energy efficiency

The IMO has been working to reduce emissions from international shipping since the early 2000s. The Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) were the first regulatory measures, which came into effect on January 1, 2013. More recently, in 2021, the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) were introduced as part of IMO’s short-term GHG reduction strategy, with both coming into effect on January 1, 2023. The first annual CII reporting is expected by the end of 2023, and ratings will be available in 2024.

IMO's regulatory approach is goal-based and technology-neutral, allowing flexibility for stakeholders to innovate without mandating specific technologies. This encourages a broad range of innovations throughout the value chain. Under MARPOL Annex VI, adopted by member states, key energy efficiency measures have been introduced, including the EEDI, EEXI, and CII.

Ship Energy Efficiency Management Plan (SEEMP):
Introduced in 2013 and revised in 2023, SEEMP is a ship-specific plan designed to improve energy efficiency and environmental performance. It consists of three parts: management plans to improve efficiency, fuel oil consumption data collection, and an operational carbon intensity plan. SEEMP is supported by the Energy Efficiency Operational Indicator (EEOI), which measures fuel consumption per unit of transport work.

Data Collection System (DCS):
Since 2019, ships over 5,000 GT—responsible for around 85% of shipping CO2 emissions—have been required to report fuel consumption under MARPOL Annex VI. Starting in 2023, this data is used to calculate a ship's operational Carbon Intensity Indicator (CII) and guide decision-making on enhancing energy efficiency in shipping. The data collected through the IMO's Data Collection System (DCS) will be invaluable for driving innovations, such as the application of machine learning and artificial intelligence algorithms to optimize fuel efficiency, improve ship design, and advance the use of hybrid propulsion systems. These

developments will unlock further opportunities for energy efficiency improvements within shipping operations.

Energy Efficiency Design Index (EEDI):
Implemented on January 1, 2013, the EEDI applies to new ships over 400 gross tonnage and mandates a minimum energy efficiency level per tonne-mile based on ship type and size. Originally developed for the most energy-intensive segments, such as tankers and bulk carriers, the EEDI has expanded to cover additional ship types, accounting for around 85% of CO_2 emissions from international shipping. By 2025, new ships are expected to achieve a 30% reduction in emissions compared to the 2000–2010 baseline. Compliance is verified by third parties before new ships are cleared for service.

These measures, while helpful, exhibit certain gaps that limit their effectiveness in fully driving energy efficiency adoption (MMMCZCS, 2023). The EEDI focuses on the CO_2 emissions per tonne-nautical mile of a vessel, which allows ship-owners to comply by switching to fuels with lower CO_2 emissions (tank-to-wake), such as liquefied natural gas (LNG), rather than focusing on comprehensive energy efficiency improvements. This creates a scenario where vessels may meet the EEDI requirements without deploying any significant energy efficiency measures. Strengthening the EEDI by prioritizing energy consumed, rather than emissions (or using combination), could remove fuel choice biases and encourage a broader uptake of efficiency technologies.

Energy Efficiency Existing Ship Index (EEXI):
Applicable to all ships over 400 GT, the EEXI measures the energy efficiency of existing ships. Ships must calculate their "attained EEXI," which is compared against the "required EEXI," based on the most recent EEDI standards. For many vessels, limiting shaft or engine power has been the primary method for achieving compliance with the Energy Efficiency Existing Ship Index (EEXI). This approach is cost-effective and has a significant impact on EEXI.

However, also here there are gaps that limit their effectiveness towards energy efficiency adoption (MMMCZCS, 2023). The reduction in available on-board power is unlikely to immediately decrease global CO_2 emissions, as most vessels already operate below the new power limits. In the future, EEXI compliance may restrict vessels' ability to increase speed under favourable conditions or compensate for delays. This is a one-time certification that considers ship type, capacity, and propulsion method. Compliance measures for existing ships may include power limitation, wind propulsion, and propeller optimization.

The EEXI allows compliance through power limitations rather than technological retrofits. Most vessels already operate below their maximum service speeds, so power limitations may not significantly increase energy efficiency adoption. While the EEXI aligns older vessels with those compliant under the EEDI, retrofitting older ships with energy-saving technologies could be incentivized further to enhance overall fleet performance.

Carbon Intensity Indicator (CII):
Mandatory for ships of 5,000 GT or more, the CII rates operational carbon intensity annually. The CII scale ranges from A to E, with ships rated D for three consecutive years or rated E for one year required to develop corrective action plans. Ships rated A or B may be incentivized by administrations, ports, and the financial sector using tools enabled by CII. The CII framework, in effect since January 2023, includes measures such as ship speed optimization, weather routing, and the use of alternative fuels.

MMMCZCS (2023) has identified risks that also CII as a measure will fail to attain the desired goal. The CII measures a vessel's operational efficiency but requires close collaboration between various stakeholders, including ship-owners, operators, and ports. Improving CII ratings often relies on operational measures, such as speed reductions, rather than technical upgrades. The complexity of collaboration can limit the impact of CII on efficiency improvements, and a more holistic approach, such as shared responsibility among all stakeholders, would strengthen its influence on emissions reductions.

2.6.3 Slow steaming

Benefits of slow steaming, i.e. sailing at lower speed, include lower fuel consumption but also reduced wear on the machinery and related systems, as well as lower emissions. Since carbon dioxide emissions are proportional to the amount of fuel consumed, slow steaming contributes significantly to carbon dioxide emissions reduction. Slow steaming is particularly suitable for large container ships with a design speed of more than 20 knots, but the effectiveness of the measure is limited by the ability of the vessel’s propulsion system to adapt to long-term travel at reduced speed. Experiences are positive[32] and are adopted as part of strategies to reduce costs, in addition to other measures as described below.

2.6.4 Hull cleaning

Sailing on open waters sees marine organisms build up over ship hulls, reducing overall performance and can cause several maintenance issues. If frequent cleaning does not occur a clumpy slimy layer, known as biofilm – a layer of microorganisms and bacteria – will build up on the ship’s hull.

Hull cleaning to remove marine debris and species built up over time traditionally takes place at port between voyages. However, a severe build-up requires harsher cleaning processes that see hull hydrodynamics being degraded, which can lead to increased fuel consumption and CO2 emissions. In severe cases where cleaning has not occurred for some time hulls can begin to accumulate barnacles and seaweed which can amount to a significant increase in weight and drag for a ship. The additional weight of these marine stowaways, combined with the weight of the hull biofilm, results in increased drag for the vessel which can result in fuel penalties.

Manual, semi-autonomous or autonomous/robotic methods to clean hulls while ships are at sea may reduce fuel cost and time in the harbour. Automated solutions also reduce staff cost, and allows frequent cleaning which optimizes and maintains hull efficiency.

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[32] https://shipandbunker.com/news/world/655913-more-slow-steaming-for-maersk-on-far-east-north-europe-services-report

2.6.5 Sails

Sails could reduce the fuel use per ton-km for tankers and container ships. Several stakeholders develop projects for the deployment of more or less fixed wings on ships. Sails, for this generation of shipping, can be either rotor sails, utilizing the Coriolis effect, or more like wings, utilizing the so called Coanda effect.

Several examples of these technologies exist. French startup AYRO develops wings for sailing ships, including container ships, and saw four of its wings, with a height of 37m and each with a surface area of 363 m^2, fitted on *Canopée,* a 121 m hybrid industrial cargo ship. The company raised €19.2 million in its Series B investment round in September 2023.

The 81 000 DWT *Pyxis Ocean*, has two 37.5 m high sails from steel and fiberglass, developed by BAR Technologies and Yara Marine Technologies, mounted in 2023.

The company Oceanbird was founded in December 2021 as a 50/50 joint venture by Alfa Laval and Wallenius Lines. An existing Wallenius vessel, the 2009-built Tirranna, is set to undergo a transformative retrofitting process with six wing sails running in parallel across the expansive deck.

The ship design project for the first fully sailing vessel based on the Oceanbird concept—**Orcelle Wind** – is funded by the EU. Negotiations with shipyards for construction are scheduled to commence in early 2025.

2.6.6 Hydrofoil

Hydrofoils which lifts the hull out of the water, considerably reduces drag and/or increases speed for vessels such as ferries, are developed for different markets. The applications are smaller vessels and not for deep sea, but very relevant to enable efficient passenger transport in and around waterfront cities. Hydrofoil technology is not in itself a novelty, but was developed as early as the 60s and 70s.

2.6.7 Reduced fuel use, and reduced demand for shipping of fuel

As is discussed in chapter 3 in this report, decarbonization of maritime fuels, including marine bunker fuels and lighter distillates has commenced. Further, also demand for fuel for road vehicles and other purposes may be reduced from electrification not only regarding transport, but also steel making, enhanced by improved energy efficiency across demand types and markets. To the extent that demand for biofuel may be met more regionally, production, distribution and blending of the fuel in ports would increasingly become regional and/or more local. This could particularly be the case for biogenic e-fuels[33].

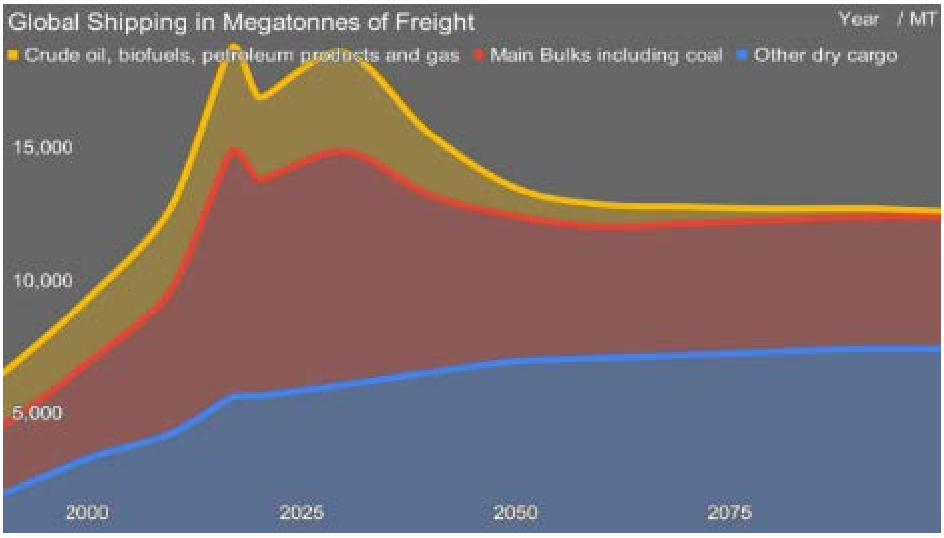

Figure 13. Demand for shipping (Source: Michael Barnard, 2023)

Regional balance in fuel supply would in itself represent a large potential in reducing fuel consumption in shipping since today, around 40 percent of shipping capacity is consumed globally to ship fuel.

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[33] https://www.forbes.com/sites/michaelbarnard/2023/12/05/how-will-climate-action-change-the-face-of-global-shipping/

2.6.8 On-board carbon capture and storage

Carbon Capture and Storage from on-board combustion of biofuels and/or fossil fuels may be a means to reduce carbon emissions from ships and fleets. While there are no IMO regulations that include provision for on-board carbon capture exist in MARPOL or other instruments, at MEPC 81 in March 2024, the IMO agreed to develop a detailed work plan for establishing a framework to regulate on-board carbon capture technologies. EU ETS and FuelEU Maritime have provisions for on-board carbon capture and storage/utilization.

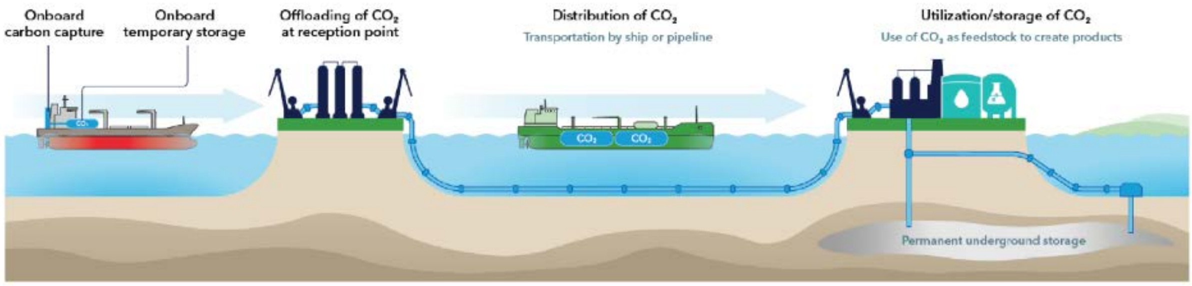

Figure 14. Onboard carbon capture value chain. (DNV, 2024a)

At this time, there is however no infrastructure in place as outlined in Figure 14. Further, a major constraint is the fuel penalty, which may be in the order of between 10% and 40%, depending on the capture method and capacity. Indicatively, for conventional technologies to capture the CO_2, the fuel penalty caused by the extra heat for solvent regeneration, and the electric power to run the fluid pumps, the exhaust gas force draft fan, and the CO2 liquefaction plant. Nevertheless, under certain circumstances the technology may be viable or even competitive once the infrastructure is in place (DNV, 2024a). CCS is an important part of the net-zero scenarios as described in section 4.1.

3 Overcoming barriers for biofuels in maritime shipping

3.1 Introduction

This section consists of a number of topical articles, describing scenarios and specific enablers for the transition, covering the dynamics and discussing how to overcome inherent challenges for decarbonization of shipping fuel by large-scale introduction of maritime biofuels.

The different sections present different perspectives on the ongoing transition. Opportunities and barriers form a complex web across markets, goods types transported and technologies employed.

3.2 A systems' level scenario outlook

Frauke Urban (Royal Institute of Technology, Sweden), Mahrokh Samavati (Ramböll), Fumi Harahap (Ramböll)

3.2.1 Introduction

The shipping industry is a vital component of global trade, responsible for approximately 90% of all goods traded worldwide (OECD, 2023). Despite being the most energy-efficient mode of cargo transport per tonne-kilometre, shipping remains a significant source of greenhouse gas (GHG) emissions, posing a major challenge on the international policy agenda. Maritime shipping —including international, domestic, and fishing activities— contributed 3% of annual global GHG emissions measured in CO_2 equivalents (IMO, 2019). The sector's heavy dependence on fossil fuels, especially oil-based products, highlights the urgent need for a transition to sustainable energy sources.

The Paris Agreement is a policy driver for aiming to limit the global average temperature increase to well below 2°C above pre-industrial levels, with efforts to restrict the increase to 1.5°C. Consequently, the International Maritime Organization IMO's revised targets from 2023 aim for reducing total annual GHG emissions from international maritime shipping by 20-30% by 2030 and 70-80% by 2040, relative to 2008 levels, peaking GHG emissions as soon as possible and achieving net-zero GHG emissions around 2050 (IMO, 2023).

The transition to non-fossil fuels for maritime shipping is slowly emerging as alternative fuels are becoming increasingly available on the market. Research on sustainable energy transitions in the maritime shipping sector is an emerging multidisciplinary field. In the past, studies concentrated on incremental measures to reduce fuel consumption and GHG emissions, such as enhancing energy efficiency and implementing technical solutions (e.g. cold ironing) and operational solutions (e.g. just-in-time arrival). Besides, most of the available studies related to alternative fuels are generally dedicated to natural gas and its potential impact on the operation of vessels. Recently, however, a growing body of literature has begun to explore various decarbonization pathways within the shipping industry, examining the potential of different technologies and alternative fuels from non-fossil sources to reduce emissions (Taljegard et al, 2014; International Renewable Energy Agency, 2021; Grahn et al, 2022; Kanchiralla et al, 2022, Harahap et al, 2023a and b; Urban et al, 2024a and b).

The transition to suitable sustainable marine fuel(s) is highly complex due to factors such as diversity in vessel designs, applications and routes, complexity and number of different stakeholders involved in the complete value chain. Consequently, such transition requires a global perspective and extensive collaboration that involves all critical stakeholder groups from fuel production, distribution and bunkering facilities, to port authorities, shipping companies and logistic companies, vessel and engine designers, regulators and numerous other participants across the value chain.

3.2.2 Use of alternative fuels and technologies

Most marine vessels currently use diesel engines that can switch to alternative fuels such as Fatty Acid Methyl Ester (FAME) and Hydrotreated Vegetable Oil (HVO) with minimum to no change in the design fuel system. On the other hand, changing the fuel system to accommodate utilization of alternatives with different composition and properties (e.g. Liquid Natural Gas (LNG), methanol, hydrogen) than the conventional ones might require significant modifications not only in engine but also in on-board fuel storage system and fuel delivery system (Moirangthem, 2016). Several fuels have been considered to replace the conventionally used marine fuels, including:

- LNG is increasingly used in ferries and cruise ships due to its lower emissions compared to petroleum-based productions. However, its fossil-based origin presents challenges for long-term sustainability (Hansson et al., 2019). Generally, this alternative fuel is currently considered as transition fuel due to its emission reduction potential in comparison to business as usual. The general assumption is that LNG would eventually be replaced by biogas or e-methane.

- Hydrogen is considered to be one of the most promising alternative fuels that could help decarbonize the maritime industry completely in the future. Green Hydrogen is produced through electrolysis powered by renewable energy, while pink hydrogen is being produced by nuclear energy. While still expensive today, green hydrogen benefits from potential feasibility of up-scaling for the maritime industry thanks to its reliance on renewable electricity and water. In such cases, green hydrogen can be produced where there is abundance of renewable electricity such as solar and wind close to ports around the world. Hence, efforts to up-scale its use are being supported by policy-makers and industry world-wide, including in Europe, North America and Asia (Grahn et al., 2021; Kanchiralla et al., 2022; Harahap et al., 2023a and b).

- Methanol: Both bio-methanol and e-methanol are versatile fuel options for marine propulsion. With major shipping companies like Maersk and others investing in methanol-powered ships, it is emerging as a practical alternative to traditional marine fuels (Grahn et al., 2021; Kanchiralla et al., 2022; Harahap et al., 2023a and b). All in all, it is expected that methanol regardless of its origin plays a key role in the shipping fuel mixture of the future.

- Advanced Biofuels: Complex biofuels such as HVO, Fischer-Tropsch diesel, Dimethyl ether (DME) etc. are alternatives to conventional fuels as they have the highest engine/fuel system compatibility among other options while having the potential to reduce the emissions as they are generated from biogenic sources. Moreover, their density is usually comparable to marine fuels currently used in the vessels and therefore the risk of losing cargo space is minimal. (Hansson et al., 2019).

- Ammonia is another non-carbonaceous alternative fuel that has a high potential in decarbonizing the marine industry. Ammonia has an inherent advantage over hydrogen as it is in liquid form in near ambient conditions and no specific equipment is required such as the ones for storing hydrogen. Due to such characteristics and despite health and safety concerns related to its explosiveness and toxicity, its use for energy sector including maritime has attracted large attention. For example, several guidelines and safety standards have been developed or are being developed to address concerns associated with utilization of ammonia as an alternative fuel onboard different vessels (American Bureau of Shipping, 2023). Research continues to address these issues and maximize its potential (Harahap et al, 2023a).

- Battery-Electric Propulsion: Best suited for smaller vessels, this propulsion method relies on renewable or nuclear energy sources. While current battery limitations restrict its use to smaller ships, ongoing advancements aim to expand its application. Smaller electric boats and ferries are already in operation (Urban et al, 2024a).

- Wind and solar propulsion: Wind and solar technologies have been utilized in small boats for years. Projects like Wallenius' Oceanbird are now exploring large-scale wind-powered ships, aiming to reduce dependency on fossil fuels and minimize environmental impact (Wallenius Marine, 2023).

3.2.3 Overcoming barriers for the use of biofuels and other alternative fuels and technologies for decarbonizing maritime shipping

Barriers and challenges

Introducing new fuels to the marine industry involves numerous challenges, such as retrofitting existing vessels or building new vessels, resolving technical issues, navigating policy uncertainties and investment uncertainties, building adequate infrastructure and securing necessary funding. Alternative fuels’ prices, particularly hydrogen and electrofuels, are much higher than fossil-based shipping fuels. These obstacles highlight the complexity of transitioning to sustainable marine fuels and emphasize the need for collaborative efforts among stakeholders to overcome them. Achieving the transition to sustainable marine fuels is essential for reducing emissions, addressing environmental concerns and attaining long-term sustainability goals.

Major challenges for the transition to decarbonize maritime shipping is limited fuel availability and accessibility world-wide. Currently, no alternative marine fuel is considered as “the solution” in terms of its use and availability. Firstly, each suggested alternative fuel comes with its own disadvantages that makes its implementation challenging. Secondly, none of the suggested alternative fuels are produced in sufficient quantities to meet the total demand of the shipping industry. There are estimations that the maritime shipping industry requires more than 300 million tons of fuel annually and alternative fuels are currently only covering a small fraction (Foretich et al, 2021). Thirdly, their production methods are either costly or inefficient resulting in considerable loss of material and energy in the process and consequently increase the production costs. Moreover, the slow development of production methods, especially in case of electrofuels, hinders their integration in the industry. Nonetheless, the future fuel market will most likely include a mix of different fuels. Hence, the production of biofuels and other alternative maritime fuels needs to be sped up and scaled up to meet fuel demands. Enabling local production in the vicinity of major ports might also help with the transition (Harahap et al, 2023a and b; Urban et al, 2024a and b).

Another major challenge for decarbonizing maritime shipping is the lack of suitable infrastructure in the value chains. The necessary infrastructure includes production, supply and transportation, bunkering capabilities and vessels. Although advanced biofuels are generally compatible with the existing fuel infrastructure, other suggested alternatives require substantial adjustments. Consequently, ports, terminals and vessels might require altering and expanding their storage and fuel delivery systems to accommodate such changes. For example, LNG necessitates cryogenic tanks, dual-fuel engines and port liquefaction facilities. Similarly, hydrogen requires cryogenic tanks with proper insulations to limit the boil-off losses as well as reduce the safety risks associated with its high flammability potential and range.

Such adjustments require proper investigation and planning to minimize any potential risk to life and cargo. More specifically for the vessels, such changes might translate to the loss of cargo space. This could not only result in additional shipping costs due to more expensive fuel but also reduce the emission reduction potential, as the number of journeys needed to deliver the same cargo would increase. Besides the storage considerations, the vessel fuel delivery system and engine should be adaptable to the selected alternative fuel. Although similar to fuel infrastructure, onboard fuel delivery systems and engines are quite adaptable to the advanced biofuels such as HVO, major changes might be required when moving towards other options such as hydrogen or methanol. Therefore, besides the need for investments in design of adaptable fuel systems in the new vessels, new plans and investments should be coordinated among all stakeholders to ensure a harmonized transition in every aspect of the infrastructure. For example, new investments are being made for constructing methanol-powered vessels, with the largest container shipping lines currently transitioning to methanol. However, these new methanol-vessels can only be fully used if the fuel production and bunkering facilities are up-scaled at the same pace.

In addition to infrastructure concerns, there are significant technical limitations to scaling up biofuels for shipping, primarily related to securing sufficient feedstock. The availability of biomass feedstock that can be allocated to the energy sector is limited, raising concerns about competition with the food industry. This limitation calls into question the potential for increasing production on a scale that could meaningfully contribute to the decarbonization of the maritime shipping industry. Studies have shown that the current and projected rates of biofuel production may be insufficient to meet the current fuel demands of the shipping sector, potentially making a large impact on reducing emissions less likely. This challenge is further exacerbated by competition among different transportation sectors for access to sustainable fuels, such as road transportation and aviation.

Moreover, not all countries or regions have access to enough sustainable biomass resources, forcing them to explore other production pathways or alternative fuels. This disparity in resource availability adds another layer of complexity to the scalability and availability of fuel on a global scale. For instance, while Northern Europe is rich in forests and waste from the forestry industry, which can be utilized for biofuel production, Southern Europe is better suited for producing e-fuels. An unintended consequence of such market imbalances could be the allocation of more land to growing energy crops, potentially risking deforestation, loss of natural habitats, and increased emissions from land-use changes. Hence, while the push to increase the share of biofuels might reduce emissions from shipping operations, the associated emissions from other parts of the value chain might negate some of these benefits.

Potential solutions

One way to address these concerns is to focus on fuels with simpler molecular structures, such as hydrogen, ammonia and methanol, which can be produced relatively efficiently from both biomass and green electricity. However, current production costs for biofuels are significantly lower than those for e-fuels, which may lead to difficulties in regulating the market and could cause considerable market fluctuations. This disparity might result in economic advantages for regions with abundant sustainable biomass resources.

Economic factors and the typical chicken-and-egg dilemma linked to transitions to new alternative technologies are the other factors impeding the scaling up of infrastructure: fleet operators often tend to be reluctant to invest in retrofits and new vessels due to high costs and uncertain fuel availability, while fuel producers are hesitant to invest due to current low demands. Yet, the situation is slowly changing, for example with the transition to methanol-powered vessels. From a financial perspective, more investments are required to decarbonize maritime shipping, lower biofuel prices are required in the long-run and higher carbon prices are needed to make the transition economically advantageous (Harahap et al, 2023b; Urban et al, 2024a and b).

The lack of guidelines and standards for new alternative fuels presents another challenge that must be properly addressed before any alternative fuel options can successfully penetrate the market. Designing vessels that ensure the safety of both crew and cargo would be extremely difficult, if not impossible, without proper studies, guidelines, and standards—especially for fuels with high explosivity or toxicity. Additionally, the quality of alternative fuels is highly dependent on the feedstock used and the production methods employed. Variations in fuel quality could lead to issues with storage and utilization. All in all, the absence of standardization poses challenges to widespread adoption of certain alternative fuels (Harahap et al, 2023a and b).

Defining and implementing suitable policies can facilitate creating markets and secure demand for alternative fuels. An example of such policies is the European Union’s Emissions Trading Scheme (EU ETS) which includes maritime shipping since 2024, introducing energy taxes and blending quotas for biofuels that have been in place for road transport and aviation in many countries for many years.

First, including maritime shipping in the EU ETS increases the pressure on shipping companies to reduce their emissions, thereby also encouraging the use of and investment in alternative shipping fuels, especially under high carbon prices beyond 100-150 Euros/ton (Harahap et al, 2023b; Urban et al, 2024). Carbon prices have been fluctuating over the years since the introduction of the EU ETS in 2005. Carbon prices have however increased in recent years and have been particularly high since 2021, with a peaking of about 100 Euros per ton CO_2 in 2022 and early 2023 (IEA, 2024b). This is the pricing level at which today's biofuels for maritime shipping are competitive compared to fossil fuel prices. BloombergNEF forecast that the EU carbon price will be about 200 Euros by 2035 (Bloomberg NEF, 2024), making both biofuels and hydrogen financially viable for maritime shipping compared to fossil fuels (Harahap et al, 2023b).

Second, energy and carbon taxes can be effective tools to decarbonize maritime shipping. Fuels can be ranked and taxed according to their energy content and environmental performance. This would provide a financial incentive for shipping companies that have lower emissions fuels and a financial penalty for shipping companies that have high-carbon fuels. Such proposals are currently being discussed at the EU level.

Third, introducing a blending mandate for biofuels like in road transportation and aviation would create a market, increase demand and encourage sustainable energy transitions in maritime shipping. Recent research shows that introducing a blending mandate for biofuels for maritime shipping could potentially contribute to significant emissions reductions, while being cost-competitive (Harahap et al, 2023b).

Finally, subsidies could be made available at the national level by governments to help create a market for biofuels.

3.2.4 Scenario outlook at the systems' level

Maritime shipping is part of complex systems made of technical, economic, social, political and environmental factors. Technologies for fuels and vessels play as much a role in these systems as policies and regulations, and socio-economic factors like demand, markets and pricing of fuels and products. Future global maritime shipping volumes are linked to consumption levels which in turn are linked to economic growth and international trade. The GHG emission levels from global maritime shipping depend on the shipping volumes, the fuels used and the impact of climate and energy policies. The level of biofuels used in maritime shipping depends on the stringency of sectoral climate and energy policy and financial instruments, demand and availability of biofuels, which in turn depends on fuel prices (carbon prices, oil prices and biofuel prices) and the up-scaling of investments in production facilities and infrastructure for biofuels. The IMO aims for net-zero GHG emissions around 2050 (IMO, 2023). There are also strong regional climate policies for maritime shipping, such as the EU's Fuel EU Maritime regulations (EU Parliament, 2023), part of the Fit for 55 policy package and the EU's aims to have net zero emissions by 2050. Other important policies include carbon pricing, energy taxes and emissions trading, such as for the EU ETS, as well as the potential introduction of blending mandates. International policy such as at the IMO level, is the most effective as it has a global reach that is integrated with maritime shipping's international scale. Regional climate and energy policy can also be effective, such as policy within the EU, followed by national policy which faces more challenges due to limited jurisdiction, free-rider problems and limited scale.

Figure 15 and Table 6 show qualitative scenarios for the future of biofuel use for maritime shipping. There are four types of scenarios, depending on the effectiveness of climate and energy policy for maritime shipping, fuel prices (especially carbon pricing), levels of economic growth and international trade as the motor of international maritime shipping.

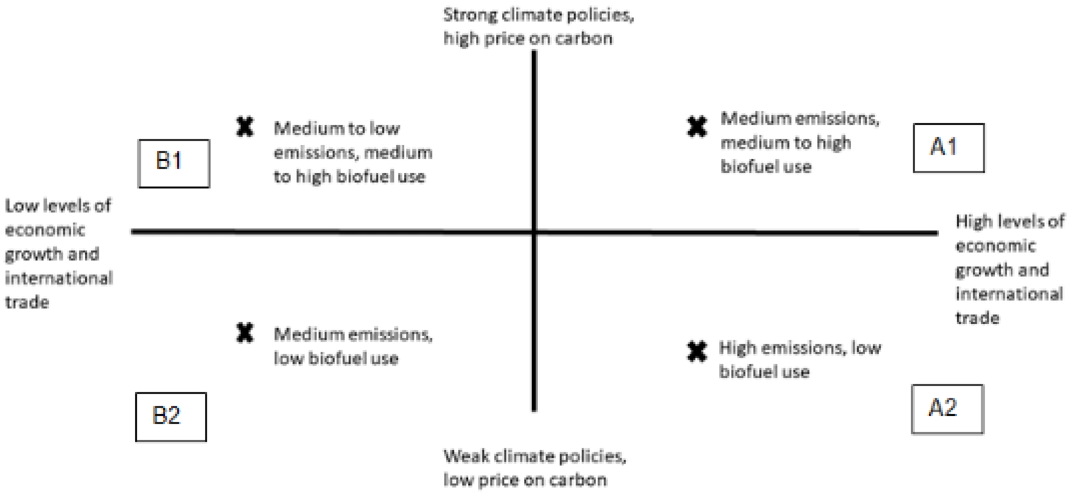

Figure 15. Different scenarios for the use of biofuels in maritime shipping

The effectiveness of climate and energy policy depends on its ambitiousness, ability to be legally binding and enforceable at the international level and the commitment at which parties are implementing the policy. Figure 15 shows that the highest emissions are likely to occur in the A2 scenario with weak climate policies, low prices of carbon and fossil fuels, high economic growth and high levels of international trade. Biofuel use is low in this scenario. The biofuel is expected to be low in this scenario. The lowest emissions are likely to occur in the B1 scenario with strong climate policy, high prices on carbon, lower levels of economic activity and international trade. Biofuel use is medium to high in this scenario.

Yet, economic growth is usually considered a pre-requisite for the financial well-being of nations, including the creation of wealth, employment and tax revenues. The "sweet spot" scenario A1 is likely to result in a medium level of emissions, yet medium to high biofuel use driven by strong climate policies, a high price on carbon and high levels of economic growth and international trade. This scenario is driven by high maritime shipping volumes that create demand, strong and enforceable international climate policy, high carbon prices that result in lower use of fossil fuels and higher use of biofuels.

Table 7 shows in more detail the factors that drive emissions and the use of biofuels for maritime shipping.

Table 7. Factors that influence the adoption of biofuels and emissions in international shipping, according to different scenarios

Economic growth	International trade	Climate policy	Carbon price	Fossil fuel use	Increased use of biofuels	GHG emissions
High	High	Strong	High	Medium	Medium to high	Medium
		Medium	Medium	High to medium	Medium to low	Medium
		Weak	Low	High	Low	High
Medium	Medium	Strong	High	Medium	Medium	Medium
		Medium	Medium	Medium	Medium	Medium
		Weak	Low	High	Low	High
Low	Low	Strong	High	Low to medium	High to medium	Low to medium
		Medium	Medium	Medium	Medium	Medium
		Weak	Low	High to medium	Low to medium	Medium

3.2.5 Conclusion

In conclusion, the decarbonization of the shipping industry is an urgent and complex challenge that demands a multifaceted approach. As the global maritime sector faces increasing regulatory pressure to reduce its carbon footprint, alternative renewable marine fuels, such as various biofuels, are emerging as a key component of the solution. Despite their potential, these fuels are currently used at relatively low levels, necessitating a significant boost in both adoption and infrastructure to support their wider use.

To increase the uptake of biofuels in maritime shipping, several critical steps are needed. First, there must be substantial investments in infrastructure, including facilities for biofuel production, storage, and bunkering close to major ports. This also extends to the development of robust transport and distribution systems to ensure a steady supply of these fuels. Additionally, ship owners may need to invest in new vessels or retrofit existing ones to accommodate alternative fuels, such as methanol, which requires specific engine and storage adaptations.

A crucial factor in expanding biofuel use is the reduction in prices, which can be achieved through economies of scale in production and by implementing financial incentives. Policies such as blending mandates, emissions trading schemes, and high carbon pricing can effectively drive the adoption of sustainable fuels. These financial and regulatory mechanisms can create a more attractive market for biofuels, thereby accelerating their integration into the maritime industry.

The success of these measures hinges on the implementation of stringent international and regional policies by organizations such as the International Maritime Organization (IMO) and corresponding regional bodies. Coordinated policy-making and international cooperation are essential to align financial instruments and regulatory frameworks across different regions. By fostering a unified approach, the maritime sector can navigate the transition towards decarbonization, ensuring a sustainable and economically viable future for shipping.

3.3 The Role of Research in Lowering Hinders for Maritime Biofuels

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In the quest to transition the maritime industry from conventional fossil fuels to more sustainable alternatives, this chapter draws on scientific literature from 2020 to 2024 to assess whether current technologies meet the demands of maritime biofuel applications – or if targeted, substantial research is still essential. Using recent reviews and studies, we examine five promising biofuels—biocrude (from hydrothermal liquefaction (HTL)), lignin-based fuels, bio-alcohols (biobased methanol and ethanol), bio-DME, and pyrolysis oil – each with distinct characteristics and potential for reducing emissions in marine transport. This exploration considers not only the technical feasibility of these fuels but also the gaps and challenges in sustainability and engine compatibility.

While biofuels present a feasible route toward decarbonization, they pose specific and often complex challenges, many of which remain unresolved. From developing stable, high-energy biofuels to adapting engines for varied fuel properties and meeting stringent environmental standards, significant unknowns still hinder the path to widespread adoption. This chapter highlights research as a critical component of the biofuel value chain, playing a foundational role in fuel development, environmental assessment, and technical adaptation.
Through reviewing the latest advancements and pinpointing areas where critical knowledge gaps persist, this chapter underscores the need for continued, cross-disciplinary research to drive innovation in maritime biofuels. As the sector moves forward, it is clear that research will not only address current barriers but also define future breakthroughs in fuel technology, sustainability, and marine engine design – providing decision-makers and stakeholders with a clear case for supporting biofuel research within the maritime industry.

3.3.1 Current State of Research within Maritime Biofuels

Assessing the scientific literature from the past five years reveals a clear rise in attention toward marine biofuels as viable alternatives to conventional fossil fuels. Researchers and industry stakeholders are increasingly exploring biofuels to meet stringent emissions regulations and support sustainability targets in the maritime sector, and many novel fuels and/or production routes are being described. However, certain biofuels are receiving more focused attention than others due to their unique properties and potential benefits for marine applications. Among the biofuels frequently discussed, biocrude, and bioalcohols – especially methanol – are particularly prominent. However, Bio-DME, bio-oil from pyrolysis, and lignin-based fuels are also gaining attention from the research community.

Biocrude, a renewable, dense oil, is produced through Hydrothermal Liquefaction (HTL), which converts wet biomass into an energy-rich liquid fuel under high-temperature (250–400°C) and high-pressure (10–35 MPa) conditions in the presence of water [Mishra et al., 2022; Lozano et al., 2022]. HTL is particularly advantageous because it can process wet feedstocks directly, eliminating the costly drying steps required in other biofuel production methods [Mishra et al., 2022]. The resulting biocrude contains chemical characteristics similar to fossil crude oil, enabling it to be partially integrated into conventional refinery infrastructure as a potential drop-in fuel. Studies suggest that, after upgrading, biocrude could be co-processed with petroleum products in existing refineries, provided that key modifications are made to handle its unique properties [Lindfors et al., 2022; Gray et al., 2021]. This compatibility, however, is contingent on reducing the high oxygen content present in raw biocrude, which impacts stability and increases corrosiveness. To address this, hydrodeoxygenation (HDO) is commonly applied to lower oxygen levels and improve biocrude's stability and energy density. Currently, this process often relies on hydrogen sourced from fossil fuels, which is both energy-intensive and undermines the sustainability of biocrude production [Vidovic et al., 2023; Demirbas, 2017]. Developing cost-effective, low-carbon sources of hydrogen is a crucial research priority to enhance the environmental benefits of HTL biocrude for maritime applications. Also, biocrude's properties can vary significantly depending on the feedstock used in the HTL process. Differences in biomass composition—such as protein, lipid, and carbohydrate content—affect the yield, heating value, and stability of the resulting biocrude. This variability poses challenges for refinery integration, as inconsistent biocrude quality requires additional upgrading steps to achieve uniform standards for co-processing. Such adjustments increase resource demands and can undermine the sustainability of biocrude, especially given the high energy input required for hydrodeoxygenation [Mishra et al., 2022; Lindfors et al., 2022; Lozano et al., 2022].

Bio-alcohols, primarily biobased methanol and ethanol, are increasingly considered as low-emission alternatives for maritime fuel applications. Methanol can be synthesized from various biomass sources through processes such as syngas production from biomass gasification, followed by conversion into methanol using hydrogen (H_2) and carbon monoxide (CO) or carbon dioxide (CO_2) [Parris et al., 2024; Pu et al., 2024]. Ethanol is produced through biochemical fermentation, traditionally and most commonly from sugars or starch (often sourced from sugarcane or corn), but now also commercially from lignocellulosic biomass, offering a renewable pathway often performing well in sustainability assessments. [Demirbas, 2017; Tanzer et al., 2019]. Methanol, in particular, has a well-established supply chain and benefits from compatibility with existing infrastructure, especially in port storage and distribution systems, making it a relatively seamless choice for integration into marine fuel supply lines [Wang et al., 2022; Parris et al., 2024].

Both methanol and ethanol are liquids at room temperature, simplifying storage and handling, though they are less energy-dense than traditional marine fuels. This lower energy density requires larger fuel storage volumes on vessels, impacting overall cargo capacity [Vidovic et al., 2023]. One promising avenue for bio-alcohols in marine engines is their use in dual-fuel systems, where bio-alcohols can be blended with conventional marine fuels, allowing engines to switch between fuel types depending on availability and operational needs. This dual-fuel adaptability reduces the dependency on pure bio-alcohols while helping to meet emission reduction targets. However, both methanol and ethanol have a low cetane number, which can make ignition challenging in compression-ignition engines commonly used in maritime settings. To address these issues, modifications to engine injection systems and the use of pilot fuels are being explored to stabilize combustion and enhance efficiency in heavy-duty maritime applications [Pu et al., 2024; Sahu et al., 2022].

Bio-DME (dimethyl ether) and pyrolysis oil are increasingly studied as potential marine fuels. Bio-DME can be produced through methanol dehydration or directly via biomass gasification, with synthesis methods including both one-stage and two-stage routes. These methods use feedstocks like agricultural residues or forestry waste, often paired with renewable electrolytic hydrogen to improve carbon efficiency [Kofler et al., 2024; Styring et al., 2021]. Due to its similarity to liquefied petroleum gas (LPG), bio-DME is compatible with existing LPG infrastructure, allowing for straightforward storage and handling with minimal retrofitting. Furthermore, its high cetane number enhances its suitability for compression-ignition engines, making it applicable in marine settings with modest engine adjustments [Styring et al., 2021; Vidovic et al., 2023]. However, bio-DME has a lower energy density than conventional marine fuels, necessitating larger fuel storage on vessels, and its production costs remain high, posing scalability challenges [Li et al., 2022; Kofler et al., 2024].

Pyrolysis oil, a renewable bio-oil, is produced through the thermal decomposition of biomass in an oxygen-free environment, commonly known as fast pyrolysis. This process converts biomass into a liquid bio-oil rich in oxygenated compounds and water, alongside minor products such as biochar and gases [Das, 2021; Lozano et al., 2022]. Fast pyrolysis is particularly efficient, yielding 60–75% bio-oil depending on the biomass type and operating conditions. The high oxygen and water content in pyrolysis oil contribute to its chemical instability, low energy density, and corrosive nature, posing challenges for long-term storage and direct use in existing engines and fuel systems. To increase compatibility with conventional refinery processes and marine applications, pyrolysis oil often requires extensive upgrading, including hydrotreating to reduce oxygen levels and catalytic cracking to stabilize fuel properties [Ohra-aho et al., 2024; Vidovic et al., 2023]. While the potential for co-processing with fossil fuels exists, the variability in feedstock and quality means that integrating pyrolysis oil into existing refinery infrastructure is complex and may require tailored processing adjustments to ensure uniform fuel quality. Despite these challenges, pyrolysis oil remains an attractive waste-derived option for renewable marine fuels, particularly if issues with consistency, stability, and feedstock flexibility can be addressed through further research and technological advancements.

Lignin, an aromatic polymer found in plant cell walls, represents a significant byproduct stream in industries like pulping and lignocellulosic bioethanol production. Predominantly obtained from the pulping industry, lignin is generated as a lignocellulosic byproduct, with two common types being kraft lignin and soda lignin. Kraft lignin, derived from the kraft pulping process, often has elevated sulfur content, which complicates its use as a marine fuel due to sulfur emissions that contravene maritime environmental standards. Similarly, while soda lignin from soda pulping generally has lower sulfur levels, it can still exhibit elevated sulfur content when sulfuric acid is used for pH neutralization during processing [Menezes et al., 2023; Brienza et al., 2024]. The emerging biorefinery lignin, can however be completely free of sulfur but is often impure with residual carbohydrates. The production of lignin-derived fuels involves isolating and processing lignin into bio-oil or dispersions compatible with combustion engines.

Approaches like cold-processed lignin ethanol oil (CLEO) represent innovative methods for lignin fractionation, producing stable lignin-alcohol dispersions at ambient temperatures. CLEO technology has shown promise in maintaining stability at higher lignin concentrations while achieving energy densities suitable for marine fuel use. However, issues such as high viscosity and storage stability still need further refinement for effective integration [Simonsen et al., 2024a; Simonsen et al., 2024b]. See also section 3.3.5. While lignin-based biofuels align with sustainability goals by utilizing a typically underused biomass component, their direct compatibility with existing refinery infrastructure is limited. The high oxygen content and structural variability of lignin-derived fuels necessitate significant upgrading, including depolymerization and reduction in sulfur and oxygen content, to meet maritime fuel standards. This variability in composition across different lignin sources, such as kraft versus soda lignin, also means that further research is needed to standardize fuel properties.

Overall, the scientific community's current research trajectory underscores both the potential and the remaining gaps in our understanding of these biofuels. Continued exploration is essential to address the technical, environmental, and compatibility challenges associated with each fuel type, supporting a more sustainable transition within the maritime sector. As shown in Table 10, recurring issues, including fuel stability, engine compatibility, and environmental impact, vary in severity across fuel types. This figure assesses the seriousness of these challenges for integrating six alternative fuels into the maritime sector, based on recent scientific literature (2020-2024).

Table 8. Recurring problems for integrating six alternative fuels into the maritime sector.

Problem/Challenge	**Biocrude**	**Bioalcohols (methanol, ethanol)**	**Bio-DME**	**Pyrolysis Oil**	**Lignin Fuels**	**Ammonia**
High oxygen and water content	4			5	1	
Corrosive properties	4	3	4	5	2	4
Low heating value	3			4		
Engine compatibility	4	3	3	4	4	4
High production cost	4	3	5	2	4	5
Flammability and toxicity		3	4		1	5
Requires pressure-zation/cooling			4			
Limited infrastructure	4	3	4	4	4	4
Regulatory development	4	3	4	4	4	5

In the table above (Table 10), the seriousness is indicated by a number from 1 to 5, where 1 is the least serious and 5 is the farthest from being solved. Ammonia, an electro fuel, is included for comparison.

3.3.2 Need for scientific Advancements in Fuel Development Upgrading and Stabilization Techniques

Advancements in upgrading and stabilization techniques are essential to transform raw biofuels into viable alternatives for maritime use. A consistent and uniform fuel quality is particularly critical to ensure seamless bunkering across the globe – providing ship operators with reliable, predictable fuel performance wherever they are. Each biofuel considered for marine applications in this chapter – biocrude, lignin-derived fuels, bio-alcohols, bio-DME, pyrolysis oil, and potential future fuels – has unique characteristics that require targeted refining processes to improve stability, increase energy density, and enhance compatibility with marine engines. Addressing these requirements through scientific innovation is crucial for the maritime sector's sustainable transition to biofuels.

Biocrude from HTL has high oxygen content, which impacts stability and increases corrosiveness, necessitating extensive upgrading for marine use. Hydrodeoxygenation (HDO) – a process that removes oxygen atoms via catalytic hydrogenation – is a primary technique used to improve fuel quality by reducing acidity and increasing energy density, enhancing compatibility with refinery infrastructure [Mishra et al., 2022; Usman et al., 2024]. Current HDO catalysts, like sulfided cobalt-molybdenum and nickel-molybdenum, are prone to deactivation from sulfur and nitrogen impurities in biocrude, emphasizing the need for more resilient catalysts. Alternative methods, including catalytic cracking and co-processing with fossil fuels, also hold promise. Catalytic cracking can reduce oxygen content without as much hydrogen, though issues with coking persist [Usman et al., 2024; Lindfors et al., 2022]. Co-processing in refineries allows partial blending with petroleum feedstocks, yet is limited by biocrude's viscosity and oxygen levels, which can disrupt refinery operations [Shahbeik et al., 2024].

Similar to biocrude, pyrolysis oil faces challenges due to its high oxygen and water content, which reduce energy density and cause chemical instability over time. Upgrading methods such as catalytic hydrotreating and catalytic cracking are employed to address these issues. HDO, or catalytic hydrotreating, lowers oxygen content, improving stability and energy density, though it requires high hydrogen inputs that often rely on fossil sources, reducing some environmental benefits [Gea et al., 2023; Das, 2021]. Additionally, HDO catalysts can deactivate in the presence of impurities like sulfur and nitrogen, underscoring the need for more resilient catalyst options. Catalytic cracking offers an alternative by breaking down larger molecules into shorter, more stable hydrocarbons compatible with marine engines. However, this method can lead to catalyst coking and unwanted by-products. New approaches that combine mild hydrotreating with cracking aim to reduce coking while achieving sufficient oxygen removal [Lozano et al., 2022; Ohra-aho et al., 2024]. Ensuring consistency in pyrolysis oil quality is also crucial, as feedstock and production variability affect storage stability and compatibility with marine fuels. Recent studies highlight the importance of storage protocols and blending guidelines to prevent degradation during storage, making pyrolysis oil a more practical option for renewable marine fuel integration.

Like pyrolysis oil, lignin-derived fuels face significant stability and compatibility challenges due to lignin's complex, aromatic structure. Lignin, sourced as a by-product from both the pulping industry and advanced biorefineries, often contains sulfur – especially kraft lignin, which is challenging for marine fuel use because of sulfur emission concerns. Even soda lignin, though lower in sulfur, can have elevated levels if sulfuric acid is used for pH adjustment [Patel et al., 2023; Menezes et al., 2023]. To enhance stability and reduce viscosity, catalytic depolymerization and solvolysis are widely used. These techniques break down lignin's polymeric structure into smaller molecules, which are more chemically stable and easier to blend with other fuels [Brienza et al., 2024; Kocaturk et al., 2023]. Chemical fractionation further refines lignin by isolating specific fractions that exhibit better thermal stability and higher energy density, improving compatibility with combustion applications [Tanzer et al., 2019; Brienza et al., 2024]. Emerging methods like lignin-first biorefining focus on stabilizing lignin's reactive intermediates early in the process, reducing condensation reactions that lead to high molecular weight and instability. This approach offers a more uniform lignin product that is more compatible with refinery infrastructure but requires further development to ensure low sulfur content and commercial feasibility [Brienza et al., 2024; Menezes et al., 2023]. Advancements in these upgrading techniques are essential to making lignin-derived fuels a practical option for maritime use, while also more basic research into linin chemistry depending on biomass source and upstream refining technology will be able to advance the deployment.

Unlike biocrude, bio-oil, and lignin-derived fuels, bio-DME and bio-alcohols such as methanol and ethanol are relatively homogenous, requiring fewer complex upgrading steps to stabilize them for marine use. Bio-DME is typically produced by biomass gasification followed by methanol synthesis and dehydration. This multi-step process yields a clean, high-cetane fuel with low emissions, compatible with compression ignition engines and adaptable to existing LPG infrastructure, though storage under moderate pressure is needed to keep DME in liquid form. To improve scalability and cost-efficiency, advancements are needed in integrating renewable hydrogen into DME synthesis to make the process more sustainable and cost-effective [Styring et al., 2021; Kofler et al., 2024]. For bio-alcohols, methanol production from renewable sources such as CO_2 hydrogenation has gained interest as a lower-emission alternative to traditional marine fuels, and other alternative routes for bioalcohols should still be pursued in research.

Blending with Conventional Fuels and Utilization of Existing Refinery Infrastructure
To make biofuels viable for maritime applications, technological integration with existing systems – including blending biofuels with conventional fossil fuels and leveraging current refinery infrastructure – is crucial. Blending biofuels with conventional fuels provides a practical path to gradually introduce renewables, minimizing immediate engine modifications and infrastructure overhauls. For example, co-processing biocrude and pyrolysis oil with petroleum fuels can improve stability and combustion characteristics by leveraging fossil fuels' chemical properties. This approach helps mitigate issues like high oxygen content and corrosiveness, making these biofuels more compatible with current marine engines and systems [Lindfors et al., 2022; Das, 2021]. Methanol, when used in blends, has also shown success in maritime trials, offering emissions reductions with relatively minor engine adjustments [Wang et al., 2022; Parris et al., 2024].
Utilizing existing refinery infrastructure is equally important for integrating biofuels into the maritime sector. Co-processing bio-oils, such as biocrude, within conventional refineries enables operators to use established distribution networks, reducing the need for significant new investments [Shahbeik et al., 2024; Lindfors et al., 2022]. Bio-DME can benefit from existing LPG infrastructure, requiring only moderate adaptations at storage and fueling facilities [Styring et al., 2021; Vidovic et al., 2023]. This integration allows biofuels to enter supply chains with minimal disruption, bridging the gap between production and real-world application.

Continued research plays a pivotal role in refining these integration strategies. Future studies must optimize blending ratios, address long-term stability during co-processing, and explore enhanced materials for engines and storage to counteract corrosion. Research into scalable production methods for renewable hydrogen, which can improve sustainability in upgrading processes, is also vital. By supporting these efforts, the scientific community can help solidify biofuels' role in maritime decarbonization.

3.3.3 Research in Sustainability Assessments of Marine Fuels

Research into the sustainability of marine biofuels has accelerated, with a growing emphasis on comprehensive assessments that address environmental, social, and regulatory aspects. Life Cycle Assessment (LCA) remains central to these evaluations, as it provides a systematic framework for quantifying environmental impacts across a fuel's lifecycle – from production to disposal. Through LCA, researchers assess greenhouse gas (GHG) emissions, energy consumption, and impacts on air and water quality, delivering insights that are critical for comparing biofuels to conventional marine fuels.

Recent studies highlight the regional nuances in sustainability profiles. For example, Mandegari et al. (2023) demonstrated that biocrude could significantly reduce GHG emissions in British Columbia by leveraging local biomass resources and supportive policies. Methanol studies show similar regional advantages; biomass-derived methanol exhibits reduced emissions compared to fossil-based alternatives, particularly in areas with abundant renewable resources [Pu et al., 2024; Wang et al., 2022]. However, biofuels like pyrolysis oil present mixed results, as the energy-intensive processes needed for their upgrading can offset some environmental benefits, suggesting a need for further nuanced LCAs to fully understand their long-term viability [Lozano et al., 2022; Das, 2021]. Additionally, Bilgili (2021) emphasized that achieving IMO's environmental goals requires more comprehensive LCA data on both conventional and alternative marine fuels to understand their full lifecycle impacts.

Looking forward, advancements in LCA methodologies aim to improve the precision and contextual relevance of sustainability assessments. Future LCAs are expected to incorporate localized environmental impacts, factoring in region-specific feedstock availability, infrastructure, and regulatory requirements, thus enhancing the assessments' applicability to specific maritime contexts [Tanzer et al., 2019]. Moreover, integrated assessment models that combine LCA with economic and social metrics could provide a holistic view of each fuel's sustainability, supporting decision-making for policymakers and industry stakeholders. An emerging trend in this field is the development of dynamic LCA models. These models are adaptable to the evolving nature of biofuel production technologies and feedstock sources over time.

For example, Zincir (2024) highlighted the importance of incorporating technological improvements, such as advancements in renewable hydrogen for biofuel production and innovations in waste-to-fuel conversion, into LCA to better predict future impacts [Zincir, 2024]. Such models allow sustainability assessments to remain relevant as technology and policies advance, offering the maritime sector a more accurate view of biofuels' potential over time. While current sustainability assessments provide valuable insights, there remains significant opportunity for deeper research. Future efforts should prioritize adaptable, context-specific LCA models that integrate environmental, economic, and social dimensions, ultimately guiding the maritime sector toward a sustainable adoption of biofuels.

3.3.4 Engine Development and Compatibility

Despite the adaptability of marine engines to various fuel types, introducing new biofuels into maritime applications presents significant technical challenges. Marine engines are indeed more versatile than their counterparts in sectors like aviation, often able to handle diverse fuels without immediate extensive modifications. However, each biofuel introduces specific issues regarding engine performance, ignition, emissions, and fuel handling that require careful adaptation and development. Bioalcohols, while promising as a renewable marine fuel, has a low cetane number, making it difficult to ignite in compression ignition (CI) engines that are standard in marine applications. The low cetane value necessitates enhanced ignition techniques or modifications to achieve reliable combustion. Pu et al. (2024) explore the potential of using high-pressure injection systems and dual-fuel strategies to counteract methanol's poor ignition quality in heavy-duty CI engines. Additionally, methanol’s corrosiveness and high heat of vaporization impose further requirements for robust materials in fuel systems and injectors, as well as advanced cooling methods to prevent engine component degradation and ensure efficient combustion. Research into blending methanol with water has shown promise in reducing NOx emissions, potentially enabling compliance with stringent maritime emissions standards without the need for exhaust after-treatment systems [Parris et al., 2024].

Sahu et al. (2022) discuss the use of alcohol-based fuels, such as ethanol and methanol, in CI engines, focusing on how they improve emissions compared to diesel due to lower soot and NOx production. However, these alcohols generally require dual-fuel operation or additives to improve their ignition characteristics. This dual-fuel approach, while effective, can complicate engine systems and require additional storage, potentially reducing cargo capacity in marine vessels. For lignin-derived fuels, Terauchi et al. (2024) examine a specific blend of lignin with ethanol, noting severe challenges in engine start-up and shutdown due to lignin’s tendency to solidify at low temperatures. This fuel type also risks causing deposits in engine components, such as piston rings, due to incomplete combustion, which can lead to significant maintenance demands and reduced engine lifespan.

Given these challenges, further research is needed to enhance fuel flexibility in marine engines while optimizing fuel injection, ignition, and combustion systems to handle alternative fuels. Advanced pre-chamber ignition technologies, as discussed by Kohse-Höinghaus (2020), offer a promising approach for biofuels with low cetane numbers by promoting a more distributed and efficient combustion process. Additionally, integrated systems for automatic fuel switching could help mitigate issues related to fuel viscosity and ignition delays, ensuring that biofuels can be smoothly transitioned with minimal disruption to engine operation. So, while marine engines have a higher fuel tolerance than many other engines, adapting them for new biofuels requires extensive technological innovation. As demonstrated in studies by Terauchi, Pu, and Sahu, optimizing engine systems for these biofuels involves addressing specific compatibility issues and requires dedicated research efforts to make marine engines fully compatible with sustainable biofuels in the future.

3.3.5 Bridging Fuel Development, Sustainability, and Engine Adaptation

Successful integration of biofuels into the maritime sector requires a well-coordinated approach that combines advances in fuel technology, sustainability research, and engine compatibility. Interdisciplinary research collaboration plays a central role in achieving these goals, bringing together fuel developers, chemists, environmental scientists, engine researchers, and marine engineers to address the technical and environmental challenges of biofuel adoption. The CLEO project serves as an illustrative example of such an integrated approach. In this project, a novel lignin-based biofuel, CLEO (Cold-processed Lignin Ethanol Oil), was developed and tested for marine applications. The project was aimed at producing a stable and sustainable biofuel from lignin and ethanol that could meet the needs of the maritime sector. The CLEO fuel development involved extensive research into lignin fractionation and solvation at ambient temperature, and on fuel properties, with a focus on producing a biofuel that was both stable and efficient for marine engine use. Researchers achieved promising results by demonstrating CLEO production at a pilot scale, with lignin concentrations up to 60%, effectively valorizing lignin in a new way for marine fuel applications [Simonsen *et al.,* 2024a; Simonsen *et al.,* 2024b].

The project also included testing the biofuel on a small-bore CI marine engine, which revealed challenges such as lignin’s tendency to solidify under low temperatures and cause deposit formation [Terauchi *et al.*, 2024]. Through experimental trials, the project team developed a fuel switching system and optimized injection parameters to address these issues, showcasing how fuel development and engine adaptation must go hand-in-hand to achieve functional solutions [Terauchi *et al.*, 2024]. Research on LCA and “Energy return on Investment” further supported the CLEO project’s sustainability goals [Unpublished]. This example underlines the critical role of collaboration in overcoming the technical hurdles that often arise when introducing novel fuels.

Looking forward, several promising areas for future research include the refinement of biofuel properties through improved fractionation techniques, as well as the development of dynamic LCAs that account for evolving production methods and regional differences in feedstock availability. Projects like the CLEO initiative highlight the importance of breakthroughs in fuel formulation, which can significantly improve compatibility with existing marine engines, reducing both technical and economic barriers to widespread adoption.

Advancing Research in Maritime Biofuel Technologies: Necessity and Promise

Scientific advancements in maritime biofuels are essential for addressing the sector’s complex challenges, from optimizing fuel properties to ensuring sustainability and compatibility with marine engines. The future of maritime biofuels is promising, with ongoing research and technological advancements paving the way for new solutions. Continued support from both the scientific community and policymakers is crucial for pushing the frontiers of biofuel innovation, including breakthroughs in fuel synthesis, engine design, and emissions reduction strategies. Independent research plays an integral role, potentially uncovering unforeseen technologies and approaches that go beyond current projections. As we continue to explore, adapt, and innovate, the maritime sector moves closer to achieving a more sustainable and resilient energy future.

3.4 The role of regulation

Marco Buffi, European Commission Joint Research Center

3.4.1 The EU scenario

In EU-27, the decarbonization of maritime sector is set by the FuelEU Maritime Regulation[34], which is an initiative aimed at increasing the use of sustainable alternative fuels in the maritime sector and reducing its greenhouse gas (GHG) emissions. It forms part of the Fit-for-55 package[35] (a set of policy proposals preparing the implementation of the European Green Deal[36], which sets out a strategy for achieving climate neutrality by 2050, and the intermediate goal of 55% reduction by 2030), and contributes to the goals set by the EU's Renewable Energy Directive (EU) 2001/2018[37] (recently amended by the Directive (EU) 2023/2413[38]), which establishes an overall policy framework for the production and promotion of energy from renewable sources.

Under the Renewable Energy Directive (RED), the EU has set targets for the overall share of energy from renewable sources in its energy consumption and specific sub-targets for sectors such as transport. The inclusion of sustainable biofuels and RFNBOs (Renewable Fuels of Non-Biological Origin) in the maritime sector supports these targets by providing lower-carbon alternatives to the traditional marine fuels.

In order to decarbonize the EU maritime sector, FuelEU Maritime set a limit on the greenhouse gas (GHG) intensity of energy used on board by a ship arriving or departing from EU Member States' ports. Additionally, the Regulation mandates the use of zero-emission technologies for docked vessels by requiring the use of on-shore power supply (OPS) or other zero-emission alternatives, particularly for passenger and container ships. The zero-emission technology defined as technologies that do not result in the release of greenhouse gases and air pollutants into the atmosphere by ships and are listed in Annex III of the regulation: fuel cells, on-board electrical energy storage or on-board power generation from wind and solar energy. This measure aims to reduce air pollution in port areas, which frequently lie in proximity to high-density residential zones.

FuelEU Maritime establishes strict annual caps on the average greenhouse gas (GHG) intensity for the energy utilized by vessels over 5,000 gross tonnage that visit EU ports, without distinction of their registered flag. These benchmarks are designed to initiate a progressive decline in the GHG intensity of maritime fuels, with an initial reduction target of 2% by 2025, 6% by 2030, culminating in an ambitious 80% cut by the year 2050. The benchmarks will progressively tighten, introducing both technology improvements and increased quota of renewable and low-carbon energy sources.

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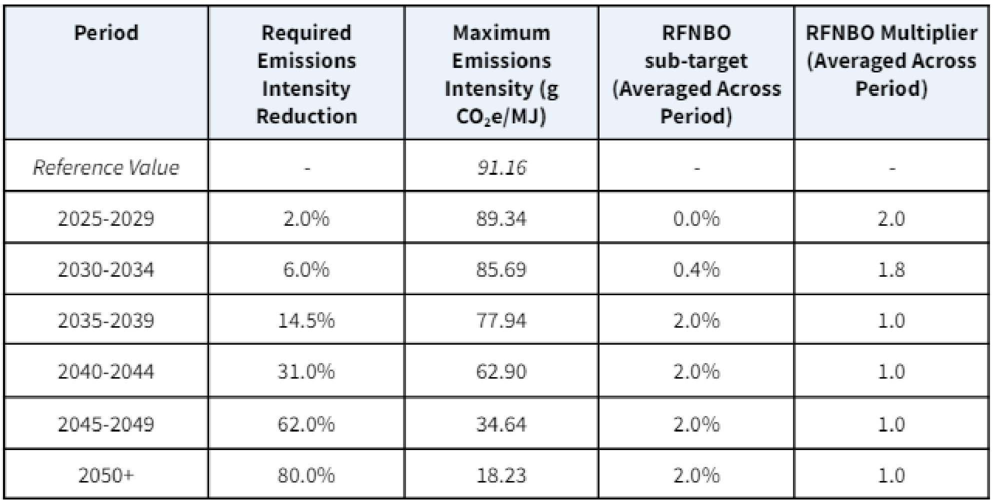
[34] https://eur-lex.europa.eu/eli/reg/2023/1805
[35] https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:52021DC0550
[36] https://eur-lex.europa.eu/legal-content/en/TXT/?uri=COM:2019:640:FIN
[37] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018L2001
[38] https://eur-lex.europa.eu/eli/dir/2023/2413/oj

Table 9. FuelEU Maritime policy inputs into all "final agreement" scenarios[39]. Source: https://www.transportenvironment.org/uploads/files/FuelEU-Maritime-Impact-Assessment.pdf



Period	Required Emissions Intensity Reduction	Maximum Emissions Intensity (g CO_2e/MJ)	RFNBO sub-target (Averaged Across Period)	RFNBO Multiplier (Averaged Across Period)
Reference Value	-	*91.16*	-	-
2025-2029	2.0%	89.34	0.0%	2.0
2030-2034	6.0%	85.69	0.4%	1.8
2035-2039	14.5%	77.94	2.0%	1.0
2040-2044	31.0%	62.90	2.0%	1.0
2045-2049	62.0%	34.64	2.0%	1.0
2050+	80.0%	18.23	2.0%	1.0

The scope of these targets extends beyond carbon dioxide emissions to include gases with greenhouse effect, such as methane and nitrous oxide, considering the entire lifecycle of marine fuels from production to consumption, following a Well-to-Wake (WtW) approach.

FuelEU Maritime adopts a broad framework that does not provide technology barriers, leaving open the choice of the best powertrain and fuel supply depending on the ships and operations. To facilitate compliance and encourage early adopters, the Regulation incorporates various flexible mechanisms that assist existing fleets in devising effective compliance strategies and reward early investments in the energy transition.

The implementation of FuelEU Maritime is slated to commence on January 1, 2025, with the exception of Articles 8 and 9, which pertain to monitoring plans and will come into effect earlier, on August 31, 2024.

It is worth also mentioning that EU has other tools supporting the green transition of the maritime sector as:

- The EU Emissions Trading System (EU ETS)[40] will be extended to the maritime sector from January 2024, complementing FuelEU Maritime as another key initiative in the EU's efforts to reduce maritime emissions. The extension will cover CO_2 emissions from all large ships (of 5 000 gross tonnage and above) entering EU ports, regardless of the flag they fly.
- The Alternative Fuels Infrastructure Regulation[41] sets mandatory targets for the deployment of alternative fuels infrastructure in the EU, for road vehicles, vessels and stationary aircraft.

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[39] The Regulations provides for the use of multiplier of ”2” for RFNBO, from 1 January 2025 to 31 December 2033 only. Additionally, an RFNBO ‘sunrise clause’ is included, providing that if in 2031 the share of RFNBOs in the yearly energy used on-board ships is less than 1%, a mandatory quota of 2% RFNBOs shall apply by 2034.

[40] https://eur-lex.europa.eu/EN/legal-content/summary/eu-emissions-trading-system.html

[41] https://eur-lex.europa.eu/eli/reg/2023/1804/oj

- The Renewable and Low-Carbon Fuels Value Chain Industrial Alliance (RLCF Alliance)[42] is an initiative that focuses on boosting production and supply of renewable and low-carbon fuels in the aviation and waterborne sectors. It is a key flanking measure to the FuelEU Maritime initiative.

The regulations introduce some exemptions for specific routes and ports for passenger ships other than cruise passenger ships connecting a port located on an island with fewer than 200,000 permanent residents, passenger ships performing transnational voyages for Member States sharing no land border with any other Member State and voyages between ports located in an outermost region.

3.4.2 Sustainability of fuels according to EU legislation

Differently than REFuelEU Aviation[43], FuelEU Maritime allows the use of renewable and low carbon fuels, goal-based and respect the principle of technological neutrality. Low-carbon hydrogen, which have been introduced in the revised Gas Directive[44], are fossil fuels that have a lower carbon intensity compared to conventional fuels. Examples include natural gas coupled with carbon capture and storage (CCS) and hydrogen produced using low-carbon energy sources such as nuclear power. These fuels are particularly valuable for immediate emission reductions in sectors where decarbonization is still challenging and more efficient or cost-effective alternatives are not yet available. Additionally, the Directive emphasizes the necessity of incorporating methane emissions, carbon capture rates, and comprehensive upstream emissions in the lifecycle analysis of low-carbon fuels to accurately assess their emission profiles. Definitions for 'low-carbon hydrogen' and 'low-carbon gases' are found in Articles 2 and 9 of the Gas Directive. These articles establish a benchmark for greenhouse gas emission reduction at 70% relative to a conventional fossil fuel benchmark, which is set at 94 g CO2/MJ according to the RED. The methodology for calculating these emission intensities is due to be adopted within 12 months after the Gas Directive takes effect, as Delegated Act.

Among and in addition to the renewable options, there are several fuels that may contribute to the FuelEU Maritime GHG reduction targets:

- Advanced Biofuels: These are derived from feedstocks listed in Annex IX Part A of the Renewable Energy Directive, which includes materials such as algae, straw and certain types of waste and residues.
- Biofuels from Annex IX Part B Feedstock: These are biofuels produced from additional types of sustainable feedstocks listed in Annex IX Part B, like certain types of animal fats and tall oil pitch.
- Renewable Fuels of Non-Biological Origin (RFNBOs): This category includes hydrogen and synthetic fuels produced from renewable electricity. These fuels are particularly promising for their potential of GHG reduction since renewable hydrogen comes with zero GHG emissions.
- Recycled Carbon Fuels (RCFs): These are fuels produced from (often fossil) waste carbon streams that would otherwise be released into the atmosphere, such as from

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[42] https://transport.ec.europa.eu/transport-themes/clean-transport/alternative-fuels-sustainable-mobility-europe/renewable-and-low-carbon-fuels-value-chain-industrial-alliance_en
[43] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023R2405
[44] https://eur-lex.europa.eu/eli/dir/2024/1788

industrial processes. Together with RFNBO, the rules for their use are listed in the Delegated Acts (EU) 2023/1184[45] and 2023/1185[46].

However, they have to comply with the sustainability and GHG emissions saving criteria set out in Article 29 of Directive (EU) 2018/2001. The fuels that do not comply with such sustainability requirements and GHG emission savings, or that are produced from food and feed crops, shall be considered to have the same emission factors as the least favourable fossil fuel pathway (e.g. most carbon-intensive pathway), in order to disincentive the use of such fuels.

It is important to note that ‘food and feed crops’ biofuels, as defined in Article 2, second paragraph, point (40), of Directive (EU) 2018/2001 shall be considered to have the same emission factors as the least favourable fossil fuel pathway when used in the maritime sector.

Finally, liquefied natural gas (LNG) is a fossil-based fuel and is not renewable. Even so, it is sometimes included in discussions about maritime decarbonization due to its lower GHG emission profile compared to traditional heavy fuel oil when it comes to combustion in engines. However, the full life-cycle emissions of LNG, including production, processing, transport, and potential methane leakage (fugitive emissions), can compromise its greenhouse gas benefits. The EU's upcoming Methane Regulation[47] aims to address these concerns by introducing measures to reduce methane emissions along the natural gas supply chain.

Once selected the eligible fuels for each application, GHG reduction is calculated by considering difference between the calculated carbon intensity and the average well-to-wake fuel GHG intensity of the fleet in 2020, estimated at 91.16 gCO_{2e} per megajoule (MJ). See Annex II of Fuel EU Maritime regulation.

The EU regulation has drawn criticism from e.g. lobby group T&E, who argue that the FuelEU mandate does not give incentive to sufficiently rapid transition to renewable fuels.

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[45] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R1184

[46] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R1185

[47] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2021%3A805%3AFIN

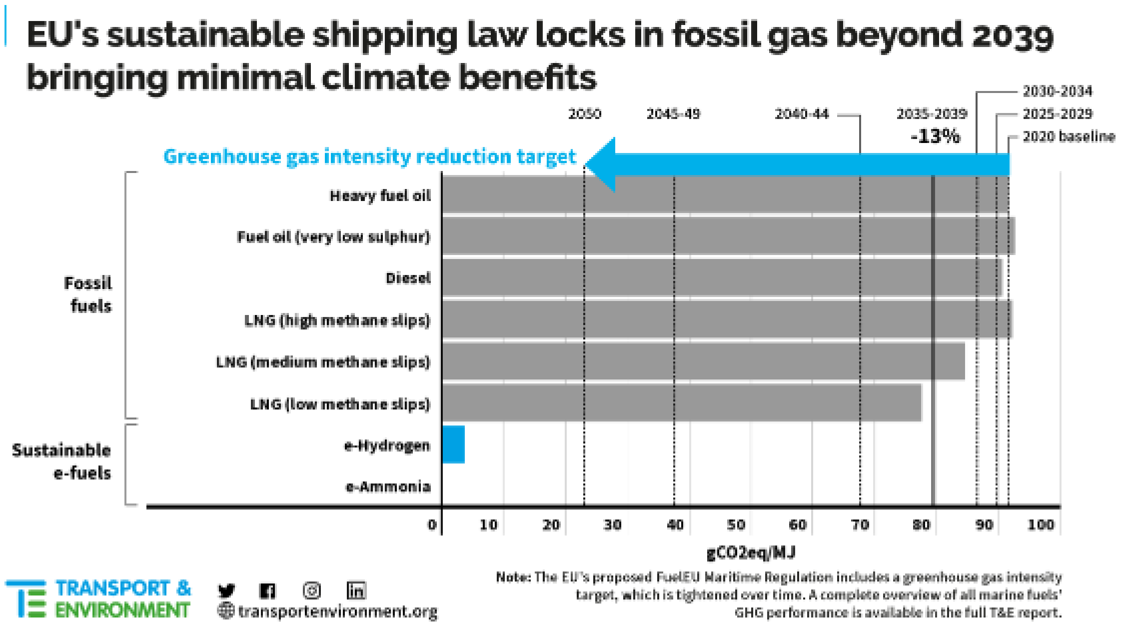

Figure 16. Assessment by T&E on Fuel EU regulation, Source: https://www.transportenvironment.org/uploads/files/FuelEU-Maritime-Impact-Assessment.pdf

3.4.3 IMO GHG strategy

The policy framework of the EU to support the transition to a decarbonized maritime sector by encouraging the uptake of alternative fuels and by setting out specific requirements and incentives for their use, also aligns to the targets set at International level by the International Maritime Organization (IMO). IMO plays a pivotal role in the global effort to mitigate greenhouse gas (GHG) emissions from the maritime sector, contributing to United Nations Sustainable Development Goal 13, which calls for urgent actions to mitigate the climate change. On July 15, 2011, the IMO adopted the first set of mandatory international measures to enhance the energy efficiency of ships. Building on this foundation, the IMO has implemented further regulatory measures and adopted the initial IMO' GHG Strategy in 2018, followed by the revised "Strategy on Reduction of GHG Emissions from Ships" in 2023[48].

The updated strategy, endorsed at the Marine Environment Protection Committee (MEPC 80), envisions achieving net-zero GHG emissions from international shipping by around 2050. It emphasizes the adoption of alternative zero and near-zero GHG fuels by 2030 and sets indicative milestones for 2030 (a reduction of at least 20%, aiming for 30%) and for 2040 (a reduction of at least 70%, aiming for 80%).

The strategy is described in more detail in section 2.5.4.

Specifically, the 2023 strategy aims to decrease the carbon intensity of international shipping – reducing CO_2 emissions per unit of transport work – by at least 40% by 2030. The strategy

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[48] https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/MEPC%2080/Annex%2015.pdf

also includes goals for the adoption of zero or near-zero GHG emission technologies, fuels, and energy sources, which should replace at least 5% (preferably 10%) of the energy consumed by international shipping by 2030.

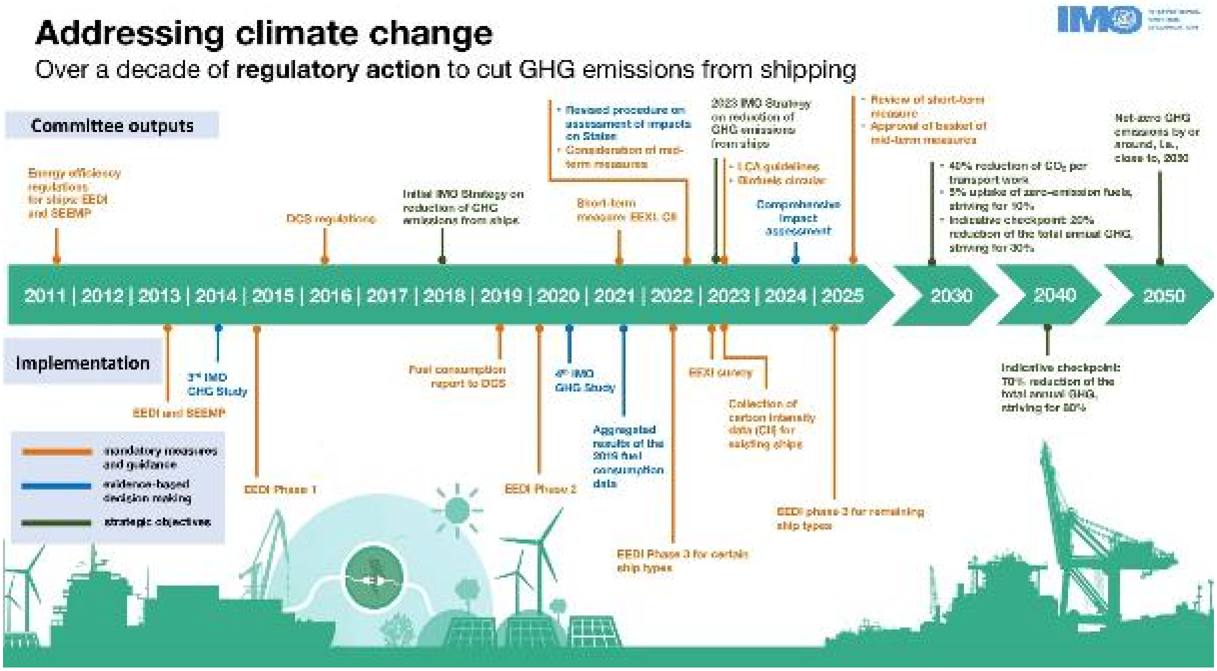

Figure 17. IMO initiatives to reduce carbon emissions from shipping. Source : https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx

A review of this strategy is projected to be completed by the Marine Environment Committee in autumn 2028, paving the way for the adoption of the 2028 IMO Strategy on reduction of GHG emissions from ships.

The 2023 GHG Strategy outlines a series of candidate mid-term GHG interventions (the IMO Net Zero framework), including both technical aspects, such as a goal-based marine fuel standard for the phased reduction of marine fuel GHG intensity, and economic aspects, like a maritime GHG emissions pricing mechanism. These measures are currently under evaluation, considering various criteria for a thorough impact assessment, which aims to facilitate the finalization of these initiatives.

The timeline for the adoption of pricing mechanisms is integrated into the 2023 GHG Strategy, with approval of mid-term measures expected by spring 2025, and their anticipated entry into force in 2027. A Steering Committee is tasked with conducting a comprehensive impact assessment to guide the development of these measures.

The IMO is also focused on supporting developing countries, especially least developed countries (LDCs) and small island developing states (SIDS), in implementing the GHG Strategy. Through financial assistance from participating Countries, the IMO offers a range of capacity-building and technical cooperation programs.

3.4.4 IMO LCA Guidelines and comparison with other methodologies

The IMO has developed a Life Cycle Assessment (LCA) methodology to evaluate the greenhouse gas (GHG) intensity of marine fuels across their entire life cycle, encompassing Well-to-Tank (WtT), Tank-to-Wake (TtW), and Well-to-Wake (WtW) emissions. The last version of the methodology is proposed in the document "2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels”[49], which provides a framework that includes all fuels and energy carriers used on maritime fleets, aiming to cover the entire fuel life cycle from feedstock extraction to fuel utilization on board a ship. The guidelines also address sustainability aspects of marine fuels such as carbon source, water use, air and soil quality, waste and chemical management, and conservation efforts, and define a Fuel Lifecycle Label (FLL) that carries information about fuel type, feedstock, production pathway, GHG emission factors, and sustainability issues.

The methodology emphasizes the importance of an attributional approach to LCA, considering all processes along the supply chain of fuel/energy carrier pathways. It also discusses the expansion of system boundaries for specific pathways, the role of co-products, and the accounting of carbon from biomass.

In section 5.2 of a recent report of RICARDO produced for the IMO[50], the IMO LCA methodology is compared with other frameworks such as the EU RED, California LCFS, RenovaBio, and CORSIA. The main points of comparison include:

- GHG Emission Savings: The IMO LCA methodology sets targets for GHG emission reductions similar to those in the EU RED, with specific goals for reducing carbon intensity and promoting the use of low-carbon fuels.
- Use of Default Values: Like the EU RED and CORSIA, the IMO LCA methodology provides default values for common fuel pathways but also allows for the use of actual values to demonstrate better GHG performance.
- Inclusion of Land Use Changes: The IMO LCA methodology includes emissions from direct land use changes. Concerning Indirect Land Use Change (ILUC), the "risk-based" method mentioned in the IMO guidelines appears to align closely with the system utilized by the EU RED, which categorizes feedstocks based on their potential ILUC risk as either high or low. Additionally, the overarching definitions provided for high and low ILUC risk within the LCA guidelines share a general agreement with the definitions outlined in the EU RED.

It can be noted that for the aviation sector, the International Civil Aviation Organization (ICAO), a UN agency, has developed a market-based mechanism in the form of the *Carbon Offset and Reduction Scheme for International Aviation* (CORSIA) to regulate the obligation of airlines to purchase offsets above certain emission limits. As SAF can be used in place of offsets, CORSIA has defined eligible fuels, developed sustainability criteria, a framework for assessing and approving sustainability certification schemes under CORSIA, and a life cycle methodology for calculating the carbon reduction potential of eligible fuels. A similar offtake agreements register could be developed by IMO or regional agencies for the marine area.

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[49] https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/MEPC%2081/Annex%2010.pdf

[50] https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/FFT%20Project/Second%20study%20-%20sustainability%20and%20verification.pdf

3.5 Overcoming barriers along the value chains

3.5.1 Increasing Drop–in biofuel production

Tomas Ekbom, Swedish Bioenergy Association (sections 3.5.1 – 3.5.3)

Policies for increasing drop-in fuel production

There are major challenges associated with achieving a CO_{2e} (GHG emissions) neutral society by 2050 and fulfilling sustainable development goals (SDGs) and the IEA’s Sustainable Development Scenario (SDS). Transport biofuel production is expected to continue growing, however, only at annual rates below 5% according to IEA in the near future, whereas sustained levels of 10% output growth per year are needed until 2030 to get on track with SDS.

Despite the minor share of renewables in transport (globally about 3%; primarily used for road transport), biofuels continue to be the central fuel option in most strategies to decarbonise transport with additional measures in electrification and renewable hydrogen as strong contributors. Biofuels production continues to increase globally with at an average annual rate of 4% over the past 10 years. Conventional biofuels like ethanol and biodiesel/FAME continue to dominate the market but drop-in biofuels such as HVO/HEFA has been growing rapidly. It is estimated, that 69% of the biofuel produced (in volume terms) was ethanol, 26% was biodiesel/FAME and 5% was HVO/HEFA in 2020. Biomethane use is growing, but constitutes less than 1% of all biofuels.

For the past and future development of the biofuel market biofuel policies are essential. Technology-push policies (e.g. CAPEX/OPEX for technology development) are focussing on research, development and demonstration (R&D&D) while market-pull policies (e.g. blending mandates, quotas, multi-counting mechanism) allow creating a certain demand of fuels for relatively mature technologies. Sustainability requirements are being increasingly incorporated into policies.

Biofuel mandates alone usually are not sufficient enough to support actors reducing the carbon intensity along the biofuel value chain. Reducing carbon intensity along with renewable fuels based on biomass is incentivised by low carbon fuel standards (like in parts of the US and Canada as well as in Brazil) and GHG emissions quotas (like in the EU in Sweden and Germany).

Technology-push policies have been successfully used to encourage R&D&D, particularly for advanced biofuels. This is true especially in countries that already have established biofuel markets (e.g. USA, Canada, Brazil, and the EU). However, despite considerable progress being made in the technical aspects of advanced biofuels production right and stable policies are required to establish commercialization.

Countries that are using both policy instruments (technology-push and market-pull) have achieved most success in growing markets for biofuels production and use. To enhance the

effectiveness of policies in creating a target oriented stable environment for increasing shares on biofuels several uncertainties need to solved. A primary factor is long-term certain biofuel policies that allow investments incl. all the risks especially for advanced biofuels. Other factors to be addressed are: non-compliance costs, competitive resource and product markets, future funding and incentive programs, unforeseen impacts to global trade (pandemics, wars, crisis, and taxes). Moreover, the lack of commitment stopping investments in fossil based industries hinder market growth of renewables.
Policies promoting renewables for transport have been focusing primarily on road transport, which accounts for the vast majority of the total energy use. Despite being large energy consumers and carbon emitters, aviation and shipping have seen less attention until now. This is changing and recent policies clearly address also these transport sectors.

The bottom line is that despite billions of dollars of investments, ramped up production of low carbon advanced biofuels remains well below the levels needed to achieve the SDS. The quickest way to meet the targets is by blending with fossil fuels in existing infrastructure with distribution and use in vessels with existing engines. Biofuels are today used as neat fuels but have the largest potential as drop-in fuels (in addition to dual-fuel methanol).
The main conclusion out of this is: “For the successful implementation of alternative fuels and vehicles in the transport system there is the need for long-term and comprehensive policies which include markets, stakeholders and different technologies to gain benefits for all types of stakeholders along the value chain.”

3.5.2 Policies for biofuel production and use

The general developments in advanced biofuels production with thermal processes like gasification and pyrolysis and synthesis have not made broad commercial success. In an earlier IEA Bioenergy study case studies were analysed of different developed technologies with focus of producing advanced biofuels. They cases for countries of Canada, Germany, Sweden and USA showed considerable technical successes but limited commercial success. Key message of almost all studies is to continuously work on harmonised clear long-term policies that allow improvement of established biofuel options as ground base for decarbonisation in transport and as urgently needed for a sustainable carbon neutral world R&D&D of innovations of advanced biofuels incl. hybrids with other renewables that are more complex and thus (usually) more cost demanding (e.g. with regard to GHG mitigation) and entailing higher risk.

Even with ambitious national goals and policies the development has a hurdle with financing of biorefineries, where there is a large financial risk involved. The state of knowledge regarding investments in biorefineries is mainly focused on which raw materials are suitable to use, and manufacturing that meets countries' high demands for sustainability.
During the decision-making process for investments in biorefineries, a number of stances and decisions on path selection are made. The choices are decisive for how well the project will develop and achieve set goals, not least in terms of the project's possibility of financing and profitability as well as expansion. Decision factors with financial impact are essential for the decisions of technology choice and market but also the choice of raw material.
Regarding shipping, no sharp measures have been formulated on emissions reduction on a national basis, but rather on international cooperation. However, domestic sea transport is only a small proportion and the main use is in foreign sea transport through bunkering.

Aviation is more in focus both nationally and internationally politically, despite the fact that it accounts for less than half of the emissions compared to shipping, which also has a much higher fuel flexibility and less sensitive fuel distribution and use.

Basis is needed for a better understanding of what opportunities and obstacles there are for a conversion of shipping to a fossil-free one. Recommendations exist to be able to transition to fossil-free shipping within 30-40 years through the rapid implementation of several known measures, while at the same time development continues in new technologies and methods for energy-efficient and fossil-free shipping.

There is no single solution for shipping's transition to fossil-free shipping in the foreseeable future, but instead involves implementing a number of different technical, operational and structural measures in combination with renewable propulsion and alternative fuels.
Many technical innovations are not suitable for conversion of existing ships but require new design and construction. It is therefore important that this major change begins now, as the long life of the ships risks delaying development. However, the structural and operational measures are less dependent on the age of the ships and rarely require large investment costs. A summary conclusion is that the shipping industry in several parts is strongly prone to change. In order for this driving force to be steered towards a transition to fossil-free energy, coordinated efforts are required.

Globally, the fuel is changing for the better. At the turn of the year 2019-2020, one of the most extensive and requested environmental measures in world history was implemented. Then the international UN agency IMO (International Maritime Organization) raised the requirements for the maximum permitted sulphur content in marine fuels from 3.5 to 0.5 percent. The regulations are expected to have many positive effects on the environment. Given this, the fuel can thus be changed to be regulated for the mixing of bio-components which by their nature do not also have sulphur components.

It is a recommendation that either a quota obligation or a reduction obligation be introduced. The obligation would also be based on a partial quota of the fossil fuel reduction that must be met with biofuels made from raw materials according to the proposal for a targeted reduction obligation.

3.5.3 Current state of drop-in biofuels

In practical terms the drop-in biofuels which are of relevance are oils that are eligible for blending with marine fuels. Essentially, on a larger scale, the most prominent biofuel as drop-in is HVO diesel. The other fuel to be reckoned with is biomethane (also termed bio-CNG) which is optional to be blended for vessels that operate on fossil liquefied gas like LNG. The biomethane could then be liquefied and form the product LBG. The major difference is some gases present in the fossil gas. However, it depends on the specifications of the engines if they can accept a range in heating value. As of experience there are many vessels that operate on LBG or mixes with LBG and the fuel is proven to be a “drop-in” gas.
The chemical and physical characteristics of HVO are almost identical to those of diesel fuel and can be safely mixed with the latter to varying degrees. In short, today’s HVO blends are technically compatible with fuel delivery and seaport fuelling infrastructure. No investments

in delivery or fuelling infrastructure are needed. The scale-up of HVO volumes has already begun and can continue without delay.

Currently and globally, the hydrotreated esters and fatty acids (HEFA) or hydrotreated vegetable oil (HVO) pathway is still the only fully commercial technology for making drop-in biofuels. As reported in 2022, global renewable diesel production via this pathway was about 6-7 billion litres. In Figure 18 below the development for HVO is shown for USA compared with biodiesel like FAME. In general, conventional biodiesel has been the major biofuel, but with recent years increase in production HVO is becoming the dominant fuel for several countries.

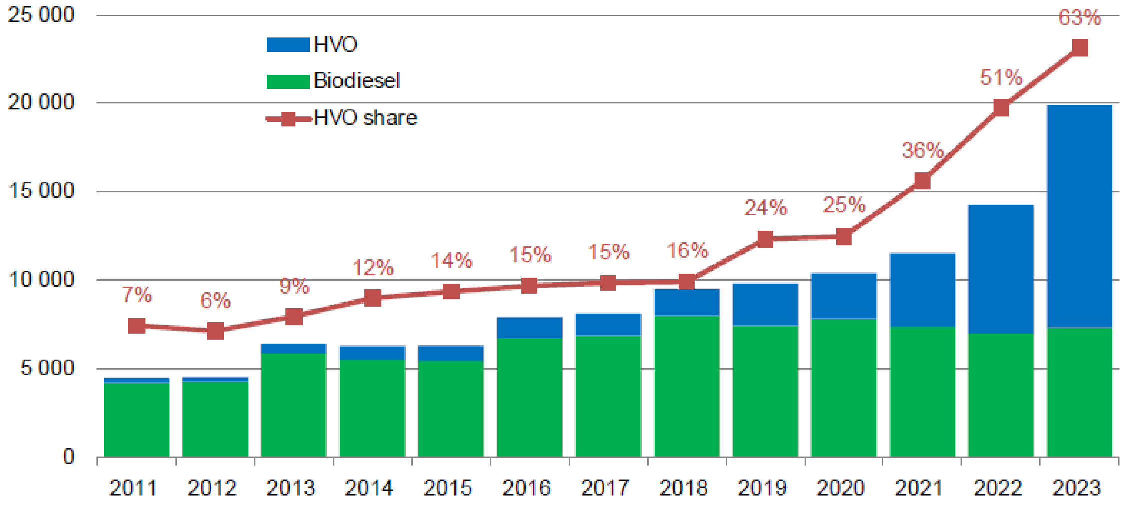

Figure 18. US production of biodiesel and HVO in 1,000 tonnes. Source: AMI, US EIA.

Over the last two years, there has been a significant increase in the commissioning of new HEFA (lipid-to-drop-in biofuels) facilities, with many more facilities currently under construction or planned. Although the estimated production amount and volume for HEFA-based facilities varies considerably between various sources, a conservative estimate is about 25 billion litres per year. In most cases, these facilities produce both renewable diesel and SAF, with the amount of each fraction influenced by the refinery configuration. However, as mentioned earlier, in most cases, the growth in HEFA-based facilities is predominantly driven by policies.

Apart from the HEFA pathway, the other routes to drop-in biofuel production have been relatively slow to develop. One small commercial facility based on gasification and Fischer-Tropsch (FT) was constructed but closed in May 2024 (Fulcrum Bioenergy). About 16 other facilities have been announced for drop-in biofuel production via biomass gasification followed by FT synthesis. However, as described in more detail in the full report, gasification and Fischer-Tropsch will typically result in a slate of products, including diesel and naphtha. Earlier IEA Bioenergy Task 39 reports (IEA, 2023) have described the technical challenges of the gasification pathway in detail.

Although there is still room for the lipid-to-drop-in biofuels to expand, some groups anticipate the alcohol-based processes, pioneered by Lanzajet and Gevo, will soon supplement this production route. For example, Lanzajet’s Freedom Pines facility was recently opened and about 20 other alcohol-to-jet (ATJ) facilities have also been announced. While the biojet fraction based on this technology can range from 70-90%, the oligomerization process is “tunable” and production could readily shift to predominantly renewable diesel.

Direct thermochemical liquefaction refers to the production of biocrudes via fast pyrolysis, catalytic pyrolysis or hydrothermal liquefaction that, typically, have to be further upgraded into finished fuels. The current commercial-scale production of biocrudes is about 136 million liters. However, the vast majority of this biocrude is used for heating applications as the upgrading step is still under development and has several challenges that need to be fully resolved. These challenges include the variability/complexity of the biocrudes, oxygen and water content, acidity, instability, etc., which contribute to catalyst inhibition and coking.

Overcoming the obstacles associated with successfully upgrading biocrudes is needed if this route to drop-in biofuels (or its potential use in co-processing) production is to be fully commercialized. However, the ability of this type of thermochemical-based process to use multiple biomass feedstocks will likely be an asset due to the need to produce substantial amounts of drop-in biofuels to meet long-term climate targets. As mentioned in previous reports, hydrothermal liquefaction (HTL) is uniquely positioned to use wet waste feedstocks (e.g., sewage sludge, algae, etc.) that cannot be readily used by other thermochemically based technologies.

While two-step hydrotreatment of fast pyrolysis biocrude has been successfully demonstrated, commercialization of the overall technology is still in progress. For example, several challenges, such as catalyst inactivation, long-term operational stability, etc., still need to be fully resolved. Even where biocrudes characteristics, such as the high oxygen content, low acidity, etc., can be reduced in processes such as catalytic pyrolysis and HTL, catalyst inactivation remains an issue. Currently, a number of facilities are under construction, such as Arbios Biotech’s Chuntoh Ghuna facility in Prince George, with other groups, such as Alder Renewables, receiving substantial government support and investment.

Recent research areas include investigating various pretreatment options to improve the quality and stability of biocrudes before upgrading. Focus areas include the pre-fractionation of biocrudes, the addition of solvents and hydrogen transfer reactions. While oxygen removal can also be considered part of the upgrading process, it is also used as a type of pretreatment to improve the stability and miscibility of biocrudes before upgrading in a coprocessing strategy.

To be economically viable, biorefineries based on direct thermochemical liquefaction must valorize the various co-products, byproducts and biochar streams that will also be produced. For example, when using catalytic pyrolysis or HTL, substantial volumes of water are usually produced with this fraction containing a significant amount of the initial carbon from the biomass feedstock. Valorization of this fraction (as opposed to merely treating it as wastewater) via anaerobic digestion (and the utilization of the methane produced) or production of volatile fatty acids could make these facilities more economically viable. Other options, such as using biochar to obtain carbon removal credits, could also contribute to climate change mitigation.

There is a current increasing trend on retrofitting oil refineries with biofuels as a quicker way for large-scale production. This has been driven by the demand for HVO blended in diesel and more recent for more SAF. However, as of July 2024 there are some projects on hold or cancelled like Shell for Rotterdam with a large HVO refinery. In the Figure below there are examples of oil refineries transforming for HVO production whereas cuts in the production can be made for marine fuels, road diesel fuels and kerosene jet fuels.

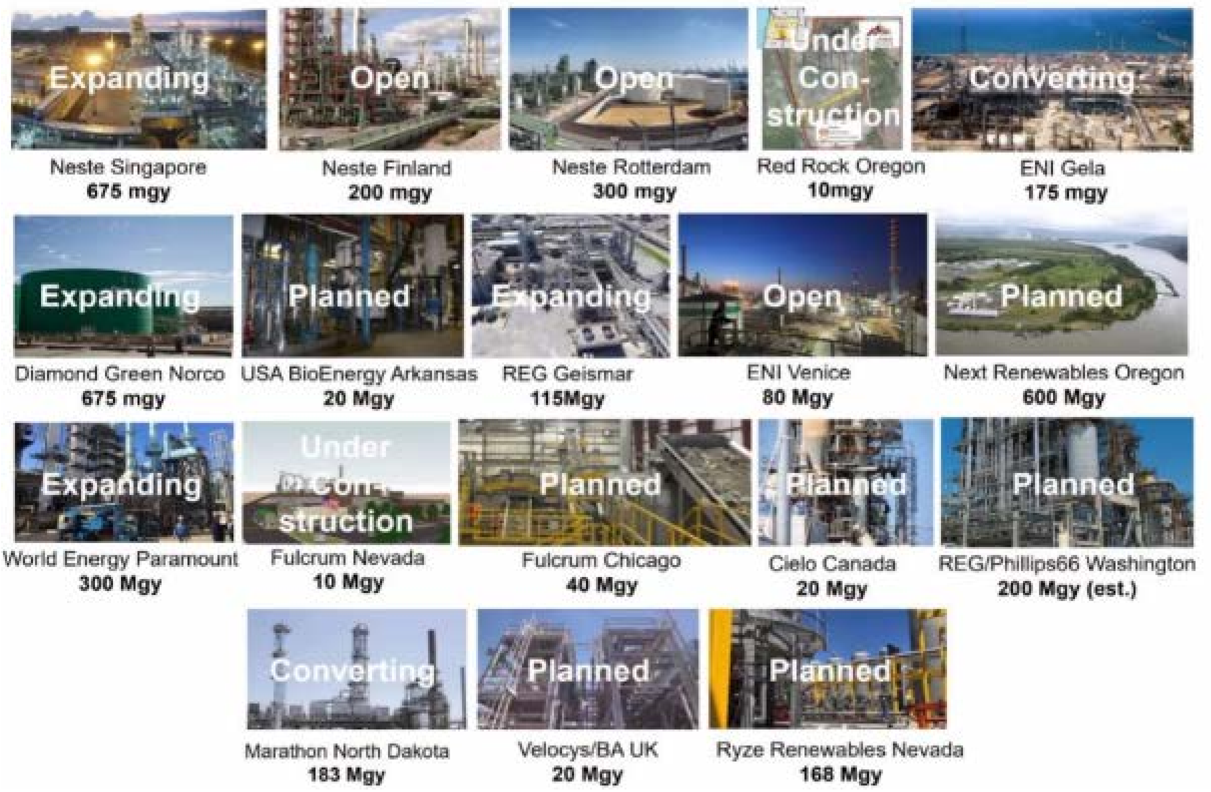

Figure 19. Examples of retro-fitting oil refineries with biofuels (100 million gallons ≈ 378 000 m^3).

Co-processing of biobased intermediates in existing petroleum refineries can rapidly increase the production of low carbon intensity (CI) fuels at a lower investment cost than building new biorefineries. Co-processing can also play an important role in the energy transition of the oil and gas sector. Several companies in the fossil-fuel industry have set ambitious targets for decarbonization, with several targeting reductions in scope 1, 2 and 3 emissions. Although refinery decarbonization is critical (Scope 1 and 2 emissions), 70% of the carbon emissions come from the combustion of the fuels (Scope 3 emissions). Consequently, replacing fossil fuels with renewable fuels in a refinery can also reduce Scope 3 emissions.

While the blending of renewable fuels with fossil fuels is already well established, a coprocessing approach, which involves the simultaneous processing of fossil and renewable feeds within a refinery, is increasing in popularity. While co-processing presents some risks to the refiner, national and international policy drivers have made co-processing more attractive. These include credits awarded via low carbon fuel standards (e.g., California and

British Columbia) or because refiners must comply with regulatory mandates (e.g., supplying low-CI jet fuel in response to the ReFuelEU Aviation mandate).

Co-processing of lipids for producing renewable diesel has been commercial for some time and multiple petroleum refineries in Europe produce low-CI jet fuel via this route. Although co-processing of other biobased liquid intermediates (e.g., biocrudes) has been limited, some groups, such as the Marathon Petroleum Refinery, are assessing the co-processing of Fischer-Tropsch biocrudes while Preem (Sweden) is evaluating the co-processing of biocrudes produced at their Pyrocell facility (fast pyrolysis) at a fluid catalytic cracker insertion point. Another way is transforming the entire oil refinery, here exemplified with Phillips 66 in Figure 20 below.

Figure 20. Phillips 66 transforms its San Francisco refinery into the world's largest biorefinery with 800 million gallons (≈3 million m3) annually of renewable diesel & gasoline, and sustainable aviation fuel (SAF). Start of operation in 2024.

It is likely that in the longer term, coprocessing of biocrudes will be needed as the substantial demand for lipids (currently used to make bio/renewable diesel and biojet/SAF) will place a constraint on feedstock availability. Biocrudes can be produced from more available biomass feedstocks, such as forest or agricultural residues, and “waste” feedstocks, such as sewage sludge. These “residual” biomass feedstocks will likely be more affordable than lipids, be more available and result in feedstocks with a lower carbon intensity (CI). However, significant challenges must be resolved before biocrudes can be successfully co-processed commercially. As will be covered in more detail, as biocrudes differ substantially from crude oils, petroleum refineries must address the risks associated with co-processing these feedstocks, such as their thermal instability, acidity, corrosion concerns and catalyst deactivation.

Although co-processing of biocrudes at the fluid catalytic cracker is likely a lower-risk proposition, recent work has shown that as much as 50% of the renewable carbon can end up in the coke fraction with less than 30% of the renewable carbon found in the liquid fraction. Other studies have also investigated co-processing biocrudes at the hydrocracker as this reactor can open aromatic rings and crack heavy fractions of the biocrudes. Some workers have also suggested that hydrocrackers are more able to deal with the temperature increases resulting from exothermic hydroprocessing reactions. However, although there have been some positive results when co-processing biocrudes at the hydrotreater, more data is needed to determine if this is a viable route.

As “what to do with the water” is a major question when following a thermochemical route to making biocrudes from biomass, wastewater treatment, including the chemical characteristics of the wastewater is covered in more detail in the main body of this report. Some recent studies have claimed that the co-processing of intermediate products reduced the MFSP by 10–19% when compared to corresponding standalone cases. As covered in more detail in the main body of the report, the economic benefits of co-processing versus building freestanding biorefineries needs to be considered.

Regarding future production, McKinsey & Company produced a report in 2020 called Clean Skies for Tomorrow where they estimate with the help of Neste roughly 11-13 million metric tons of used cooking oil (UCO) are available globally each year, and more could become available as growing populations and rising wealth increase the demand for food.
Animal fats from industry rendering waste represent roughly a third of the global supply of waste and residue lipids – 12-15 million metric tons each year, a figure that should grow as meat consumption rises, especially in Asia. The same holds true for fish oil, although only about 1 million metric tons are available each year. All other considered waste and residue lipids as described earlier total to about 11-14 million metric tons each year.

Total practical availability of this feedstock category thus amounts to roughly 40 million metric tons per year, which translates to roughly 20 million metric tons of SAF and 20 million metric tons of renewable diesel. Converting waste and residue lipids into jet fuel could meet about 5% of total 2030 jet fuel demand. These numbers are likely a conservative number, since many smaller streams of waste and residue lipids are not included in the analysis.
The largest challenge for scaling up HEFA production is the feedstock pool. HEFA fuels are produced today in commercial quantities by foremost Neste, ENI and World Energy. This changes rapidly and more producers come on-stream every year. Total production capacity could rise to more than 16 million metric tons by 2025, based on public announcements, mostly by companies such as Neste.

3.5.4 Increasing green methanol and biomethane production

David Bauner, Renetech

In its 2021 outlook, IRENA wrote "Looking ahead, the increase in methanol production is expected to see a progressive shift to renewable methanol, with an estimated annual production of 250 million MT of e-methanol and 135 million MT of biomethanol by 2050.”

According to a database developed by the Methanol Institute and Gena Solutions Oy, around 190 renewable methanol project are in planning (feasibility or pre-feasibility) phase, with startup dates by 2030 or earlier, or operational. However, only a handful - less than 10 - are operational and with a capacity in excess of 50 kt/a.

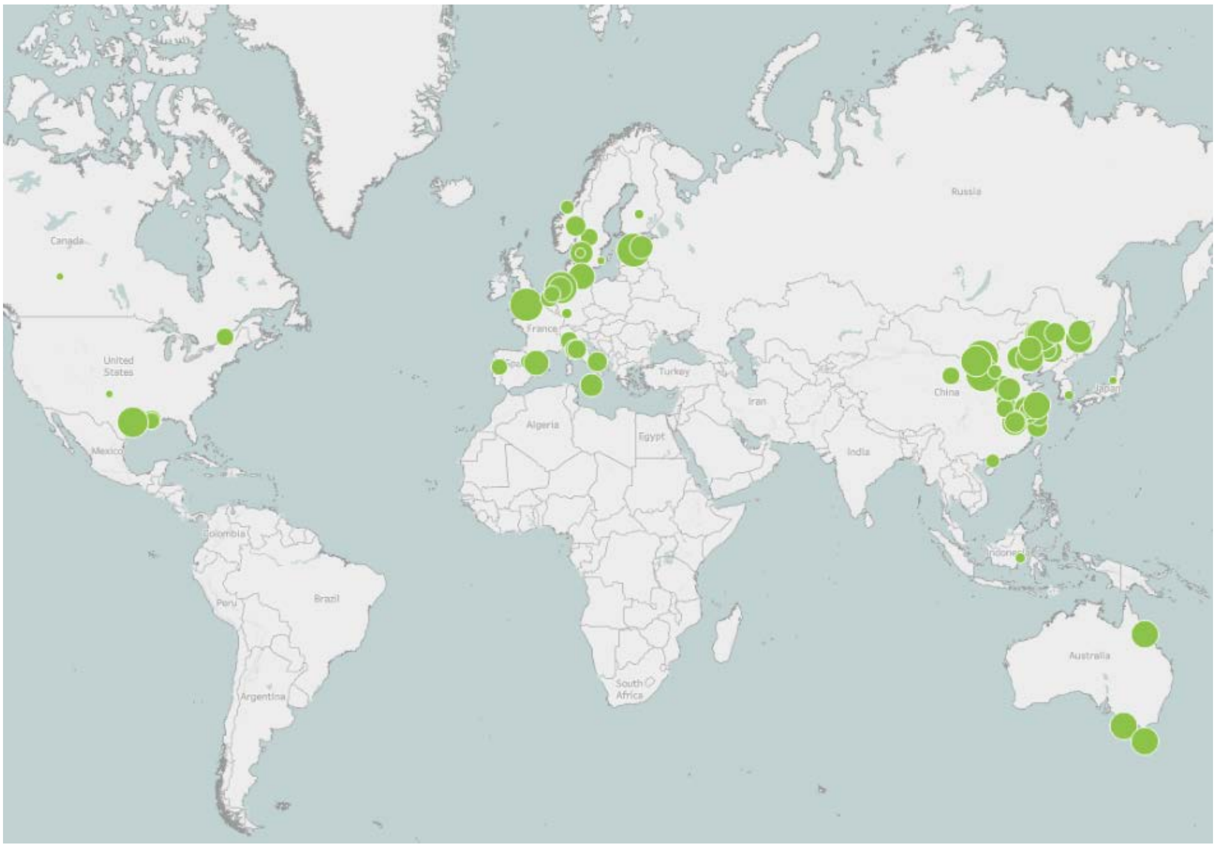

Figure 21. Operational and (mostly) planned biomethanol plants worldwide. Source: Methanol Institute and Gena Solutions Oy

As an example, the “power to methanol” or “power to x” Kassø plant under development, will be the world´s first large-scale commercial e-Methanol production facility, using hydrogen provided by a 50 MW electrolyzer plant provided by Siemens Energy. It is located at Kassø, west of Aabenraa in Southern Denmark and close to the Danish-German border. The project counts with access to low-cost renewable electricity required to make cost-effective e-Fuel through the co-located 304 MW solar park of Kassø - the biggest solar farm in the Nordics - created by the company European Energy. The end users of the e-Methanol will include the shipping company Maersk and the fuel retailer Circle K. The facility will ensure the e-Methanol supply for Maersk`s first e-Methanol driven container vessel, and thus marks the starting point into large-scale CO_2-neutral shipping. The plant will be operational at the end of 2024.

Yet one example, not included in the database above; in the BioReFuel project, running 2020 to 2023, Lemvig Biogas assessed storage of electricity in the form of methanol obtained through conversion of CO_2 in the biogas and hydrogen via electrolysis of electricity (Producing methanol from biomethane with electrolysis. The process uses 21 kWh of heat, 65 kWh in the form of raw methane, and 12.4 kWh of H_2 (electricity used for electrolysis of hydrogen) to produce 18 liter of methanol (holding 77.9 kWh), i.e. the process is reported to be 90.2 % efficient.

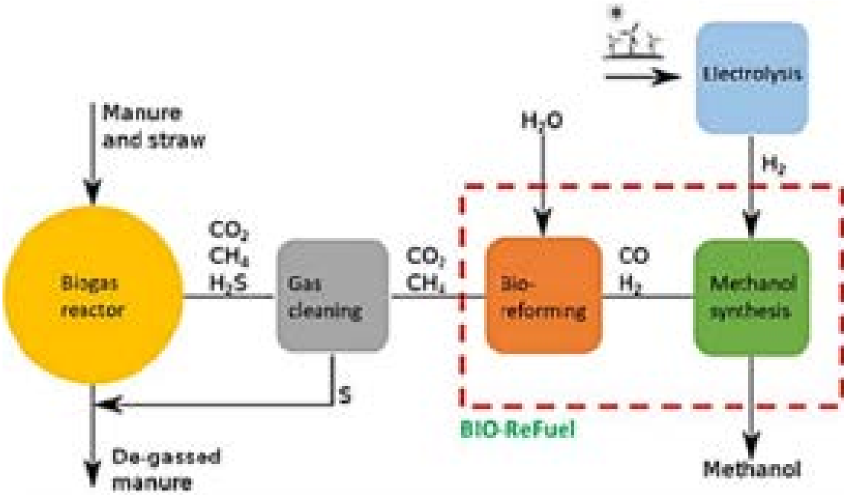

Figure 22. Methanol production process overview for the BioReFuel project process

An alternate technology for producing methanol from anaerobic digestion is by applying catalysis to the raw biogas from anaerobic digestion currently explored by DTU[51]. This would eliminate the need for costly and power consuming electrolysis for production of process hydrogen as in the process depicted in Figure 22.

3.5.5 Engines and fuel system compatibility with biofuels

Dinis Reis Oliveira, Stena Teknik, Sweden

In general, biofuels consisting of simpler molecules such as methanol (biomethanol) and methane (liquefied biogas, LBG) typically exhibit the same range of physical-chemical properties as their fossil counterparts (fossil methanol and LNG), and therefore compatibility with their respective methanol dual-fuel engines or LNG dual-fuel engines can easily be ensured.

However, for most of the existing fleet, substitutes for current heavy-to-light fuel oil and distillate marine gasoil (MGO), such as biodiesel (FAME) and renewable diesel (HVO) present a more complex compatibility cases towards on-board fuel systems and engines. In discussions with classification societies and marine engine makers, the main aspects that typically arise for engine and fuel system compatibility with biofuels are (not exhaustive):

- Cold-flow properties of the fuel and compatibility with fuel's intended use.
- Long-term stability under storage – oxidation, high affinity to water, and microbial growth.
- Compatibility with fuel remaining on-board from previous bunkering, and potential stripping of residual dirt/sludge present in fuel systems.
- Material deposition and other compatibility issues with surfaces in contact with the fuel.
- In some cases, high acidity of the fuel may lead to wear of engine and fuel system parts. E.g. FAME are acidic and can cause wear of fuel pump and nozzle rubbing

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[51] https://www.dtu.dk/english/newsarchive/2024/05/green-methanol-on-verge-of-breakthrough

parts. It is the responsibility of the seller and the buyer to agree on an acceptable acid number, based on ISO 8217:2024 specification.
- Machinery (engine and fuel oil separators) settings must be adapted to fuel properties, most importantly fuel viscosity.
- Presence of contaminants that may affect exhaust after-treatment, such as silicone damaging/poisoning Selective Catalytic Reduction equipment, need to be assessed based on lab analysis *before* using the delivered biofuel or blend, for each delivery.
- Variability in delivered biofuels is expected to be higher than for convention fossil marine bunker fuels, differing from one bunkering location to the next, but also within the same bunkering location from one blend/product to the next, and even for two batches of the same blend/product.

Regarding fuel cold-flow properties and storage on-board, tank heating may be required for some biofuels exhibiting poor cold flow characteristics, e.g. high cold filter plugging temperature point. Tank heating is typically non-existent for ships running on distillate fuels, but heating is available on residual/heavy-fuel oil tanks. Heating requirements are also dependent on factors such as area of operation for the intended voyage, as well as season / time of the year.

Fuels with high oxygen content (e.g. FAME) may suffer from chemical oxidation (properties change over time) and exhibit high affinity to water, making these challenging to store for prolonged periods of time. Shorter storage cycles may also lead to “just in time” bunkering and risk running out of fuel in case of delayed subsequent fuel deliveries. There are however procedures that can be adopted to reduce these risks, such as draining settling and service tanks more often to remove water from the fuel, fuel tank shifting routines, and avoiding storage periods of over one month (or other length of time depending on storage conditions).

Risks related to compatibility with remaining fuel on-board, e.g. risk for formation of solid precipitates, can be minimized by receiving the new fuel in empty tanks, and procuring biodiesel blends containing the same fossil fuel grade component as the previous delivery, for example: a B24 FAME blend contains 76% fossil fuel oil, which is recommended to be of the same grade as used during previous operation, and 24% FAME biofuel. These blends are delivered to the ship already blended either on-board the seller’s fuel bunkering barge or else in storage tanks on land.

Cleaner biofuel products (e.g. HVO, but also neat FAME) may have a “stripping effect”, a detergency effect leading to release of previously accumulated residues from uncleaned tanks, piping internal walls, and other surfaces in contact with the fuel. Backwashing and inspection of fuel filters and purifiers may also be required on a more frequent basis, as well as keeping on-board spares for purifiers, back-wash filters and cleaning gear.

Following approval from engine maker, classification society and Flag state of the vessel, a trialling period with new fuels will typically require the engine room to be manned throughout, with close monitoring of main engine and auxiliary engine parameters during operations. As an additional emergency safety precaution, it is recommended that the ship keeps segregated tanks with a stock of unblended regular grade fuel, to change over in case of difficulties during trial with new fuels.

Use of biofuels to directly replace fossil fuel oil and distillates is thus technically feasible for existing ships.

In addition to drop-in fuels being used in conventional engines, dual fuel compatible ships as well as ships powered by liquefied or compressed methane (LNG/LBG/CNG CBG) are increasingly becoming operational in the market. Wärtsilä also studies bioethanol used in dual-fuel configurations (see sections 2.3.4 and 3.3.1).

3.5.6 Green Corridors

David Bauner, Renetech

Green Corridors, where zero-carbon shipping is enabled and demonstrated, is an important tool to enable and showcase the utility of new fuels and digitalization. Since the launch of the Clydebank Declaration in November 2021, at the UN Climate Change COP (Conference of the Parties) 26 in Glasgow, the signatories has committed to develop six green shipping corridors – voluntary zero-emission maritime routes between 2 (or more) ports – by 2025, in order to develop and support the deployment of clean maritime fuels, zero-emission vessels, alternative propulsion systems, and the global availability of landside infrastructure to support this deployment. Many more such corridors are expected after 2030. Among other things, this would facilitate the work for fuel providers in prioritizing which ports to supply.

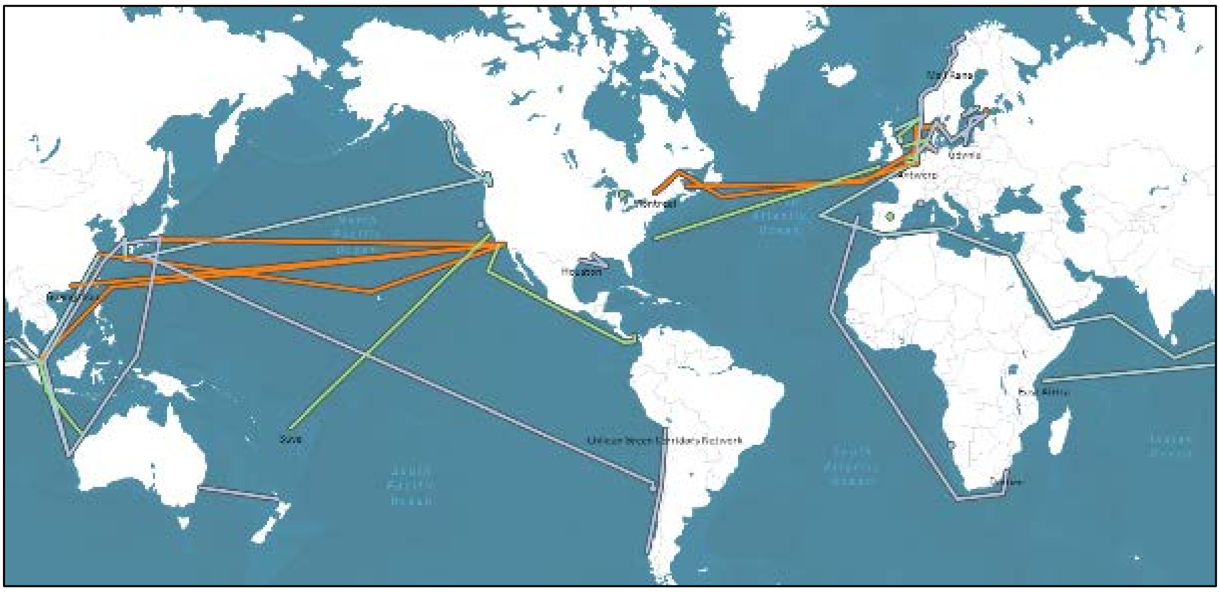

Figure 23. Examples of established Green Corridors (Source: mission-innovation.net, October 2024)

The green corridors play an essential role to iron out issues in supply, bunkering and certification of sustainable fuels for the involved ports, ships and other stakeholders. The projects have hitherto focused on e-fuels, but biofuels, being closer to commercial production, could benefit as volumes pick up.

In its 2024 Progress Report[52], the Ports of Los Angeles, Long Beach (USA) and Shanghai (China) in its Green Shipping Corridor Partnership identify the following challenges:

- Quantity, quality and price of green fuels.
- Clear and globally consistent set of rules governing the use of green fuels by shipping.
- Need to build sufficient expertise and capacity to support the decarbonization transition.
- Community engagement to support the transport of cargo by low-carbon emission vessels.
- Establishing a Corridor-wide protocol for sharing confidential information.
- Determination of cost recovery for mitigating additional costs of the energy transition.
- Developing a framework for metrics and monitoring to track the decarbonization progress.

While it is clear that there are remaining obstacles towards achieving net-zero shipping along the proposed corridor, the initiative, fostered within the C40 Green Ports Forum, has enabled a wider collaboration with a defined goal for the ports and its participating partners, including the City of Los Angeles, A.P. Moller -Maersk, CMA CGM, COSCO Shipping Lines, Ocean Network Express (ONE), Evergreen, Shanghai International Ports Group (SIPG), China Classification Society (CCS), and the Maritime Technology Cooperation Centre (MTCC) - Asia.

3.5.7 Energy efficiency measures as a catalyst to enable biofuels

Israel Biramo, Renetech

As discussed in previous sections, the maritime industry is facing growing demands to reduce its carbon footprint (Bach & Hansen, 2023), and a wider adoption of biofuels holds considerable potential. However, biofuels present challenges, particularly their lower volumetric energy density compared to conventional fuels, which leads to higher fuel storage needs, impacting vessel range and cargo capacity. Different means to increase energy efficiency in maritime shipping plays a pivotal role in overcoming these barriers. By reducing overall energy demand, energy efficiency measures can help make biofuels more viable, ensuring that the shipping industry transitions to cleaner alternatives without compromising on operational performance by reducing fuel consumption. This section explores how energy efficiency improvements can help offset the limitations of biofuels and examines the role of regulatory frameworks and emerging technologies in enabling this transition. See also section 2.6.

Energy efficiency is often described as a "low-hanging fruit" for emission reduction in shipping. According to IRENA's studies, improving vessels energy efficiency is projected to contribute to 20% of emissions reduction from 2008 levels in their 1.5°C scenarios by 2050 (IRENA, 2021). Simulations by DNV estimate that operational and technical energy-efficiency measures have the potential to reduce fuel consumption by 4% to 16% by 2030. Similarly, the DNV study highlights the feasible potential contribution of various decarbonization solutions mainly include energy efficiency measures. Logistics and digitalization can

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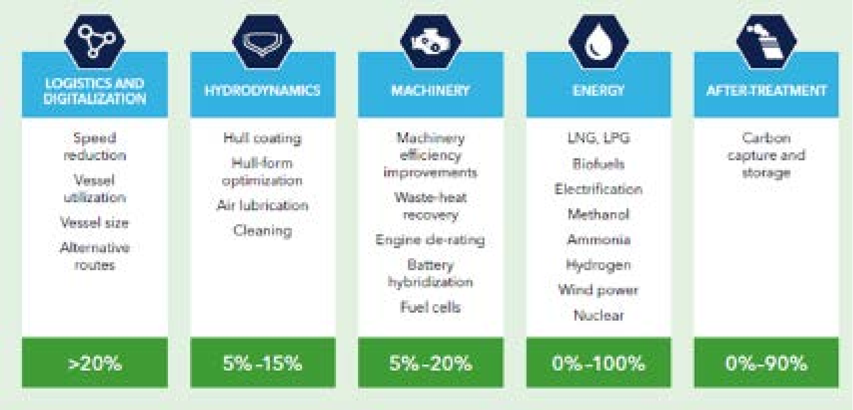
[52] https://www.c40.org/wp-content/uploads/2024/03/GSC_Annual_Report_2024_EN_WEB.pdf

contribute up to 20%, focusing on factors like speed reduction, vessel utilization, vessel size optimization, and alternative routing. Hydrodynamics measures, such as hull coatings, hull-form optimization, air lubrication, and regular hull cleaning, can contribute between 5-15%. Machinery improvements, including efficiency upgrades, waste-heat recovery, engine de-rating, battery hybridization, and fuel cell integration, offer a contribution ranging from 5-20%. See in the figure 1, the emission potential reduction of different solutions as depicted in DNV Maritime Forecast to 2050 report (DNV, 2024).

Driven by EEDX, EEXI and CII (IMO), the shipping sector is increasingly adopting various energy efficiency measures. Energy efficiency measures on board offer significant opportunities for decarbonization within the shipping sector. Operational energy efficiency can provide up to 15% improvement in fuel consumption, translating into substantial emissions reductions across the industry (MMMCZCS, 2022), (DNV, 2022).



LOGISTICS AND DIGITALIZATION	HYDRODYNAMICS	MACHINERY	ENERGY	AFTER-TREATMENT
Speed reduction Vessel utilization Vessel size Alternative routes	Hull coating Hull-form optimization Air lubrication Cleaning	Machinery efficiency improvements Waste-heat recovery Engine de-rating Battery hybridization Fuel cells	LNG, LPG Biofuels Electrification Methanol Ammonia Hydrogen Wind power Nuclear	Carbon capture and storage
>20%	5%-15%	5%-20%	0%-100%	0%-90%

Figure 24. Decarbonization solutions that can contribute to reducing a ship's energy consumption and emissions from energy use, and their GHG reduction potentials (DNV, 2024b)

The energy efficiency measures are essential not only for mitigating fuel costs but also for enabling the use of low-GHG fuels like biofuels, some of which are more expensive and less energy-dense than conventional marine fuels. Table 10 shows Standard lower calorific value for maritime fuels.

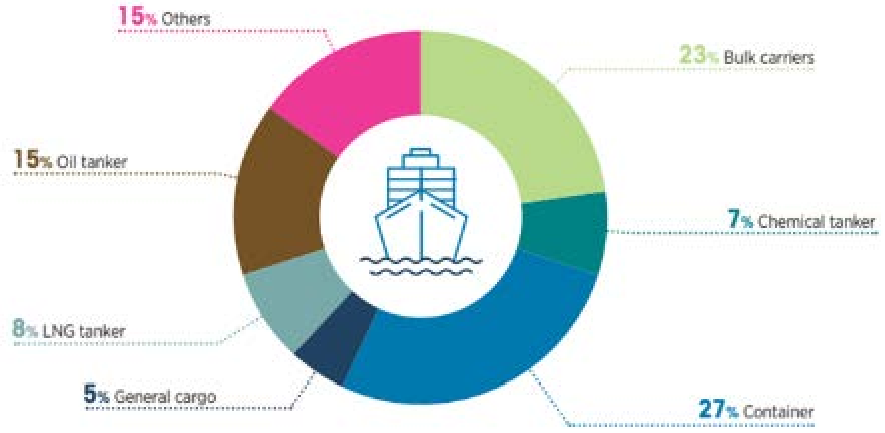
Table 10. Standard lower calorific values, carbon content, and Cf factors as defined by the IMO (MMMCZCS, 2023)

Type of fuel	Lower calorific value (kJ/kg)	Carbon content	Cf (t-CO_2/t-fuel)
Diesel/gas oil	42,700	0.8744	3.206
Light fuel oil	41,200	0.8594	3.151
Heavy fuel oil	40,200	0.8493	3.114
Liquefied petroleum gas (propane)	46,300	0.8182	3.000
Liquefied petroleum gas (butane)	45,700	0.8264	3.030
Ethane	46,400	0.7989	2.927
Liquefied natural gas	48,000	0.7500	2.750
Methanol	19,900	0.3750	1.375
Ethanol	26,800	0.5217	1.913

By improving vessel efficiency, the maritime sector can offset the higher production costs of biofuels and address the fuel storage challenges associated with their lower volumetric energy density. For example, a 10% improvement in fuel efficiency across the shipping fleet could significantly reduce biofuel consumption, making the limited supply of sustainable biofuels more impactful in decarbonization efforts. Furthermore, energy efficiency gains would allow shipping to make better use of biofuel resources that are in high demand across multiple sectors, such as aviation and chemical industries.

Given the current limited production capacity of sustainable maritime biofuels, energy efficiency will play a crucial role in supporting the transition to decarbonization while biofuel production scales up to meet the significant demand, which is likely to materialize after 2030. The differences between efficiency measures which impact the design of the ship and measures that impact the operation of the ship (i.e. speed reduction) should be noted.

The shipping sector's greenhouse gas (GHG) emissions as to operational efficiency are primarily driven by large container ships, bulk carriers, and tankers (oil, chemical, LNG), which collectively account for 80% of the sector's total emissions. Only 20% of the global fleet comprises large and very large vessels responsible for approximately 85% of total GHG emissions (IRENA, 2021). These emission patterns vary by vessel type and operational phase. For instance, for chemical and oil tankers, 20% of emissions occur at or near the port or terminal, whereas that share drops to less than 10% for container ships. The nature of goods carried on board also affects emission trends, as container ships have been operating at slower speeds over the past decade, hence a lower use of fuel, whereas oil tankers have responded to higher demand with higher operating speeds, reducing efficiency. In addition to the operational factors affecting emissions, port activities play a significant role. The world's largest 20 ports handle more than 50% of global cargo, making them crucial hubs for emission control efforts (Eysseric-Cravinho, Rose, & Shrimali, 2024).



Note: "Others" includes other liquid tankers, ferry-pax only, cruise, ferry-Ro-Pax, refrigerated bulk, ro-ro, vehicle, yacht, service-tug, miscellaneous-fishing, offshore, service-other, miscellaneous-others.

Figure 25. Voyage based allocation of energy consumption for international shipping (IRENA, 2021). Compare to Figure 3.

While emissions from near-shore shipping are smaller in scale compared to deep-sea operations, it has an impact on air quality in urban and densely populated areas. For near-shore operations, electrification, combined with energy efficiency measures will likely become the primary decarbonization strategy, with biofuels playing a more limited role. The emergence of companies such as Candela (battery-powered ferries) in Sweden, battery-powered container ships by Cosco Shipping with a capacity to carry 700 twenty-foot containers signals the growing role of electrification in the maritime sector's future (The Maritime Executive, 2023). In the long term, biofuels may be better reserved for sectors with fewer electrification options, such as deep-sea shipping and aviation, while near-shore passenger and freight transport can be increasingly electrified.

In section 2.6.2, IMO tools which leverage energy efficiency to decarbonize shipping sector are described.

The 2023 IMO GHG Strategy emphasizes the need to improve the energy efficiency of new ships and reduce the carbon intensity of international shipping. Specifically, the goal is to lower CO_2 emissions per transport work by at least 40% by 2030 (compared to 2008 levels), with the ultimate aim of reaching net-zero emissions by 2050. A review of these measures is expected by January 2026 (IMO, n.d.).

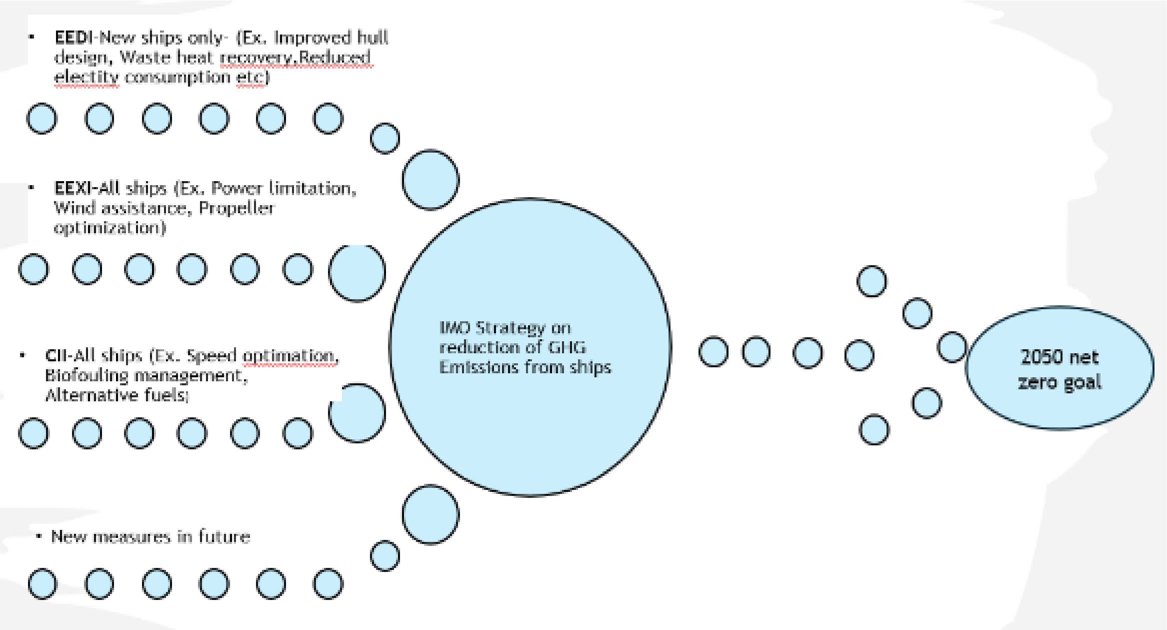


Figure 26. Key IMO tools to decarbonize shipping sector-all energy efficiency related

The global fleet currently consumes 12.6 EJ of energy, resulting in 1.2 GtCO2eq of GHG emissions annually (well-to-wake). If energy efficiency improvements led to a reduction of 1 EJ, representing an 8% reduction in fuel consumption, this would save 24 million tonnes of fuel and reduce GHG emissions by 0.1 GtCO2eq each year. For example, saving 1 EJ of energy could reduce the demand for alternative fuels like e-ammonia by 50 million tonnes, which in turn would lessen the need for approximately 140 GW of installed renewable electricity capacity (MMMCZCS, 2022). By lowering energy consumption, the sector can better manage the transition to sustainable fuels while avoiding overburdening renewable energy resources.

Figure 27 shows on-board energy losses and a range of technologies that can help reduce the losses. Approximately 50% of fuel energy is converted into shaft power, while the remainder is lost through engine exhaust or heat. After accounting for additional losses in the propeller and transmission systems, only about one-third of the fuel's energy contributes to propulsion thrust needed to overcome hull resistance (DNV, 2024b).

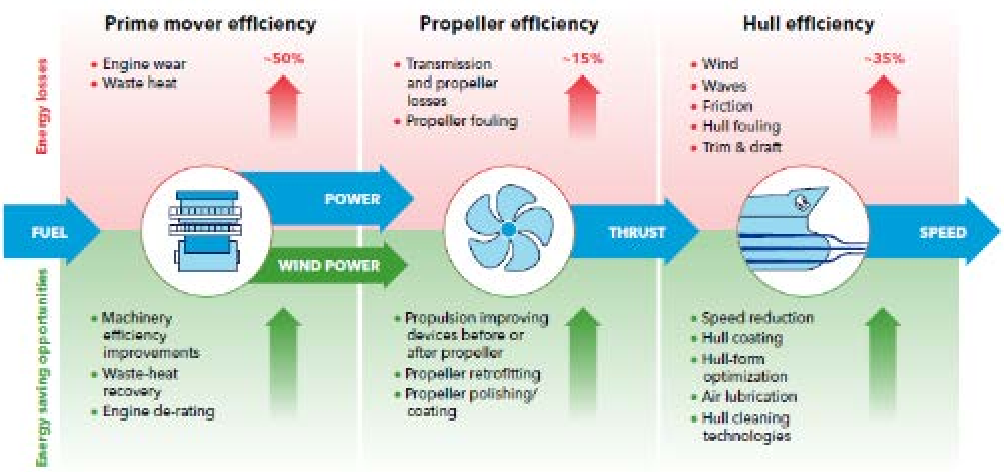


Figure 27. Energy efficiency levers (energy losses) for shipping sector. Source: DNV (2024b), inspired by Glosten 2016.

Prime mover efficiency is the areas of highest energy loss offer opportunities to enhance efficiency, for instance, by recovering waste energy from the engines. Waste Heat Recovery (WHR) systems capture the heat generated by the engine and convert it into electricity used to power the ship’s systems. Various power assistance measures including wind-assisted propulsion arrangements, such as sails, kites, fixed-wing, and Flettner rotors, have been tested on merchant ships. Fuel savings that can be achieved from wind-assistance technologies depend on ship design, operating speed, and the wind speeds and directions experienced. In general, wind assistance measures can be applied with slow steaming because wind propulsion is most effective at slow speed. Savings can typically range between 3% and 15% of the main engine consumption, but higher savings are also reported (DNV, 2024b), (Ricardo Energy and Environment, 2022).

Hull efficiency- the shape of a ship’s hull affects how efficient it is at different speeds and drafts. The drag created by the friction between the hull and water is a significant area of energy loss. Several technologies have been developed to improve hull efficiency. Efforts to optimize the hull shape typically focus on the fore and aft ship, and to improve how the water flows over rudders and propellers. Hydrodynamical measures such as propeller ducts and rudder bulbs are already well-established in the market. A fast-growing measure to reduce hull friction is the use of air lubrication systems (ALS). These inject air bubbles to create a layer of air between the hull and the water to reduce the hull’s resistance. Another approach is to apply low-friction hull coatings to reduce hull roughness and drag (DNV, 2024b).

Alternative Propulsion Technologies: Several propulsion technologies are available to enhance energy efficiency and reduce emissions. While fixed-pitch propellers dominate the fleet, alternative options like Large Area Propellers (LAPs), contra-rotating propellers (CRP), and podded thrusters can improve propulsion efficiency. Propulsion improvement devices (PIDs) further optimize vessel hydrodynamics, but their efficiency largely depends on the original ship design, hull geometry, and operational profile (Ricardo Energy and Environment, 2022), (DNV, 2024b).

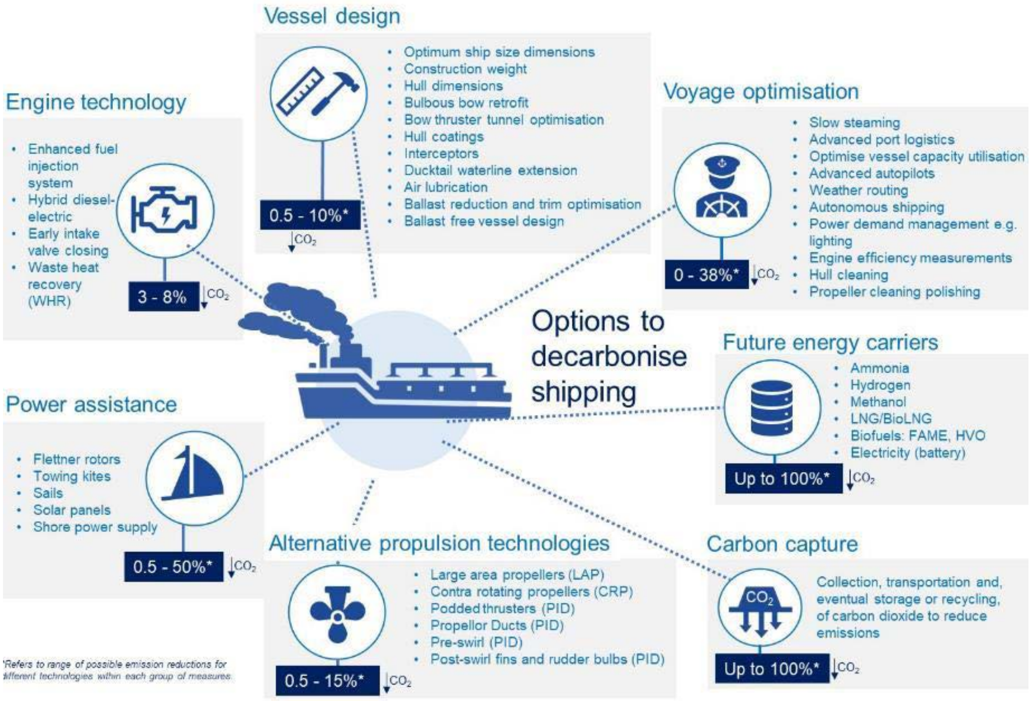


Figure 28. Solutions for shipping sector decarbonization, with focus on energy efficiency measures (Ricardo Energy and Environment, 2022)

Voyage Optimization: Voyage optimization, including practices like slow steaming, offers significant GHG reduction potential. Slow steaming reduces fuel consumption and emissions, with minimal investment costs, although it may extend voyage time and impact revenue. Optimizing speed, route, and timing can cut fuel use while maximizing operational efficiency. Real-time data from vessels, combined with sophisticated weather routing systems, can optimize voyage planning and reduce fuel consumption. AI-enabled models, including the use of a ship’s "digital twin," can predict fuel consumption, optimize propulsion power in varying environmental conditions, and improve operational efficiency (DNV, 2024b), (Ricardo Energy and Environment, 2022).

Digitalization: Digital technologies are increasingly playing a crucial role in optimizing energy efficiency and enabling decarbonization in shipping. Ships are now equipped with sensors and connected to onshore operations centers, providing access to real-time data. This data enables more precise monitoring, predictive maintenance, and improved decision-making to enhance ship performance. Digital tools such as blockchain, artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT) have advanced to support optimization and decarbonization efforts.

Digital Twin: The concept of a digital twin, where all available data and models of a ship are integrated, allows simulations to optimize system performance and maintenance. This can lead to significant improvements in efficiency, emissions reduction, and lifecycle management. Digital twins are also effective in port environments, helping optimize port calls and improving coordination to minimize idle time and fuel use (DNV, 2024b), (UNCTAD, 2023).

Current Adoption of Energy Efficiency Measures and barriers

The maritime industry has seen the implementation of various energy efficiency solutions over the years, ranging from hull and propeller cleaning to advanced voyage planning and weather routing. Operational measures such as these, which require minimal investment, offer substantial fuel savings (up to 15% compared to standard practices) and simultaneously reduce fuel costs and emissions. While a wide range of energy efficiency measures and technologies are available for implementation, their adoption remains inconsistent across different segments of the shipping industry. Table 2, based on research by the Maersk Net Zero Research Institution, illustrates the potential impacts of various energy efficiency solutions and their current uptake across different vessel segments (MMMCZCS, 2022).

Table 11. Energy efficiency levers, their potential impact and current uptake (MMMCZCS, 2022)

Area	Category	Examples	Potential energy efficiency gains per ship	Current fleet uptake*			
				Bulk	Tanker	Container	Passenger
Operational measures	Voyage optimization	Voyage planning, and weather routing, trim and draft optimization, energy management, hull, and propeller fouling management	1-10%	◑	◑	◕	◕
	Fleet strategies	Fleet portfolio optimization, vessel deployment and utilization, scheduling, and speed optimization	1-15%	◔	◔	◑	◕
Technological solutions	Hull & propeller efficiency	Hull form optimization, propeller design, anti-fouling systems, propulsion-improving devices, and air lubrication	1-8%	◔	◔	◑	◕
	Engines and systems	Engine technology, electrification and hybridization, waste heat recovery system, and shaft generator	1-5%	◔	◔	◑	◕
	Alternative power systems	Wind assisted propulsion	1-8%	P	P	○	P

○ Not applied   P Pilot installations   ◔ Limited adaption   ◑ Growing adaption   ◕ Best practice

Recent advancements have led to increased interest in technical energy efficiency solutions, particularly hybrid power systems incorporating batteries and air lubrication. Wind assist technologies are also being piloted on commercial vessels where retrofitting is feasible. However, the uptake of these technologies is more pronounced in the passenger, cruise, and container segments. In contrast, the bulk and tanker segments, despite having leading operators applying energy efficiency measures, show overall low adoption rates.
Despite the clear advantages, based on the MMMCZCS (2022) study, the most common identified barriers preventing widespread uptake of energy efficiency measures are industry-wide hesitancies, combined with various interconnected commercial and technical barriers.

Industry Hesitancy: The maritime industry is generally risk-averse and requires extensive demonstrations before adopting new technologies. Energy efficiency investments often involve non-standard technologies, leading to increased costs and lengthy payback periods. The volatility of fuel costs and charter rates also making investments in energy efficiency less attractive.

Commercial Barriers: The maritime industry, particularly in the bulk and tanker segments, is highly fragmented. Owners bear the initial costs of energy efficiency technologies, while charterers pay the fuel bills. This misalignment of financial incentives results in limited motivation for owners to invest in efficiency measures. There is often no binding framework to ensure the performance of energy efficiency measures, which exacerbates the misalignment of incentives. Charterers are generally unwilling to pay a premium for efficiency claims without guaranteed results.

Technical Barriers: Measuring the impacts of energy efficiency measures is complex due to their dependency on vessel design, deployment, and the specific combination of measures used. The lack of standardized performance benchmarks makes it difficult to quantify and compare the benefits, discouraging investment and data sharing. Many stakeholders are reluctant to share data due to competitive concerns and cost considerations. This reluctance hampers the development of transparent, quantitative assessments of energy efficiency savings.

Regulatory Gaps: While IMO regulations such as the EEDI and CII encourage energy efficiency, they allow compliance through fuel switching (e.g., to liquefied natural gas) rather than focusing on technological innovation. Strengthening these regulations to prioritize energy efficiency improvements over fuel choice (or using combined approach) could drive greater adoption of efficiency-enhancing technologies.

Conclusion

Energy efficiency is indispensable for the maritime sector's transition to sustainable fuels, including biofuels. By reducing fuel consumption and improving operational performance, energy efficiency measures can help overcome the challenges posed by the lower energy density and higher costs of biofuels. While challenges remain, the integration of digital technologies and alternative propulsion systems offers promising pathways to enhance efficiency and reduce emissions. IMO regulations have already begun to encourage efficiency improvements, but further action is needed to strengthen these frameworks and drive widespread adoption of energy-saving technologies. With continued innovation and collaboration across the shipping value chain, energy efficiency will be a key enabler of a sustainable and low-carbon future for maritime shipping.

3.6 The need for investment

Tom Walsh, Renetech

How can we describe the maritime Biofuels Investment Challenges and what should we consider as part of this context? We should consider the following issues carefully.
The investor will be looking for a return on investment over the lifetime of the asset and typically infrastructure investors are aiming for an IRR of 12 to 15 per cent for these types of investments. Ideally the investor does not want to have a technology risk within the project. They will look for proven technologies with track records.

Later in the chapter we will discuss how investment decisions can move from beaker to bucket to barrel to bunker. Given that 300 million tonnes of marine fuel is used globally on an annual basis, and we are looking at a renewable component in the range of 18-28 million tonnes by 2030; the investment requirement is of the order of 18 billion EUR spread over some 180 production facilities. We need to reach a financial investment decision on all these projects in the next seven years.

3.6.1 Investment conditions and considerations

Typically for this to happen, certain project investment conditions need to be met:

- A good site needs to be selected with the required utilities and road and port infrastructure. It will be zoned for this industrial use.
- All required permits need to be in place both to build and operate the facility. A comprehensive Environmental Impact Assessment will need to have been completed which is approved by local government and also meets the lender requirements.
- Feedstock supply agreements need to be *in situ* to cover at least the duration of the loan agreements. The logistics around the feedstock supply is an important project cost consideration.
- Likewise, the produced biofuel needs to have secured a long-term off-taker who agrees to purchase the volume at a given price point that secures the cash flow of the project and it has a sufficient debt interest rate coverage ratio.
- In terms of financing, you need strong equity partners that are a combination of industrial investors alongside financial investors.

For the investor **Availability**, **Scalability** and **Sustainability** are key considerations. Will the feedstock be available, will the feedstock continue to be available? Is the project scalable and can you repeat the concept many times so that one gets economies of scale? The project developer needs to take the learnings from one project to the next. Successful project developers have very often in-house engineering teams or an EPCM team that is both experienced and has executed on numerous projects.

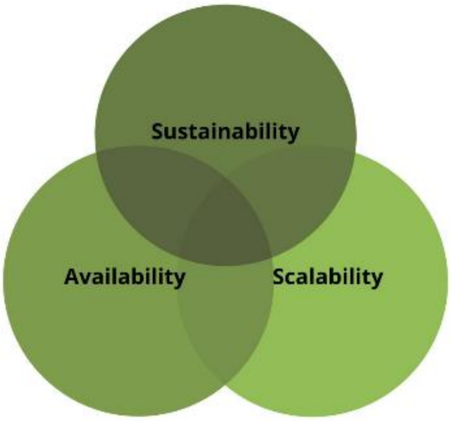


Figure 29. Key Investment Drivers

Sustainability is a key consideration, and institutional investors have significant ESG reporting requirements. So the invested asset needs to deliver a good carbon reduction possibility to the shipper and the ship owner as there reporting requirements are also increasing.
The investor will be concerned about stranded assets now or in the future. There are many different fuel development pathways. For the investor it is probably best to invest in a number of different asset classes so as to mitigate investment, operational and market risk. Bio-LNG, methanol etc. are all viable investment pathways.

3.6.2 The innovation ladder

Another key consideration from the investor perspective is the interaction with what may be named the innovation ladder (Figure 30), which directs the attention to the process of innovation from lab scale to commercial scale production volumes. There are several new fuel production pathways emerging both in terms of using new feedstocks, new technologies and even new business models. Research and Development tends to focus around the beaker to bucket level in terms of both prototyping and producing the first liters. In order to meet the challenge to 2030 our focus needs to be what production pathways can emerge at the barrel and bunker level in order to provide significant volume. The investment requirement increases exponentially for each step up on the ladder.

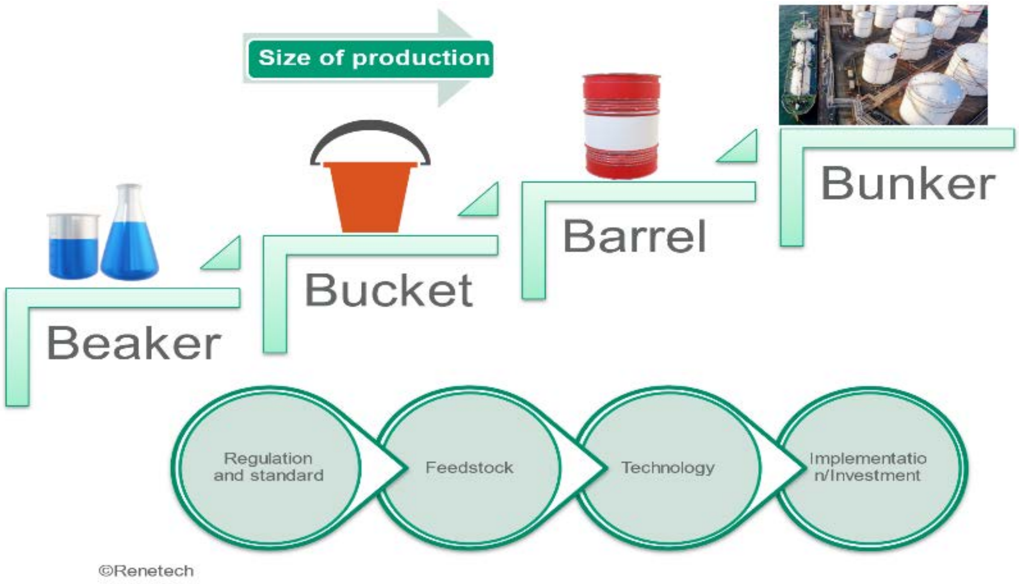


Figure 30. Innovation ladder from lab scale to commercial fuel use in engines.

Feedstock availability is a concern for investors that it will be there on a long term basis. It is estimated that Sweden alone produces 30 million tonnes of biogenic carbon on an annual basis. This is an under-used feedstock today and is returned to the atmosphere. It lends itself to e-fuel production or methanol production for the maritime industry. Currently these projects are prior to the Financial Investment Decision (FID) but in the period up to 2030 and beyond it could provide substantial volumes to the maritime industry.

There are novel feedstocks emerging such as the cactus *Opuntia ficus-indica which can be grown in dry climates and non-agricultural land.* It is estimated that each hectare can produce enough feedstock for 3,600 m^3 of biogas per annum or 63 million m^3 for a 17,500 hectare farm. This equates to 37.8 million m^3 of methane on an annual basis. Some developers are looking at cultivating up to 1 million hectares which would generate 2.16 billion m^3 of methane on annual basis or 2.16 million metric tonnes of marine fuel equivalent which is about 10% of the estimated requirement around 2030.

Notably, the need for investment as discussed above only regards sourcing and production. There are considerable need for investment in distribution, bunkering and not the least the use in ships that may need new types of engines and, as regards green ammonia, considerably developed safety procedures. Some of this is discussed in the respective sections of Chapter 2.

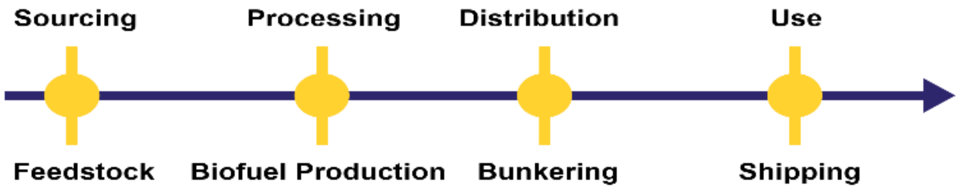


Figure 31. Maritime biofuel supply chain

There is no doubt that there will be significant investment across the value chain in the coming years all the ways from feedstock sourcing to additional biofuel production facilities to dedicated biofuel bunkering and not least new ships and ships retrofitting. We have seen in the recent past shippers making significant investment commitments in terms of dual-fuel ships, particularly in the methanol area.

3.7 Case study: Marine fuels from pyrolysis of biomass – a solution for New Zealand?

Paul Bennet and Amanda Davies, Scion research Institute, New Zealand

3.7.1 Why Marine Biofuels in New Zealand?

The marine shipping sector is one of the major drivers of world trade, contributing to 80% of all goods movement. Considered a hard-to-abate sector, the consumption of over 280 million tonnes of fossil-based fuel per annum, contributes 2-3% of the global CO2 emissions.

New Zealand relies heavily on marine shipping for exports (87% of total exports), with international two-way trade contributing $162 billion to the economy in 2021 (~45% of GDP). Globally, the marine sector is putting in place measures to reduce greenhouse gas emissions. Decarbonising marine shipping is essential to the future of New Zealand's international trade.

3.7.2 The problem

Globally there is an ever-growing emphasis on reducing greenhouse gas emissions and mitigating climate change. As individuals and companies prioritise sustainable choices, there is increasing pressure for producers and suppliers to make a meaningful change to their environmental impact.

Many companies have set ambitious sustainability goals, including a shift towards renewable and low-carbon energy sources for transportation of products. However, decarbonisation solutions are limited. With emission target deadlines for many fast approaching, company's face potential backlash, reputational damage and market access risks.

Regulatory pressure from governments and the United Nation's International Maritime Organisation (IMO) is also increasing. As discussed in section 2.5.4, the IMO is putting in place measures to reduce global maritime CO_2 emissions to zero by 2050. In January 2024, the European Emissions Trading System was extended to cover CO2 emissions from all large ships entering EU ports, with carriers now passing on an emissions surcharge to customers.

This pressure filters on to shipping lines and fuel suppliers who are actively seeking solutions to decarbonise maritime trade routes. Some shipping companies have announced green fuel programmes and marine fuel providers are starting to supply blends of conventional biodiesel (derived from natural oils and fats) with marine fuel oil to support these programmes. However, supply is very tight and faces competition from other transport sectors.

With 74% of ships on order today requiring conventional liquid fuel and a service life of at least 30 years (see Figure 29), use of drop-in biofuel is significant in all decarbonisation pathway scenarios being predicted by industry experts globally.

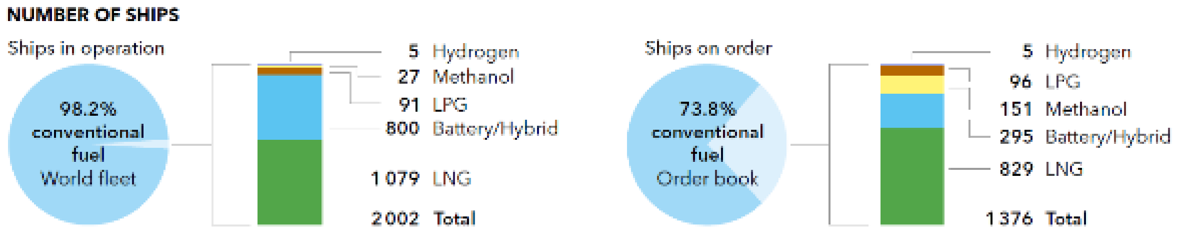


Figure 32. Alternative fuel uptake in the world fleet by number of ships (as at July 2023[53])

3.7.3 The size of the market

The global market opportunity for marine biofuels is significant, driven by the increasing demand for sustainable and decarbonised energy sources in the shipping industry, regulatory pressures, and the commitment of major ports and consumer brands to decarbonisation initiatives. Shipping consumes about 280 million tonnes of fuel annually, at a value of approximately $160 billion USD. Currently, only 0.1% of fuels used by merchant shipping are biofuels.

Industry experts DNV estimated the global demand for carbon-neutral fuel in shipping to come to 17 million tonnes in 2030. An initial New Zealand manufacturing opportunity has been estimated at $372 million USD. It is widely accepted that no single fuel type will meet the forecasted demand for the sector.

The major bunkering hubs (ports) has a key role for the transition. This is described further in section 2.4.

3.7.4 Stakeholder positions

Various players impact the driving forces of decarbonisation and a channel to market. The value chain consists of ship owners/operators, ports, and cargo owners. Each of these entities will play a pivotal role adoption of new fuels.

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[53] Source: DNV Maritime Forecast to 2050 – Energy Transition Outlook 2023

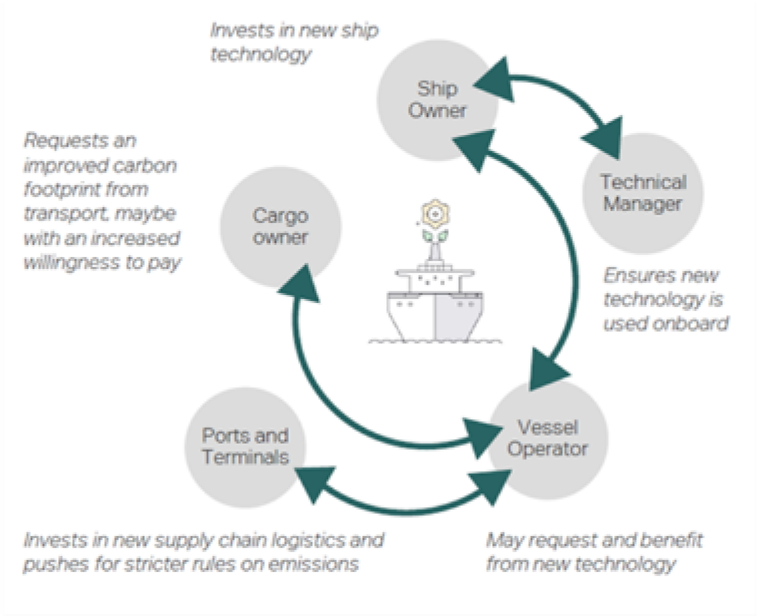

Figure 33.Decarbonisation influence in the shipping fuel value chain[54]

Cargo owners, such as NZ exporters, are becoming increasingly concerned about the carbon footprint of their products. For example, Zespri has noted that “62% of our entire industry carbon footprint (43% if we include the consumers carbon footprint as well) is from the shipping component of our supply chain. Up until now there has been no potential solutions on the near horizon that can help us resolve the ‘elephant in the room’ issue of shipping and our reliance on fossil fuels.” Zespri is very supportive of the adoption of biobased fuels in the marine sector and consider it critical for New Zealand’s export future in the medium term.

*For the 2017 crop, calculated in accordance with the PAS2050:2011 specification for the assessment of the life cycle greenhouse gas emissions of goods and services standard

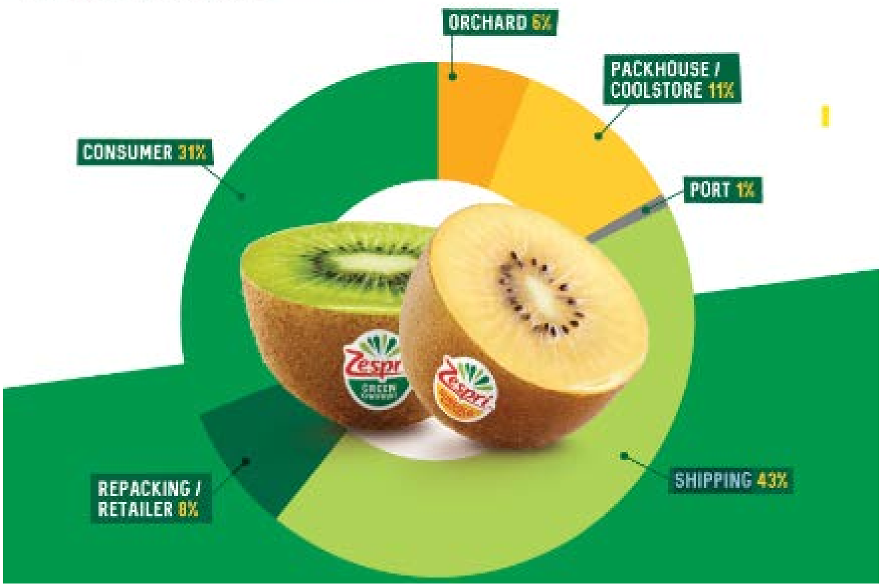

Figure 34. Indicative contribution of each stage in the supply chain to the carbon footprint of Zespri kiwifruit produced in New Zealand and consumed globally Source: Zespri Climate Change Strategy 2020-2025

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[54] Source: Maersk Mc-Kinney Møller Center for Zero Carbon Shipping, Industry Transition Strategy October 2021

Globally, Port authorities have set targets to achieve net zero emissions. The C40 green ports forum is a collective of 19 leading ports globally (including Singapore & Rotterdam) with ambitious goals of mitigating air pollution and greenhouse gas emissions (See also section 3.5.6).

Prominent global container shipping companies such as Maersk and Hapag-Lloyd, are dedicated to reaching net-zero emissions by 2050, proactively incorporating biofuels into their ships and collaborating with their affiliated clients.

New Zealand shipping companies are following the lead of their global counterparts. StraitNZ has entered a long-term agreement with BP for the supply of B24-VLSFO. Their estimated annual CO_2 reduction is expected to be 13,000 tonnes per annum from this initiative.

Large global fuel suppliers are also pledging to reach net-zero emissions by 2050, including BP, Shell, ExxonMobil, TotalEnergies, Equinor, and Chevron. These suppliers are actively looking for decarbonisation technologies globally. They are currently offering biofuel blends of cooking oil methyl ester (UCOME) blended at 20% or 34%, with very low sulphur fuel oil (VLSFO) in limited quantities.

Over the last year the Scion team has had regular engagement with one of these suppliers. They have provided market validation from a fuel supplier perspective and have helped with understanding industry requirements (including providing product specification testing) for the introduction of a new fuel to the supply chain. This supplier confirmed the demand for biofuel far outstrips the current supply.

New Zealand Venture Capital investors have validated that there is significant appetite in the private sector to consider investment in clean energy technology and the maritime sector. Respective New Zealand Government ministries and agencies (Te Uru Rākau, Ministry of Transport and Maritime NZ), shipping companies and Port infrastructure are all supportive of low carbon shipping.

In 2021, New Zealand became a signatory to the Clydebank Declaration, along with 26 other countries. The agreement strives to establish at least six green corridors by 2025 (see also section 3.5.6). Green shipping corridors are designated maritime routes designed to minimise environmental impact by promoting sustainable and eco-friendly practices in shipping, by encouraging the use of clean energy, efficient vessel design, and reduced emissions.

3.7.5 Current activity

All current marine biofuel use is focused on blending conventional biodiesel (Fatty Acid Methyl Esters). In this region, the predominant feedstock is Used Cooking Oil, and is largely sourced in Asia. The volumes oils and fats that can be diverted to biofuel production in New Zealand is very low, and what is available is being transported to Singapore for the production of the more lucrative HVO (SAF).

New Zealand needs to deploy a technology to convert lignocellulosic feedstocks (wood residues, and low value logs) to biofuels. New Zealand has 1.8 million hectares of plantation pine forestry, which generates 3.7 million green tonnes (or 25.5PJ) of forest residues per year during the harvesting process. Additionally, New Zealand exports 9.15 green tonnes (or 63 GJ) of low grade/ low value industrial log per year. The amount will vary year upon year due to previous planting rates and the cut rates (determined by market prices), however there is abundant material to develop a lignocellulosic marine biofuels industry initially in New Zealand.

Access to the global market opportunity is supported by the location of some of the world's biggest ports and their proximity to pine and other softwood plantations.

3.7.6 The solution

Fast pyrolysis is a commercial technology producing a bio-oil from biomass that can be used as a liquid fuel for heating. However, some typical bio-oils properties (i.e. instability, corrosivity, low energy content compared to fossil fuels), have been hindering their use as transportation fuels.

Wood-to-liquid conversion technology under development (e.g. Valmet, Pyrocell) are aiming to produce a low quality bio-oil that requires a further expensive process step, upgrading at an oil refinery, to meet the requirements for use in marine engines (not an option in New Zealand due to the decommissioning of Marsden Point Oil Refinery) and struggle to be cost competitive as a result. Other low carbon fuel options (e.g. ammonia, methanol, hydrogen) will require significantly more infrastructure investment to enable their use.

The production of a bio-oil that can be blended with fossil derived marine fuel oils, whilst meeting the fuel oil specification would be the ideal solution for New Zealand. Catalytic fast pyrolysis is a promising way to upgrade bio-oils through deoxygenation in an integrated process. Marine biofuels being the least refined oil and therefore possibly the easiest to produce via this route. Nevertheless, there are still key fuel characteristics that need to meet the required fuels standards. Key fuel parameters include the energy density, acid number, sediment formation, water content, flash point. Some of the methodologies to test these parameters have been developed for fossil derived fuels and may not be appropriate or accurate for biofuels.

3.7.7 Barriers to inclusion of bio-oils (and solutions)

Significant modifications were brought to the 2024 version of the ISO:8217 to facilitate the introduction of low GHG fuels into the marine market. It is expected that some updates will be provided when more data will be available to better define the required specifications of recently introduced fuels. Indeed, due to difference in origin and composition, some specifications defined for marine fuels from fossil origin are not adapted to some biofuels, otherwise perfectly suitable for marine applications.

It is worth reminding that when a fuel does not conform exactly to any of the ISO:8217 categories, it can still be used, providing the buyer and seller agree on the fuel characteristics or limits. The buyer is responsible for ensuring that the sulfur content complies with the relevant statutory limitations.

Following many successful sea trials, FAME (Fatty Acid Methyl Esters) can now be used at 100% as a distillate marine fuel, with specifications defined in Table 1 of the ISO:8217 document (Distillate and bio-distillate marine fuels). Some grades were also introduced in Table 3 of the ISO:8217 (Bio-residuals marine fuels) for blends of petroleum residual marine fuels with liquids derived from biomass.

Looking for fuels from alternative feedstock and a relatively mature technology to produce them, bio-oil from catalytic fast pyrolysis of lignocellulosic biomass appears as a promising option. Fast pyrolysis is a commercial technology developed in several countries that can yield a bio-oil product through an energy self-sufficient process. It is well accepted that fast pyrolysis bio-oil is not suitable for use as a transportation fuel in several sectors, due to its relatively high content of oxygenated groups responsible of instability, acidity and low energy density. Amongst the several options considered to improve its properties, mild deoxygenation via a catalytic treatment of the pyrolysis volatiles, brings significant economic advantages. Catalytic fast pyrolysis bio-oils contain a significant number of compounds with molecular weights higher than 300 g/mol. As such, their properties should be compared to that of Bio-residual marine fuels defined in Table 3 of ISO 8217:2024.

Considering recent sulfur limitations, the use of fast pyrolysis bio-oils from woody biomass as a blending component of residual marine fuels is extremely advantageous as their sulfur contents are generally < 0.1 wt.%. Another advantage is a potential viscosity reduction of the resulting blend, as values for upgraded bio-oils are commonly reported to be lower than 50 mm^2/s (Veses, Collard), while out of five categories of the Bio-residual marine fuels, three are for fuels with viscosities higher than 80 mm^2/s. Properties requiring more careful attention include energy density, acidity, water, stability and compatibility with petroleum fuels.

Combustion characteristics

The heat of combustion of conventional (petroleum) residual and distillate fuels can be calculated, based on their density and contents of water, sulfur and ash, with a degree of acceptable accuracy. Net heat of combustion of petroleum residual fuels is generally around 40 MJ/kg. As such equation is not applicable to fuels from biomass origin, it is now required to determine and report the heat of combustion of marine fuels containing biofuels. The oxygen content of fast pyrolysis bio-oil (dry basis) is usually in the range of 35-40 wt.%. A mild catalytic upgrading to decrease the oxygen content to 20 wt.% can result in a fuel product with a net heat of combustion higher than 30 MJ/kg. It means that a blend containing 10% of this type of upgraded bio-oil with petroleum residual fuel would have an energy content higher than 39 MJ/kg.

Considering how much fuel can be filled on board in terms of volume, it is interesting to note that, due to its relatively high density around 1100 kg/m3, the net heat of combustion of such upgraded bio-oil is higher than 33 MJ/L, which is comparable to that of FAME currently used in the marine sector.

The calculated carbon aromaticity index (CCAI) was developed to detect any anomaly in the relationship between density and viscosity in petroleum fuels. It is unlikely that this index with its current recommended values could be a reliable method to assess the combustion characteristics of a fuel made from lignocellulosic biomass.

Water content and acidity

Following the isolation of the organic phase from catalytic fast pyrolysis liquid, the majority of the water product can be found in the aqueous phase. At laboratory scale, the water content of the organic phase remains between 3 and 10%, still too high compared to the recommended value of 0.5% max. Targeting the introduction of blends with more than 10% bio-oil, some engineering solutions will be required to further decrease the water content. Strong inorganic acids remaining from petroleum refinery processing are known to contribute to the corrosive activity of a fuel. Annex E of ISO 8217:2024 specifies that some fuels made from naphthenic crudes, which have an acid number higher than the limit of 2.5 mg KOH/g, are acceptable for use.

Napthenic acids identified in crude oils have pKa values around 4-5 (Chongchong wu). The main contributors to the acidity of upgraded bio-oils (acid numbers around 20-40 mg KOH/g) are also carboxylic acids with similar acidity constants. Current work to assess the corrosive activity of carboxylic acids in bio-oils could bring important information to set a maximum content (Kass). More selective catalytic treatment or post treatment of the upgraded bio-oil could be considered to further decrease the acid number.

Stability and compatibility

The stability and compatibility of residual fuels (ISO 10307) are assessed by determining the Total sediment content left on a filter following hot filtration. Total sediment potential (TSP), measured after 24h heating of a fuel sample at 100 °C, should not exceed 0.1 wt.%. It is well accepted that the catalytic upgrading of bio-oils makes them more stable. However, mixing two stable fuels can sometimes result in incompatibility issues, evidenced by relatively high sediment content. More data will be required to assess the potential risk of incompatibility between bio-oils and petroleum residual fuels.

For the development of production, an additional challenge is the barrier to entry due to the scale of testing. To de-risk a bio-oil component, it will require a large amount of performance and endurance testing before it can go commercial. On-board endurance testing of the new fuel type may require 100+ tonnes of bio-oil, which would be prohibitive for early stage innovators. An important feature to lower the bar for development would be to develop tests that require lower volumes for testing for initial approval.

3.7.8 Policy Environment

New Zealand policies need to align closely with the range of international activity being led by the United Nations and relevant transport sectors, such as targets of International Civil Aviation Organisation and the International Maritime Organisation (IMO). The IMO revised its target in 2023 to include a reduction in carbon intensity of international shipping by at least 40 per cent by 2030 compared to 2008; uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources to represent at least 5%, striving for 10%, of the energy used by 2030; and GHG emissions from international shipping to reach net zero by or around, i.e. close to, 2050.

The strategy also sets out indicative checkpoints to reduce the total annual GHG emissions from international shipping by at least 20%, striving for 30%, by 2030, and to reduce the total annual GHG emissions from international shipping by at least 70%, striving for 80%, by 2040. The IMO have been discussing measures to facilitate this transition, such as:

- a goal-based marine fuel standard regulating the phased reduction of the marine fuel's GHG intensity; and
- an economic mechanism(s) to incentivise the transition to net-zero.

It is not clear, at this stage, how these initiatives will be enacted, but when enacted these measures will accelerate the deployment of low carbon technologies into the sector.

There are policies and initiatives around the globe that are now encouraging or incentivising the reduction in GHG emissions from shipping, for example; the inclusion of maritime emissions into the EU Emissions Trading System, capturing emissions from voyages that start outside of the EU, including New Zealand.

Green shipping corridors are being developed to accelerate the achieving the IMO's net-zero emission targets by 2050. Focusing on specific routes allows the development of low GHG options and close co-operation between ranges of stakeholders, such as ports, fuel providers, shipping lines etc. There are many green corridor initiatives that have been announced, with North American ports being particularly active.

For instance, the ports of Los Angeles and/or Long Beach harbour have developed corridors to China, Japan and Singapore. The Maersk Mc-Kinney Moller Centre for Zero Carbon Shipping has conducted a workshop, on behalf of the New Zealand Ministry of Transport, to identify possible Green Shipping Corridors in and from New Zealand.

There is a range of policy instruments that have been used around the world that could be adopted in New Zealand. These include mandates, incentives, capital grants, R&D grants etc. Currently, the New Zealand Climate Change Commission is consulting on whether emissions from international shipping and aviation should be included in New Zealand's 2050 emissions reduction target.

The Commission's assessment that including international shipping and aviation emissions in the target would create a requirement for these emissions to be included in the New Zealand's emissions budgets, emissions reduction plans, and monitoring reports – this is likely to prompt policy action to reduce emissions faster.

3.8 Case Study: Interview with MPA, Singapore

The following interview with the Maritime and Port Authority of Singapore was carried out to demonstrate the range of current activities of a major Port with regards to the distribution and use of biofuels. It shows the proactive stance of the Port and the important role of different stakeholders to lower hinders for biofuel deployment in shipping.

Interview transcript IEA TCP Task 39
Project T39T3
Interview date October 16th, 2024
Maritime and Port Authority of Singapore (MPA)

Participants:	**MPA**	**Renetech**
	Liane WONG	**David Bauner**
	Minerva LIM	**Tom Walsh**
	Hafiz RAHMAT	
	Kenneth PANG	

Lowering Hinders to Maritime Biofuels **IEA BIOENERGY TCP: Task 39**

1. *Brief Introduction/overview of MPA and the Port activities - regulatory, bunkering and shipping.*

MPA manages the Port of Singapore, which handled 39 million TEUs in 2023. It handled 591.70 million tonnes of cargo and for the first time surpassed 3 billion tons of Gross Tonnage. As part of the handling, the Port sold 51.8 million metric tons of bunker fuel. MPA regulations require all bunker service providers operating in the Port of Singapore to be licensed by MPA, with licensing requirements and terms & conditions to adhere to for license renewals.

2. *How do you see the role of biofuels for decarbonization in shipping?*

Singapore port has delivered 523,000 metric tons (MT's) of biofuel, with most being the B24 (a blend of 24% FAME, including Used Cooking Oil Methyl Ester (UCOME), and 76% VLSFO, Very Low Sulfur Fuel Oil) in 2023 and the figure for the first ten months up till October 2024 is 660,000 MT's. Also in 2024, B100 (neat biofuel) bunker fuel has been delivered in the Port of Singapore. MPA is collaborating with Institutes of Higher Learning (IHLs) and industry partners to support trials involving biofuels.

For example, this year, MPA had facilitated a sea trial conducted in Singapore on tugboats using biofuel, and a report on these trials is targeted to be published in 2025. Given the relative scarcity of FAME supply, the different types of biofuels feedstocks available are deemed needed, including non-FAME products, pyrolysis oil etc. MPA generally views drop-in Biofuels as one of the more popular fuels, in advance of deployment of other fuels such as ammonia and green methanol.

3. *What do you see as the biggest hinder for introducing more biofuels in the respective sectors of shipping? Here, you may of course deliberate also on how any limiting factor could be addressed or overcome.*

One of the key challenges the industry is facing is the limited number of Type 2 tankers. Bunkering of higher blends of biofuels requires the use of Type 2 tankers, which involves additional investments. Drop-in lower blends of biofuels are more convenient as Type 1 tankers can be used and there is no additional capex investment required. As fuels forms a major cost component for a ship's operating expenses, the substantial price differentials between biofuels and conventional fuels requires strategic planning and intentional executions.

Alternative feedstock availability is also seen as a barrier to more biofuel deployment, given potential supply competition with other sectors' decarbonisation needs, such as aviation.

4. *If you could describe briefly how IMO (and local) regulations in practice impacts the bunkering strategies of the most common categories of ships (e.g. container/dry bulk/tanker) that dock/bunker at the Port. Here, some questions could arise following your answers, for example if you have insight in how a fleet owner would choose between bunkering LSFO and a biofuel blend.*

In collaboration with the other government agencies and industry partners, MPA provides feedback to ISO and IMO on an ongoing basis on standards and regulations. Currently the negotiations are on-going with the IMO in terms of mid-term measures for the reduction of GHG emissions from ships, to be implemented from 2027. Both the technical and the economic elements of the basket of mid-term measures would be technology and fuel agnostic, with the intention of kickstarting the supply and uptake of green fuels and closing the price gap.

5. *Do you see a specific technology, e.g. as regards propulsion, energy/fuel conversion, fuel storage and distribution, that would be of particular interest for the transition?*

Like many others in the industry, Singapore foresees a multi-fuel future for the maritime sector, encompassing Biofuels/ Biomethane/ Methanol/ Ammonia and Hydrogen. In addition, energy efficiency measures will play a role going forward. As a case in point, three wind assisted ships came into the Port of Singapore in the last year. Wind propulsion, using so called rotary sails, is viewed as a near term measure.
Batteries and charging infrastructure are being implemented for harbour craft domestically.

6. *What types of regulation and incentives do you see as central to facilitate change? What changes in the market structure for given types of shipping would you see as important to bolster biofuels?*

The Maritime Singapore Green Initiative (MSGI) was established in 2011 with a budget of 100 million Singapore Dollars (equalling around 76.1 MUSD). MPA has updated the various green initiatives and incentives under the MSGI to encourage early adoption of zero and near-zero emission technologies and fuels. MPA will commit $50 million to support the implementation of the refreshed MSGI.

Establishing a robust and responsive supply chain, with clear operating standards from all aspects, is key to facilitate the increased adoption of biofuels. MPA works with industry partners and other stakeholders to develop and refine the standards. Collaborations with key respective stakeholders throughout the value chain is crucial.
Enforcement is carried out by strict spot checks. There is also a Bunker mal-practice Hotline.

7. *What do you see as driving decarbonization in the coming decades in addition to increased use of biofuels?*

There are five pilot Green and Digital Corridors under development where zero-carbon fuel will be offered. From Singapore, the Corridors extend to Rotterdam, Los Angeles/Long Beach, Japan, China and Australia, respectively. Digital bunkering will be a reality at the Singapore Port from 2025.

As an example, in August 2022, the MPA and the Port of Rotterdam signed a memorandum of understanding (MoU) for the creation of the Rotterdam-Singapore Green and Digital Shipping Corridor (GDSC). Under the MoU, the partners aim to cut emissions on the 15,000-kilometer route by facilitating the use of zero- and near-zero-emission fuels. The partners to the corridor are expected to operate over 200 vessels by 2028 that can use bio- or e-versions of methane or methanol. Activities at the two Ports include coordinating bunkering standards and safety frameworks.

4 Discussion and roadmap

4.1 IEA, IMO and DNV pathways to sustainable biofuel supply for maritime shipping

IEA has developed two scenarios to illustrate different principles in looking at the means for decarbonization; the **Stated Policies Scenario** (STEPS) is a conservative evaluation of existing policies, including Nationally Determined Contributions under the Paris Agreement and includes pricing policies, efficiency standards and schemes, electrification programmes, and specific infrastructure projects. Its results for international shipping suggest a plateau around 2030 and a moderate reduction until 2050. Its **Announced Pledges Scenario** (APS) includes all recent major national announcements as of the end of August 2024, both 2030 targets and longer-term net zero or carbon neutrality pledges - regardless of whether these announcements have been anchored in legislation or elsewhere. Countries are assumed to implement their national targets in full and on time.

The two scenarios – for natural reasons – present a striking difference in the outlook for emissions by 2050. Notably, biofuels plays a major part during the crucial period from 2030 to 2045 where investment and implementation effectively results in a replacement of fossil fuels. However, given the assumed cost advantage of (renewable) ammonia, this fuel is assumed to be the preferred option already from around 2035, and its use represents the majority of GHG emission reduction by 2050.

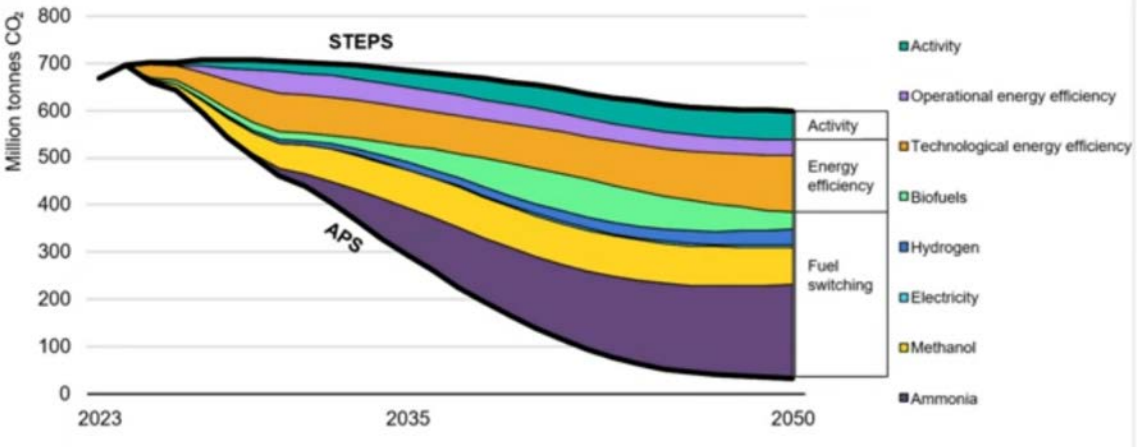

Figure 35. Difference in emissions from international shipping between the STEPS and APS scenarios. (IEA)

To translate the **IMO GHG strategy** or roadmap into a pathway is challenging since it is, and should be, technology neutral. Its 2023 revision, with its rather strict updates including an end date for fossil fuels, requires absolute emission reductions of -20%, striving for -30% already by 2030. By 2040, -70% should be achieved, striving for -80%, and by 2050, net zero should be achieved. As to emission intensity, the 40% reduction (compared to 2008) prescribed for 2030 would require major investment, whereas a fuel uptake target for 2030 of 5% (striving for 10%) may be attained given the current orders of alternative fuel compatible vessels and planned increases in renewable methanol and different drop-in fuels.

In its 2024 Energy Transition Outlook, rather than attempting to predict the future proper, **DNV** presents four "exploratory" scenarios, each with a set of assumptions. Assuming high biomass availability, integration of electrification, CCS and biofuels is presented as a possible pathway for decarbonizing. Its major features are electrification, CCS to compensate for emissions from the fossil fuel used and major introduction of bio-methanol, bio-LNG and bio-MGO, while phasing out its fossil counterparts.

The Biofuel scenario (Figure 36) is based on the assumption of high biomass availability and low CCS deposit cost (60-80 USD/tCO_2), however shows very little use of biomethanol, which seems unlikely considering the present introduction rate of alcohol dual-fuel ships, in combination with IMO and EU regulation and incentives. Bio-LNG (methane) and bio-MGO (FAME and F-T diesel) are the main biofuels as projected. The absence of bioethanol, the largest biofuel commodity on the market today, is also surprising, as is the introduction of nuclear propulsion, exclusively for this scenario assumed more widely viable from 2040.

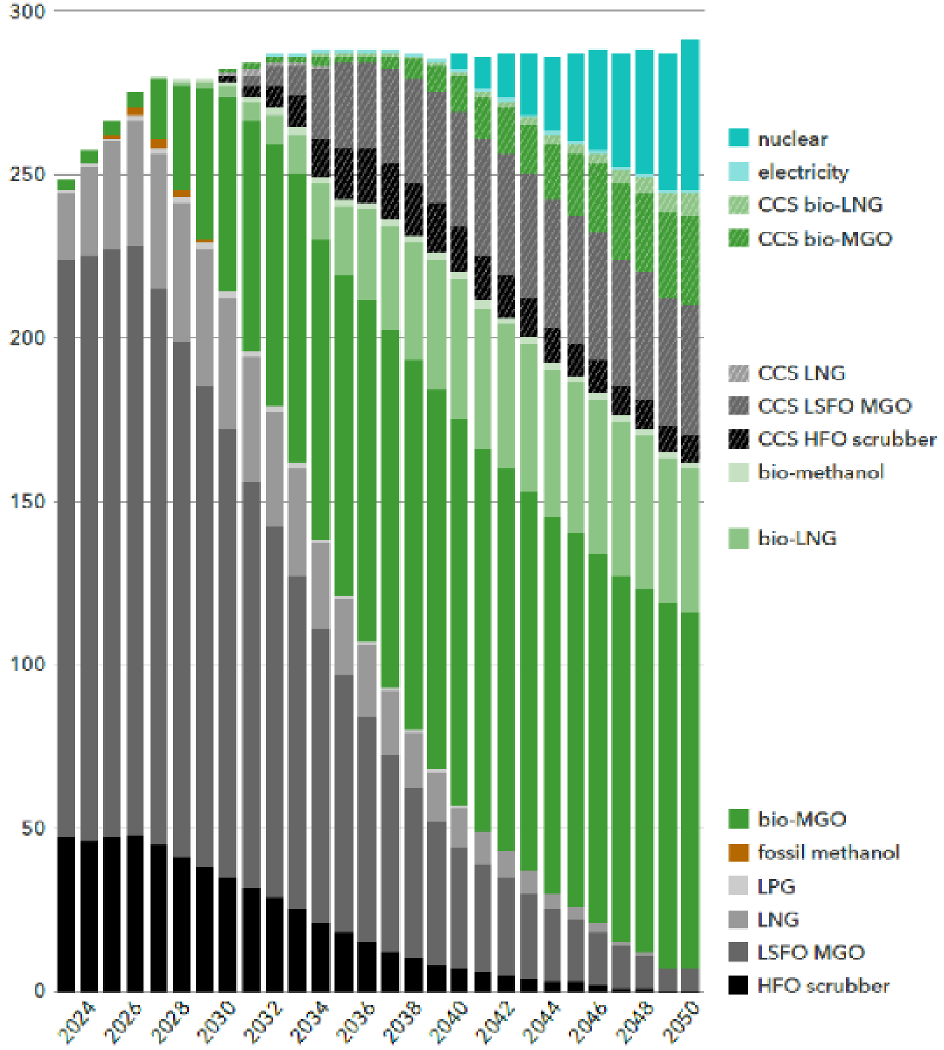

Figure 36. Biofuels and fossil fuels with CCS scenario – fuel use in shipping by energy (DNV, 2024b)

Three scenarios are then presented which assume low availability of biomass, instead relying on e-fuel production besides similar CCS and renewable electricity as a source of energy for e-fuels. The Methanol scenario (Figure 37) suggests about a third of shipping to be propelled by methanol from the 2040s and on, first by bio-methanol and then by e-methanol, phasing out bio-MGO by 2035. CCS of fossil fuels and e-fuels play an important role also here in spite of the higher assumed cost for CCS deposition (130 USD/tCO2).

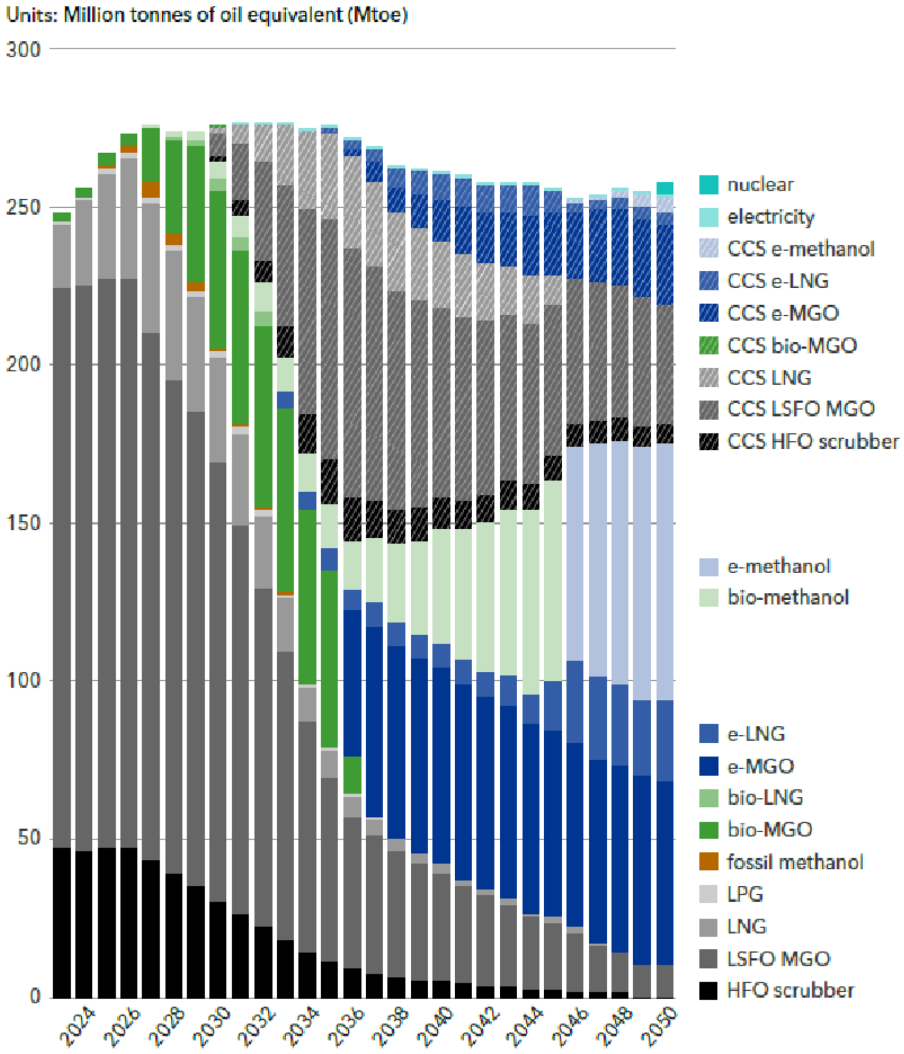

Figure 37. Methanol scenario – fuel use in shipping by energy. DNV, 2024b

The DNV Ammonia and Hydrogen scenarios differ mostly from the Methanol scenario in that Ammonia and H_2, respectively, replaces the methanol as illustrated in Figure 37. The two latter scenarios - rather naturally – assumes high availability of low GHG electricity, but low availability of sustainable (biogenic) carbon. Given the present development of drop-in biofuels and methanol, and the anticipated cost advantage of ammonia, it would be easy (easier) to see an integrated scenario where all three energy carrier types – drop-in biofuels, renewable methanol and zero carbon ammonia - make up the lion’s share of the replacement for today’s fossil MGO, HFO and natural gas.

The methanol, and even more the ammonia, demand would be dependent on the market ability to absorb the cost of expanding the supply chain for the respective fuel, as well as the added cost for on-board adaptation and potential loss of payload space due to lower total energy density.

DNV goes on to project fuel prices, and finds a considerable uncertainty as to carbon neutral fuels – beginning at around 20 USD per GJ for hydrogen, ammonia, methanol and liquefied methane, maximum estimates for 2030-2050 go from just below 50 USD for ammonia, between 50 and 60 USD for hydrogen, methanol and methane to over 60 for carbon neutral MGO. An estimate for carbon neutral HFO, the main fuel for deep sea vessels of today, is not included. (DNV, 2024b)

4.2 Discussion

Maritime biofuels are a burgeoning reality on multiple markets, with blended biofuels already bunkered on all continents. As suggested[55], in an earlier Task 39 project, the transition in the making – if it succeeds – would represent a change comparable with the transition from coal to oil in ships or the changes that followed the introduction of the intermodal container.

As to a plausible scenario for sustaining fuel supply (see the previous section 4.1) to a global fleet of vessels conforming to IMO requirements, it would seem that a scenario involving biomethanol, drop-in bio-HFO and bio-MGO as well as biomethane together with the potential for enhanced energy efficiency would not be impossible to implement. A wild card in this regard is bioethanol. It should be noted that while the market is diversified, deep sea going ships using HFO and MGO represent up to 80 percent of fuel demand. Coastal and inland transport may also represent lower hanging fruits as to conversion to electric and alternative fuel propulsion and supply.

Overcoming the barriers Availability, Scalability, Sustainability (economic, environmental and social) may include focusing on the following challenges and opportunities:

- Common framework for sustainable value chains in achieving Availability, Scalability and Sustainability
- 95% of projects are sitting before FID (financial investment decision)
- Innovation around Beaker to Bucket - demonstrating viability for multiple feedstocks
- Barrel to Bunker is about Implementation (In-house R&D & engineering)
- Drop-In Fuels has started (increasing from 1 million tons p a 2023)
- Planned Investment is Doubling

IEA suggests the following action points:

- Strengthen transport GHG reduction targets and regulations to be consistent with a net zero pathway by mid-century
- Provide support to stimulate sizeable and predictable low-emission fuel demand
- Continue to develop international standards, protocols and pathways for fuel quality, safety and life-cycle GHG emissions, and strive for mutual recognition
- Initiate early planning and accelerate investment in the necessary infrastructure

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[55] Quote assigned to Tim Reeve, Senior Project Manager at Maersk.

- Assess and exploit potential synergies with biofuels deployment.

Biomass sourcing increasingly competes with a number of sectors increasingly supplied by virgin and residual biomass, such as aviation fuel, road vehicle fuel, production of electricity and biochar, and of late also steel production. Nevertheless, regional biofuel production is growing along with efforts regarding distribution and bunkering.

Initiatives such as the Global Maritime Forum's Getting to Zero Coalition and enable pathways to zero-emission shipping by 2050, not the least literally by opening so called Green Corridors such as Rotterdam-Singapore and ROK-USA are crucial to develop routes where zero or low-carbon shipping is promoted and enabled by availability of sustainable fuels and incentives for low-carbon operations. Investment in fuel production and distribution is also favoured by further development of Green corridors. In addition, biofuel use is favoured by new engines and improved production technologies and enhanced demand through EU and IMO regulation and incentives. It is evidenced that energy efficiency measures – including sails - can reduce the amount of fuel needed for a given transport relation and thus facilitate the use of biofuels.

The scenario outlook on systems level suggests that action is needed at least in three areas. Substantial investments in infrastructure and compliant vessels must be accompanied by achieving economies of scale in biofuel production and by implementing financial incentives to create an attractive biofuels market. By fostering a unified approach, led by IMO and corresponding regional bodies, decarbonization in shipping may be achieved. Thus, unified regulation is paramount, but will only lead to technological change if the alternative solution is economically and financially feasible, the conditions for which may differ across markets. Initiatives to ensure conditions where regulation is enacted and followed are needed in areas where institutions are weaker and capacity gaps exist.

Further research is also instrumental to find the economic and environmental optimum along the value chains and to enable technical innovation for the economically and environmentally sound alternatives. Biocrudes and bioalcohols represent opportunities to provide volume to biofuel production if present research efforts are successful. Drop-in biofuel production reduces the need for investment in distribution and bunkering infrastructure, and poses generally low safety risks.

Due to the nature of shipping, uniform fuel qualities would have to be supplied in each of the different trading corridors of today and tomorrow, requiring sustainable value chains. With the objective to reduce fuel transport, and thereby fuel cost, the sourcing and production of sustainable marine fuels such as marine biofuels should be as well paired with regional demand as possible. Economies of scale for commodity biofuels will be another option to achieve acceptable transport cost. Given the asymmetries of today (e.g. compare Figure 8), there is a global task at hand to develop incentives for market behaviour which makes regional demand more transparent than today.

There are a host of measures to increase the energy efficiency of shipping, measures which would enable biofuels by reducing demand and increasing the willingness to pay. Reducing water drag by hull cleaning and air lubrication, slow steaming and hard sails have a potential of reducing fuel consumption by 10% or more. The case study on potential production in New Zealand points to the importance of assessing the opportunities in relation to a perceived demand and develop both in tandem. It is important to evaluate emissions on a well-to-wake basis, to use direct mandates to ensure the deployment of zero-emission fuels. Market-based measures should be introduced to complement control-and- command policies. Last but not least, as mentioned earlier, investment in new vessels capable of running on zero-emission fuels is essential. The multifaceted development ahead already has a number of champions and identified stakeholders along the biofuels value chains. The international character of the maritime shipping sector makes it tenacious, and since the transition has started, it is poised to continue its positive journey towards net zero.

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Appendices

A1. List of interviewees

Interviewed organization	Representative	Date (2024)
IVL Svenska Miljöinstitutet	Ali Hedayati	Jan 10
National Treasury Management Agency – Ireland Strategic Investment Fund	Dónal Ó Céileachair	Jan 10
Stena Teknik	Elisabeth Liljeblad	Jan 9
Colabit	Fredrik Törnqvist	Jan 15
Methanol Institute	Gregory A. Dolan, Matthías Ólafsson	Jan 11, Jan 10
Södra	Henrik Brodin	Jan 9
European Commission, Joint Research Centre (JRC)	Marco Buffi	Jan 12
Licella	Steve Rogers (former manager)	Jan 10
Neste	Wolter Rautelin, Riikka-Mari Haara	Feb 8
Maersk Mc-Kinney Møller Center for Zero Carbon Shipping	Roberta Cenni	Apr 3
Scion Research	Paul Bennet	Apr 24
MPA, Singapore	Liane WONG, Kenneth PANG, Nikesh RADHAKRISHNAN, Minerva LIM, Hafiz RAHMAT	Oct 16
Havila Kustruten	Lasse Vangstein	Nov 4

A2. MSAR fuel specifications

ISO8217:2017 marine residual fuel (RMG380), MSAR® & bioMSAR™

Characteristic	Limit	RMG 380 ISO 8217 2017	MSAR® Synthetic HFO		BioMSAR	
		Specification	Specification	Example	Specification	Example
Density at 15°C, kg/m³	max.	991,0	1050,0	1010,0	1200,0	1162,0
Kinematic Vicosity at 50°C, mm²	max.	380,0	180,0	160,0	180,0	120,0
Flash Point °C	min.	60,0	60,0	60,0	60,0	60,0
Pour Point (upper): Winter/Summer °C	max.	30,0	N/A	N/A	N/A	N/A
Carbon Residue, % (m/m)	max.	18,0	12,0	10,0	12,0	7,0
Ash, % (m/m)	max.	0,10	0,10	<0,1	0,10	<0,1
Glycerine, % (w/w)	max.	N/A	N/A	N/A	42,0	40,0
Water, % (w/w)	max.	0,50	33,0	30,0	12,0	10,0
Sulfur, % (m/m) = VLS 0,5%m Compliant or	max.	3,5	2,3	2,0	2,3	1,5
Acid number, mg KOH/g	max.	2,5	2,5	<2,5	2,5	<2,5
Hydrogen Sulfide, mg/kg	max.	2,0	2,0	<2,0	2,0	<2,0
Vanadium, mg/kg	max.	350	230	120	230	90
Sodium, mg/kg	max.	100	70	50	70	40
Total Sediment Potential, % (m/m)	max.	0,10	N/A	N/A	N/A	N/A
Aluminium plus Silicon, mg/kg	max.	60	15	10	15	10
Used lubricating oil (ULO)	**max.****					
Zinc, mg/kg	max.**	15	10	<10	10	<10
Phosphorus, mg/kg	max.**	15	10	<10	10	<10
Calcium, mg/kg	max.**	30	20	<20	20	<20
Median Droplet Size, µm	max.	N/A	15	5	15	5
90% of Droplets Sized, µm	max.	N/A	75	10	75	10
Sieve Test (> 150µm), % wt	max.	N/A	2	<1	2	<1

** Fuel is considered to contain ULO when one of the following is met: Ca > 30 and Zn > 15 or Ca > 30 and K > 15

* = Dynamic Visc. mPas at 100s^{-1}. N/A = Not relevant for MSAR® or RMG.