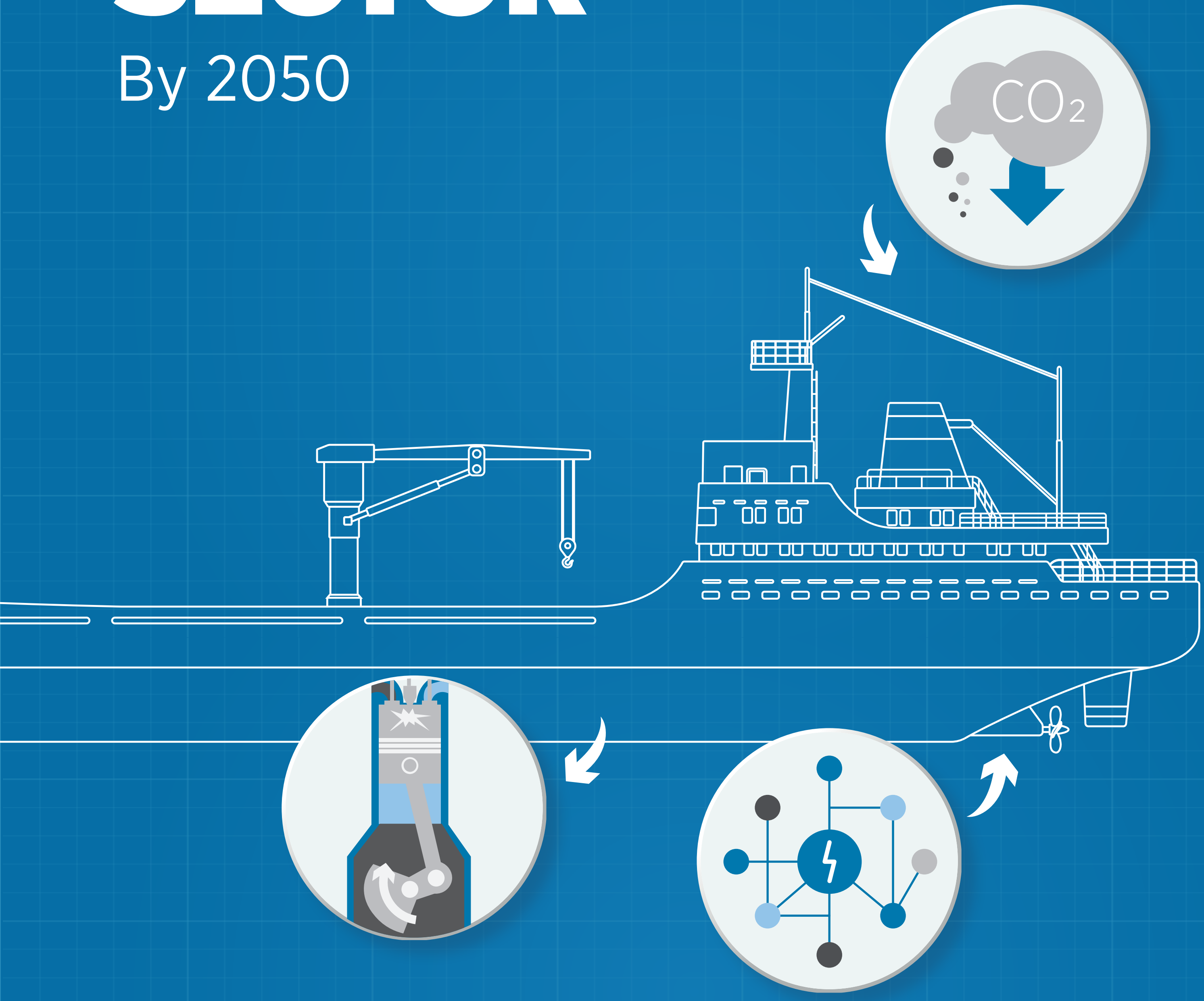
IRENA
International Renewable Energy Agency

A pathway to
DECARBONISE THE SHIPPING SECTOR
By 2050



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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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By 2050

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ABBREVIATIONS

a.a.g.r.	Average annual growth rate
ATR	Autothermal reforming
bbl	Barrel of oil
BE	Battery-electric
BECCS	Bioenergy with carbon capture and storage
BES	Base Energy Scenario
C	Celsius
CAAP	Clean Air Action Plan (United States)
CBG	Compressed biogas
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CI	Cold ironing
CII	Carbon Intensity Indicator
CMS	Carbon molecular sieve
CNG	Compressed natural gas
CO_2	Carbon dioxide
DAC	Direct air capture
DME	Dimethyl ether
DMFC	Methanol fuel cell
DNV GL	Det Norske Veritas Germanischer Lloyd
dwt	Deadweight
EE	Energy efficiency
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EEXI	Energy Efficiency Existing Ship Index
EJ	Exajoule
ESPO	European Seaports Organisation
EU	European Union
FAME	Fatty acid methyl ester
FC	Fuel cell
FOGs	Fats, oils and greases
FT	Fischer-Tropsch
g	Gramme
GDP	Gross domestic product
GHG	Greenhouse gas
GJ	Gigajoule
GMF	Global Maritime Forum
GO	Guarantees of origin
GT	Gross-tonnage
GtZ	Getting to Zero
GW	Gigawatt
GWP	Global warming potential
H_2	Hydrogen
HFO	Heavy fuel oil
HSFO	High-sulphur fuel oil
HVAC	Heating, ventilating and air-conditioning
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
ICS	International Chamber of Shipping
IEA	International Energy Agency
ILUC	Indirect land-use change
IMF	International Monetary Fund
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
J-ENG	Japan Engine Corporation
JIT	Just-in-time
kg	Kilogramme
KPI	Key performance indicator
kt	Kilotonne
l	Litre
LBG	Liquefied biogas
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas

LS	Large ships
LSFO	Low-sulphur fuel oil
m^3	Cubic metres
MARPOL	The International Convention for the Prevention of Pollution from Ships
MCFC	Molten carbonate fuel cell
MDO	Marine diesel oil
MGO	Marine gas oil
MI	Mission Innovation
MJ	Megajoule
MS	Medium ships
Mt	Million tonnes
MTBE	Methyl tert-butyl ether
MW	Megawatt
MWh	Megawatt hour
NG	Natural gas
NGO	Non-governmental organisation
NOx	Nitrogen oxide
O&G	Oil and gas
O_2	Oxygen
OBOR	One Belt One Road
OECD	Organisation for Economic Co-operation and Development
PEMFC	Proton exchange membrane fuel cell
PES	Planned Energy Scenario
PSA	Pressure swing adsorption
PV	Photovoltaic
R&D	Research and development
REmap	Renewable Energy Roadmap
RCP	Representative Concentration Pathway
RPM	Revolution per minute
SEEMP	Ship Energy Efficiency Management Plan
SFC	Specific fuel consumption
SMR	Steam methane reforming
SOFC	Solid oxide fuel cell
SOx	Sulphur oxide
SS	Small ships
SSP	Shared Socioeconomic Pathway
T&D	Transmission and distribution
TAME	Methyl tert-amyl ether
TES	Transforming Energy Scenario
TEU	Twenty-foot equivalent unit
UNCTAD	United Nations Conference on Trade and Development
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollar
VLS	Very large ships
VLSFO	Very low-sulphur fuel oil

SUMMARY FOR POLICY MAKERS

Urgent action is necessary to accelerate the pace of the global energy transition and the decarbonisation of the global economy. Green hydrogen-based fuels set to be the backbone for the sector's decarbonisation.

The International Maritime Organization's (IMO's) *Fourth GHG study 2020* reported that in 2018 global shipping energy demand accounted for nearly 11 exajoules (EJ), resulting in around 1 billion tonnes of carbon dioxide (CO_2) (international shipping and domestic navigation) and 3% of annual global greenhouse gas (GHG) emissions on a CO_2-equivalent basis. Fossil fuels. *i.e.* heavy fuel oil (HFO), marine gas oil (MGO), very low-sulphur fuel oil (VLSFO) and, more recently on a small scale, the use of liquefied natural gas (LNG) currently provide up to 99% of the sector's final energy demand.

International shipping enables 80-90% of global trade and comprises about 70% of global shipping energy emissions. If the international shipping sector were a country, it would be the sixth or seventh-largest CO_2 emitter, comparable to Germany. Yet, international shipping emissions fall outside national GHG emission accounting frameworks.

In this context, this report by the International Renewable Energy Agency (IRENA) explores the options and actions needed to progress towards a decarbonised maritime shipping sector by 2050 and seeks to identify a realistic mitigation pathway consistent with a wider societal goal of limiting global temperature rise to 1.5°C (degrees Celsius) and bringing CO_2 emissions closer to net zero by mid-century. The report discusses:

01 Market dynamics and trends, trade volumes, associated energy demand, and CO_2 emissions

02 Technology readiness and cost of relevant renewable energy fuels

03 The long-term decarbonisation pathway by 2050 and its implications

04 Enabling actions to raise the decarbonisation ambition

IRENA key partnerships contributing to decarbonise the shipping sector

Global Maritime Forum (GMF)

Following the contribution that IRENA provided to the shipping community during the GMF Annual Summit in 2019 in Singapore, IRENA officially joined the Getting to Zero (GtZ) Coalition in January 2020. The initiative comprises an alliance of more than 150 companies from across the shipping value chain with key stakeholders from the energy sector, as well as from governments and intergovernmental organisations (GMF, 2020). The ambition of the GtZ Coalition is to have commercially viable zero-emission vessels operating along deep sea trade routes by 2030 (GMF, 2020). IRENA advises the coalition on fuels, technologies and decarbonisation pathways and supports the coalition with knowledge building and by participating in expert meetings on the topic of power-to-X and carbon-zero fuels for the shipping sector. More recently, on 22 September 2021, IRENA backed a global call for action promoted by GMF. The call for action demanded that governments commit to decarbonise shipping by 2050, support industrial-scale zero-emission shipping projects through national and regional action, and deliver the policy measures that will make zero-emission shipping the default choice by 2030 (GMF, 2021).

Mission Innovation (MI)

MI is a global initiative of 22 countries and the European Commission. The initiative aims to catalyse action and investment in research, development and demonstration to make clean energy affordable, attractive and accessible to all this decade (MI, 2021a). Since MI's Third Mission Innovation Ministerial, IRENA has been listed as one of MI's key collaborators (MI, 2018) and has participated in global debates and several expert meetings. During the Sixth Mission Innovation Ministerial hosted by Chile on 2 June 2021, MI launched the Zero-Emission Shipping Mission. The mission aims is to crystalise an ambitious alliance among countries, the private sector, research institutes and civil society to develop, demonstrate and deploy zero-emission fuels, ships and fuel infrastructure by 2030 and make zero-emission ocean-going shipping the natural choice for ship owners (MI, 2021b).

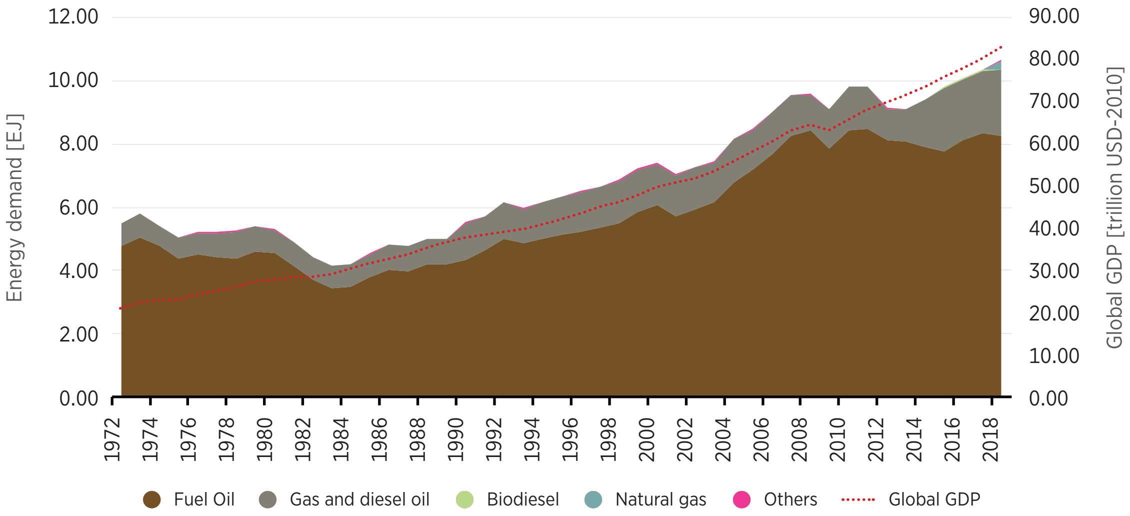
International Chamber of Shipping (ICS)

Established in 1921, ICS is the global trade association for shipowners and operators, representing the world's national shipowner associations and over 80% of the world's merchant fleet (ICS, 2020). ICS is part of an intersessional working group providing advice to IMO on how to reduce GHG emissions in the long and short term. In September 2021, ICS put forward a comprehensive proposal for a global levy on carbon emissions from ships. The levy would be based on mandatory contributions by ships trading globally, exceeding 5 000 gross tonnage, for each tonne of CO_2 emitted. The money would go into an "IMO Climate Fund" to support closing the price gap between zero-carbon and conventional fuels (ICS, 2021). Since the second quarter of 2021, IRENA and ICS have been working closely together, holding bilateral technical exchanges on how best to accelerate the decarbonisation of the international shipping sector by 2050.

Market dynamics and energy demand

Rising energy demand is a key issue for the shipping sector, with increasing trade leading to increasing demand. Factors such as global gross domestic product (GDP), as well as trade and manufacturing sector activity have been the key drivers shaping energy demand in the international shipping sector to date. As the adoption of energy efficiency (EE) measures in international shipping increases, the nexus of GDP, trade and energy demand may decouple progressively. However, given the pivotal role of international shipping in the global economy, the role of EE has limitations in terms of carbon reduction potential; hence the key role renewable energies will play in decarbonising this sector by mid-century.

Figure i **Global shipping energy demand and GDP**



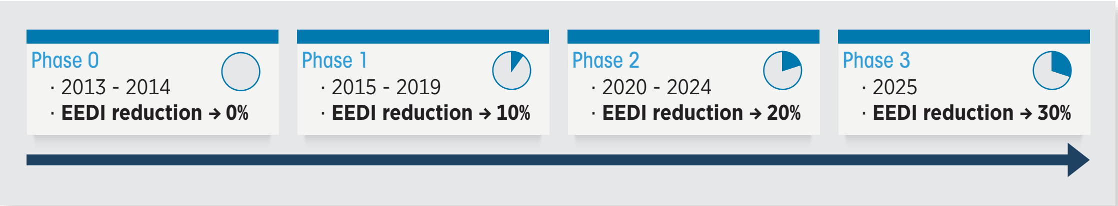
Note: Comprises energy demand from domestic navigation plus international shipping.
Source: IRENA analysis based on DNV GL (2020), World Bank (2020)

Energy efficiency

In the near term, emission reductions in the sector will mainly depend on the rapid implementation of EE design and operational measures across the vessel fleet.

During low oil price periods, the shipping sector pays less attention to its energy usage. However, during high oil price periods, the shipping sector adapts, increasing its activity while using energy resources more efficiently, without the need for external market regulations. This finding reveals the dormant EE potential in the shipping sector. Further considerations need to be made in regard to bunkering and strategic port locations to optimise route efficiency. In the near term, it will be critical to deploy monitoring and enforcing mechanisms to ensure compliance with the IMO mandates focused on improving EE across vessels, *i.e.* EEDI (Energy Efficiency Design Index), SEEMP (Ship Energy Efficiency Management Plan), EEXI (Energy Efficiency Existing Ship Index), EEOI (Energy Efficiency Operational Indicator) and CII (Carbon Intensity indicator).

Figure ii **EEDI phases, implementation periods**



Note: Time period refers to 1 January of the starting year to 31 December of the end year.
EEDI reduction in reference to the baseline year, 2013.
Source: Based on IRCLASS (2013a)

Renewable fuels

In the medium term, the primary strategy must involve progressively but rapidly replacing fossil fuels with renewable fuels. The renewable energy fuels most suited to international shipping are primarily advanced biofuels and e-fuels, *i.e.* methanol and ammonia.

Each renewable energy fuel varies in terms of benefits and challenges. The choice of fuel depends on factors such as the supply chain, engine technology, environmental impacts and production costs. The production costs of these alternative fuels and their availability will ultimately dictate the eventual deployment of renewable energy fuels. The cost of each fuel is determined by the cost and availability of feedstock, the process used for production, and the maturity of the production technology. The energy density of the various fuels and the implications in terms of onboard storage are elements that require further analysis. Depending on the fuel of choice and the type and size of a given vessel, cargo capacity and thus cargo revenue could be affected.

From an economic perspective, if compared against LNG; this latter fossil fuel is subjected to very high market price volatility. A clear example is the very high price of natural gas that is currently troubling many countries across the world, particularly in Europe. While renewable fuels production costs are currently high, in the next decades renewable fuels will become competitive, therefore, renewable fuels can shield the shipping sector from the volatility that characterises the fossil fuels market.

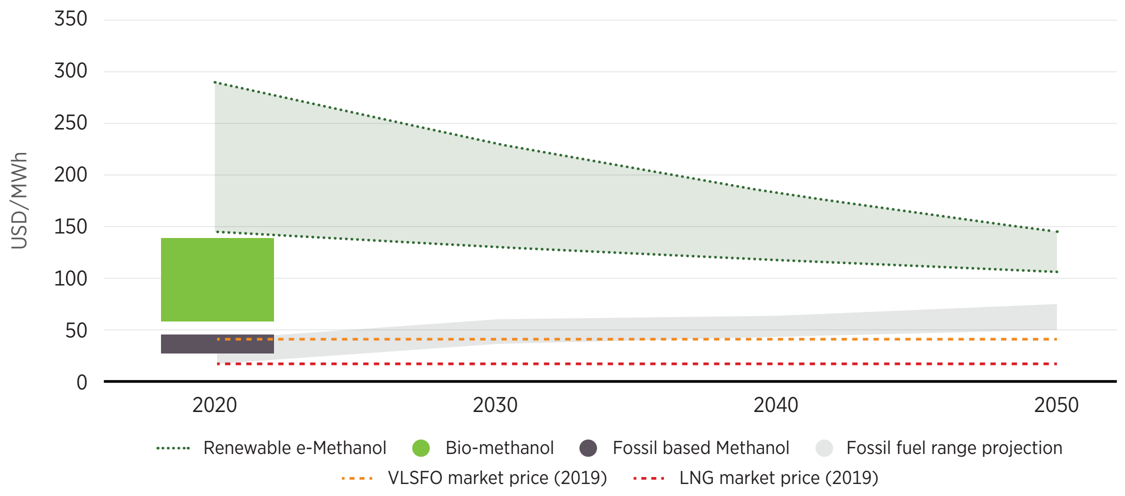
Advanced biofuels: These are a viable short-term option for the shipping industry because current rules allow for fuel blends of up to 20% without engine modifications, and tests have been conducted utilising a maximum blend of 30%. In addition, important to note that 100% methanol engines are a proven technology; hence, new ships can easily rely 100% on biofuels. Production cost ranges for advanced biofuels are similar to the various alternatives, *i.e.* USD 72-238 per megawatt hour (MWh). The sustainability of the biomass feedstocks used is a critical factor. The current focus is therefore on the use of waste fats, oils and greases (FOGs) to produce fatty acid methyl ester (FAME) biodiesel, hydrotreated vegetable oil (HVOs) that do not impact food security, and land availability. Other production routes using other feedstocks are possible but are not yet mature. The shipping sector will face competition for suitable feedstocks and fuels from other sectors, including road vehicles and aviation.

Biomethane: Biomethane could play a role but is likely limited. Production costs are highly dependent on feedstock availability and feedstock market price, which leads to wide cost rages, *i.e.* USD 25-176/MWh. Biogas produced via anaerobic digestion for the subsequent production of liquid biogas and compressed biogas has a high technological maturity and is therefore an attractive option for displacing LNG. However, due to scalability and logistical issues, the role of renewable gaseous fuel may be limited, and biogas may be more effective in end-use applications other than fuelling the shipping sector.

Hydrogen: The direct use of green hydrogen (H_2) via fuel cells (FCs) and internal combustion engines (ICEs) is an option, but mainly for short sailings, *e.g.* domestic navigation. However, the indirect use of green H_2, *i.e.* for the subsequent production of e-fuels, will be critical for the decarbonisation of international shipping. Current green H_2 production costs vary between USD 66/MWh and USD 154/MWh, but as the costs of both electrolysers and renewable energies fall, green H_2 costs will become cost competitive in some contexts from around 2030, eventually achieving 2050 costs of around USD 32-100/MWh.

Renewable methanol, *i.e.* bio-methanol and renewable e-methanol: These renewable fuels require little to no engine modification and can provide significant carbon emission reductions in comparison to conventional fuels. Renewable e-methanol is of particular interest in the shipping sector. The key constraint on the production of renewable e-methanol is the availability and cost of a CO_2 supply not sourced from fossil fuels.

Figure iii **Methanol cost projections**



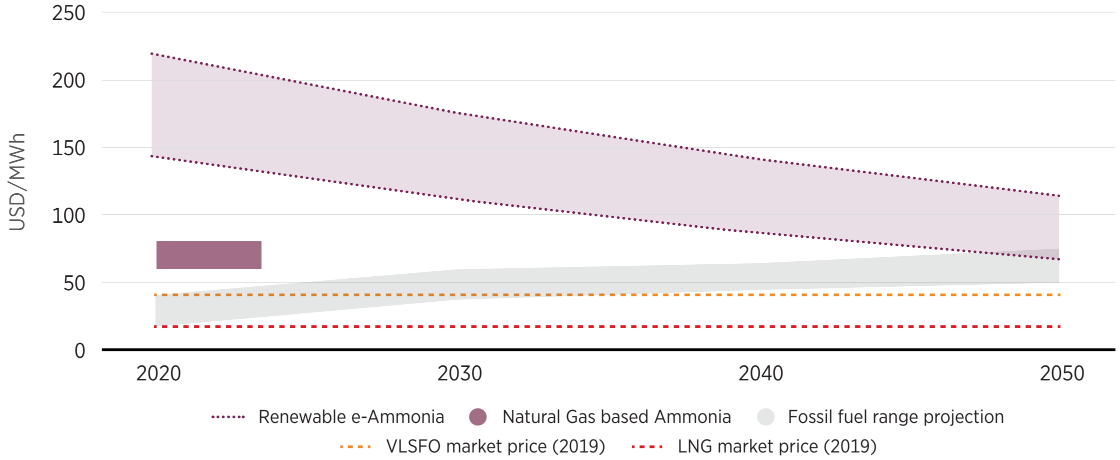
Note: Figure refers to the cost of fuel production. The total cost of ownership (*e.g.* machinery, storage and other) is not captured.

Source: Methanol costs: IRENA (2021); fossil fuel cost projections: Lloyd's Register (2019)

Renewable e-fuels, methanol and ammonia: These e-fuels are the most promising fuels for decarbonising the sector. Of the two options, ammonia is more attractive due to its null carbon content. This characteristic excludes it from the cost of capturing CO_2, which significantly adds to the final cost of e-methanol. The falling costs of green H_2 coupled with the cost reduction of CO_2 capture technologies should enable 2050 production costs to reach around USD 107-145/MWh for renewable e-methanol.

Renewable ammonia: E-ammonia looks set to be the backbone for decarbonising international shipping in the medium and long term. By 2050, production costs of e-ammonia are expected to be between USD 67-114/MWh. The validation of ammonia engine designs by 2023 will be a key milestone in unlocking the use of renewable ammonia. While ammonia is corrosive and highly toxic if inhaled in high concentrations, ammonia has been handled safely for over a century. Hence, ammonia's toxicity and its safe handling should not be considered major barriers.

Figure iv **Ammonia cost projections**



Note: Figure refers to the cost of fuel production. The total cost of ownership (*e.g.* machinery, storage and other) is not captured.
Source: Ammonia: IRENA (forthcoming), IRENA & AEA (forthcoming); fossil fuel cost projections: Lloyd's Register (2019)

Decarbonisation pathways to 2050

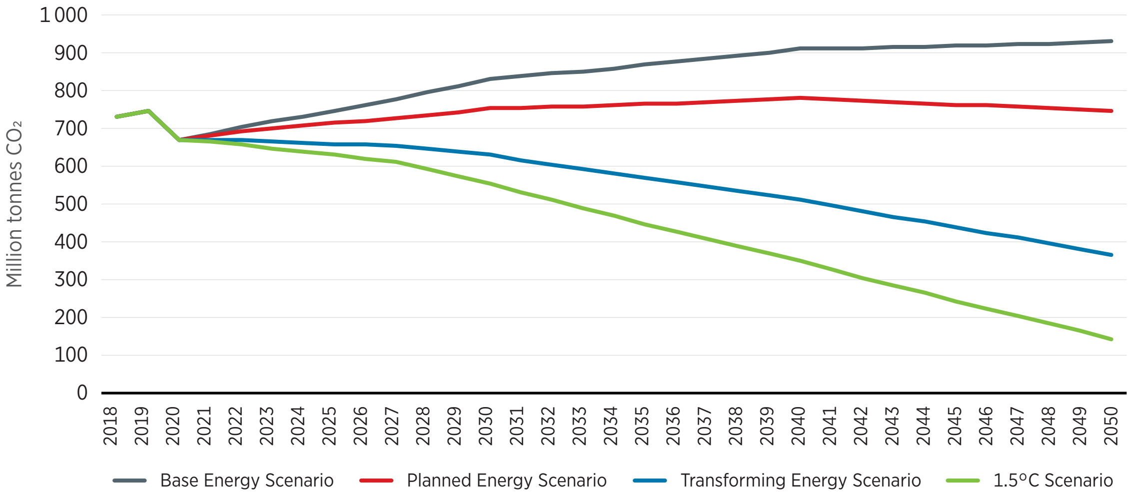
The International Renewable Energy Agency's (IRENA's) decarbonisation analysis for 2050 builds on the agency's REmap (Renewable Energy Roadmap) methodological approach. The analysis for shipping is aligned with IRENA's *World energy transitions outlook (2021), which sets out a pathway to limit global* temperature rise to 1.5°C.

In the medium to long term, green H_2-based fuels will be the foundation of a decarbonised international shipping sector. By 2050, shipping will require a total of 46 million tonnes (Mt) of green H_2. Of this total, 73% will be needed for the production of e-ammonia, 17% for e-methanol and 10% will be used directly as liquid hydrogen through FCs or combusted through ICEs.

Renewable ammonia will be the backbone of the decarbonisation of the sector. Renewable ammonia could represent as much as 43% of the mix in 2050, which would imply the use of about 183 Mt of renewable ammonia for international shipping alone – a comparable amount to today's ammonia global production. Due to insufficient supply, the immediate utilisation of renewable ammonia may be challenging. It is therefore likely that blue ammonia will play a transitional role; hence the relevance of analysing the value chain dynamics and market status of ammonia as an energy carrier. A forthcoming report from IRENA and the Ammonia Energy Association will analyse the whole spectrum of the ammonia production value chain, the market status and future prospects of renewable ammonia, as well as the current and future competitiveness of renewable ammonia versus fossil-based ammonia.

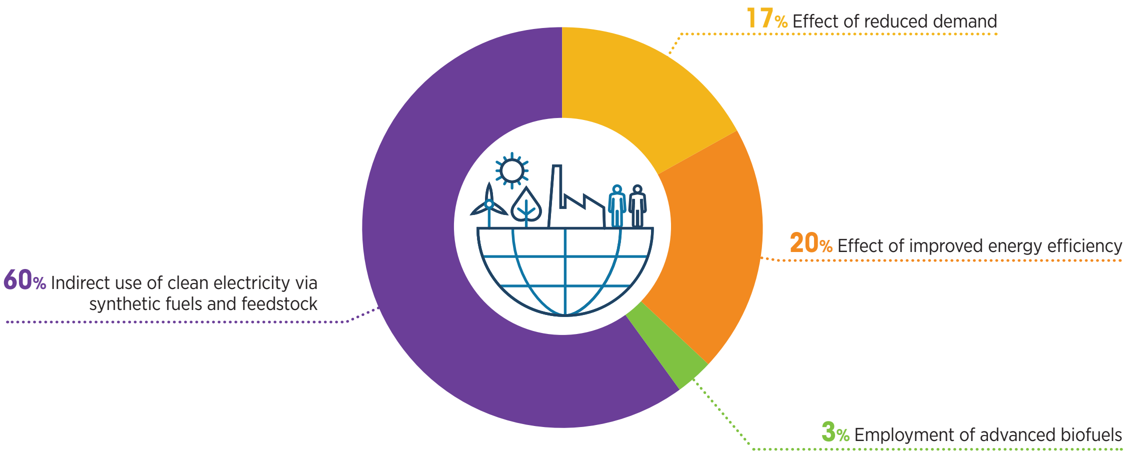
In the context of international shipping, IRENA's 1.5°C Scenario leads to 144 Mt of CO_2 in 2050 compared to the Base Energy Scenario (BES) and Planned Energy Scenario (PES), which would result in 930 million tonnes and 746 Mt in 2050, respectively. Between 2020 and 2050, 1.5°C Scenario enables the avoidance of 12.5 billion tonnes and 9.5 billion tonnes of CO_2 in comparison to BES and PES.

Figure v **Comparison of CO_2 emissions associated with each scenario, 2018-2050**



IRENA 1.5°C Scenario explores a pathway for shipping with a 70% share of renewable fuels to be achieved by 2050, resulting in 144 Mt of CO_2 in year 2050, an emission reduction of 80% in comparison to 2018 levels. Overall, the decarbonisation pathway analysed in IRENA's report is achieved by four key measures: i) indirect electrification by employing powerfuels;[1] ii) employment of advanced biofuels; iii) improvement of vessels' EE performance; and iv) reduction of sectoral demand due to systemic changes in global trade dynamics.

Figure vi **Estimated role of key CO_2 emission reduction measures associated with IRENA's 1.5°C Scenario**



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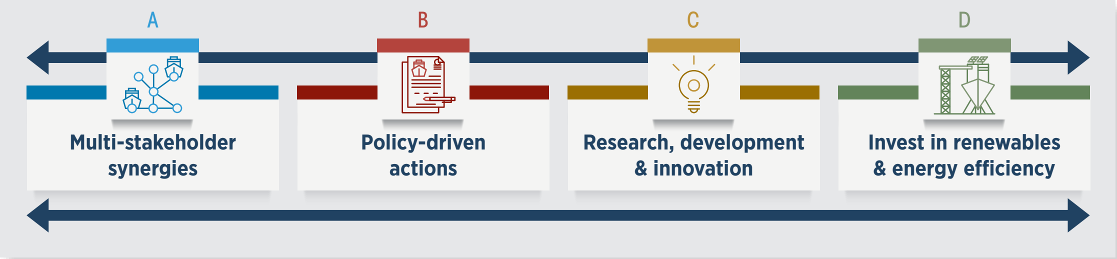
[1] Powerfuels are renewable and climate-friendly synthetic gaseous or liquid non-biofuels that draw their energy content from renewable electricity. Powerfuels can be used as energy carriers and feedstock (Global Alliance Powerfuels, 2021).

Enabling actions to raise the decarbonisation ambition

IRENA 1.5°C Scenario represents a mitigation pathway to limit global temperature rise to 1.5°C and bring CO_2 emissions closer to net zero by 2050. However, achieving this goal cannot be accomplished by technology alone. Climate goals and decarbonisation ambition can be raised by taking timely and appropriate measures.

Starting now, energy efficiency needs to be promoted and effectively embraced. Not only will this result in an immediate reduction of carbon emissions, but it can also potentially result in important energy savings and thus increase monetary revenue for shipowners and operators. From a technological perspective, renewable energies are competitive. Indeed, renewable energy costs have been falling at an accelerated rate. For renewable energy-derived fuels to become the prime choice of propulsion, further cost declines are needed, particularly in renewable energy supportive technologies (*e.g.* electrolysers and hydrogen storage). In this context, sectoral decarbonisation can be accelerated and ambition can be raised beyond the climate goals by fostering investment in the production of renewable fuels. For this purpose, adopting relevant and timely co-ordinated international policy measures is greatly needed. It also requires stakeholders to develop broader business models and establish strategic partnerships involving energy-intensive industries, as well as power suppliers and the petrochemical sector.

The actions listed below can raise decarbonisation ambition beyond the 1.5°C Scenario goals. These actions are divided into four categories:



A. Multi-stakeholder synergies

a. **Stakeholders associated with the shipping sector must be fully mapped out, fully engaged and working towards the establishment of strategic partnerships and a common goal.** Policy makers, shipowners, ship operators, port authorities, renewable energy developers and utilities should work in parallel towards a common decarbonisation goal.

b. **Synergies and enhanced international collaboration must be fostered among all stakeholders involved in the field of powerfuels: *e.g.* shipping, aviation and energy-intensive industries (*e.g.* cement, iron and steel), as well as power suppliers and the petrochemical sector.** Given the promising decarbonisation path offered by powerfuels, raising awareness across the shipping sector and governments about the role of powerfuels in both the transport sector and in energy-intensive industries is of prime importance.

c. **Engagement needs to go beyond the obvious players; acceptance by civil society is also needed.** Civil society needs to be aware of the environmental and economic impacts and benefits associated with this transition, and ultimately be supportive.

B. Policy-driven actions

a. **Enable a level playing field by establishing a realistic carbon levy. Each fuel must have a carbon price implied that may be adjustable over time as the market becomes more favourable for renewable energy fuels.** Taking early action will not only foster the deployment of renewable fuels but also prevent investments in fossil fuel infrastructure that risk becoming stranded.

b. **Immediately tighten EE mandates and develop suitable mechanisms for monitoring and enforcing the adoption of EE measures.** Mandates and policies should be comprehensive, of high technical level and provide minimum standards in terms of vessel design and operation.

c. **Promote strict local regulations to limit airborne emissions at ports and inland waterways, and make cold-ironing at ports compulsory whenever available.** Accordingly, enforce turning off vessels' auxiliary engines during shore-side operations in port areas by plugging the vessels into an electricity source offered by the port authority, thus reducing the emission of airborne pollutants and GHG during docking periods.

d. **Establish a mandate comprising the progressive increase of renewable fuels within bunkering fuel blends starting immediately with advanced liquid biofuels and biomethane, followed by the institution of effective incentives to encourage vessel fleets to shift to green H_2-based fuels.** The high technological readiness of liquid biofuels produced from second-generation feedstock coupled with compressed biomethane can be immediately harnessed as drop-in fuel. In parallel, as the development of the ammonia engine is completed by 2023, establishing effective incentives such as excise tax reductions for renewable energy fuels will be key to scaling-up the production of ammonia.

e. **Develop sustainability certifications and suitable schemes such as guarantees of origin (GO) to guarantee ship operators of the renewability index of a given fuel and its sustainable origin.** Such efforts must go together with fit-for-purpose regulatory systems focused on ensuring that increased powerfuel production is aligned with renewable power capacity additions and/or suitable schemes harnessing renewable power curtailed by the grid for green H_2-based fuel production.

f. **Anticipate the upcoming demand from end-consumers by implementing a labelling system for sustainably shipped goods.** This should be driven by the shipping sector with the successful engagement of civil society and suitable instruments. Such a labelling system will enable end-consumers to make well-informed purchase decisions on a daily basis.

C. Research, development and innovation

a. **Task research and development (R&D) institutions with the analysis of the upstream dynamics of renewable fuel production for shipping, including a GHG lifecycle analysis of the different renewable fuels.** This should also include the potential and production limits of renewable fuels, *i.e.* biofuels and green H_2-based fuels.

b. **Continue devoting efforts to the development of sectoral strategies that clearly define the volume of renewable fuels required to decarbonise the shipping sector and ensure the necessary deployment of renewable power in the context of competing demands.** Accordingly, it will be crucial to work closely with countries with high renewable energy potential and promote the development of long-term energy planning processes and thus the construction of least-cost energy.

c. **Boost efforts and ensure adequate levels of resources focused on the development of engine technology capable of harnessing green H_2-based fuels, thereby ensuring that technology is well advanced, ready to be deployed and scaled up by about 2025.** Green H_2 produced through renewable-powered electrolysis is projected to grow rapidly, while green H_2-derived fuels are expected to become the backbone for decarbonising the maritime shipping sector.

D. Invest in renewables and energy efficiency

d. **Enable affordable lines of credit and introduce incentives to foster the development of carbon-zero new vessels and financing of retrofits in existing vessels.** Subsequently, encourage shipowners to progressively place orders for carbon-zero vessels, as well as to complete retrofits that enable the employment of renewable fuels, as well as retrofits centred on enhancing EE performance in existing vessels.

e. **Allocate national resources to support the identification of geographical areas with high renewable energy potential and devote significant efforts to understanding the production costs of renewable powerfuels in the short and long term.** Make this information available to the global shipping sector by nominating an international entity to lead the planning of the shipping sector. This entity would also act as a bridge between countries and the shipping sector and consolidate data for investment planning.

f. **Invest in an efficient, safe and reliable supply of renewable fuels for the shipping sector via sector coupling mechanisms among bunkering service companies, port authorities, utilities and the renewable energy sector.** Accordingly, the primary focus should be on the identification of key investments across strategic ports and allocation of funds for the upcoming development of renewable fuel infrastructure.

1. INTRODUCTION

Urgent action is necessary to accelerate the pace of the energy transformation and decarbonisation of the economy, including the shipping sector, a strategic sector of the global economy. In the last quarter of 2019, IRENA published *Navigating the way to a renewable future: Solutions to decarbonise shipping* (2019a). This report explored the impact of maritime shipping in terms of carbon emissions and identified renewable energy solutions with the potential to reduce the carbon footprint of this key sector.

With around 80-90% of global trade enabled by maritime shipping, the shipping sector is responsible for around 3% of annual global greenhouse gas (GHG) emissions on a carbon dioxide (CO_2)-equivalent basis. International shipping alone accounts for around 9% of global emissions associated with the transport sector. To put this into context, if the international shipping sector were a country, it would be the sixth- to seventh-largest CO_2 emitter, with CO_2 emission levels comparable to Germany's (Balcombe *et al.,* 2019).

The International Maritime Organization (IMO) indicates that by 2050 maritime trade could increase between 40% and 115% in comparison to 2020 levels. At present, about 99% of the energy demand from the international shipping sector is met by fossil fuels, with fuel oil and marine gas oil (MGO) comprising as much as 95% of total demand (IMO, 2020a). If no actions are taken, IMO has flagged that GHG emissions associated with the shipping sector could grow between 50% and 250% by 2050 in comparison to 2008 emission levels. Clearly this broad range of projected GHG emissions flags a level of uncertainty in terms of how will the sector evolve over the next 30 years. Nonetheless, even the lower-level band of GHG emissions increase is an area of great concern in terms of global warming. Another area of concern is that international shipping emissions fall outside national GHG emission accounting frameworks.

To address these concerns, this report maps out a path to a decarbonised maritime shipping sector. Its primary focus is the analysis of a pathway to a mitigation structure that will limit global temperature rise to 1.5 degrees Celsius (°C) and bring CO_2 emissions closer to net zero by mid-century. In support of the global efforts to decarbonise the shipping sector, this report includes an update on IRENA's previous work in the field of shipping. To this end, this report analyses the market dynamics of the shipping sector and the latest trends regarding trade volumes, associated energy demand and carbon emissions. Additionally, the report evaluates the technology readiness of the renewable fuels suitable to the shipping sector followed by an analysis of long-term energy scenarios in which a pathway towards the deep decarbonisation of the shipping sector by 2050 is examined and tailored recommendations to accelerate the decarbonisation of the shipping sector are proposed.

2. SECTOR OVERVIEW

KEY MESSAGES:

- Global gross domestic product (GDP), trade and manufacturing sector activity are key drivers shaping energy demand in the international shipping sector. As the adoption of energy efficiency (EE) measures in international shipping increases, the nexus of GDP, trade and energy demand may decouple progressively. However, given the pivotal role of international shipping within the global economy, EE has limitations in terms of carbon reduction potential; hence the key role of renewable energies in decarbonising this sector by mid-century.
- During low oil price periods, the shipping sector pays less attention to its energy usage. However, during high oil price periods, the shipping sector adapts, increasing its activity while using energy resources more efficiently without the need for external market regulations. This finding uncovers the dormant EE potential in the shipping sector. Indeed, in the immediate future, decarbonisation of the sector depends on the rapid implementation of EE design and operational measures.
- Between 80% and 90% of international trade by volume is enabled through maritime means, *i.e.* bulk and container carriers, as well as oil and chemical tankers. Together, these types of vessels account for 20% of the global fleet, but they are responsible for 85% of the net GHG emissions associated with the shipping sector. The 2018 fuel mix for international shipping comprised 79% heavy fuel oil (HFO), 16% marine diesel oil (MDO), 4% liquefied natural gas (LNG) and less than 0.1% methanol.
- Considering the average age of the existing vessel fleet and the technical lifetime of large and very large vessels, *i.e.* 25-30 years, the development of new vessel designs and engines needs to happen between 2025 and 2030. Indeed, the vessels to be deployed in the next five to ten years will characterise energy demand and carbon emissions by 2050. This illustrates the urgency of enabling an environment focused on the deployment of zero-carbon vessels fuelled by renewables.
- In the task of decarbonising the international shipping sector, it is crucial to properly identify the locations that could fast-forward the energy transition in this sector. This includes key trading and bunkering ports, key navigation routes, and choke points. The ports with the highest global bunkering relevance include Singapore (~22%), Fujairah (~8%) and Rotterdam (~6%). The most critical choke points are the Panama Canal, the Straits of Malacca and the Suez Canal.

MARITIME TRADE DYNAMICS

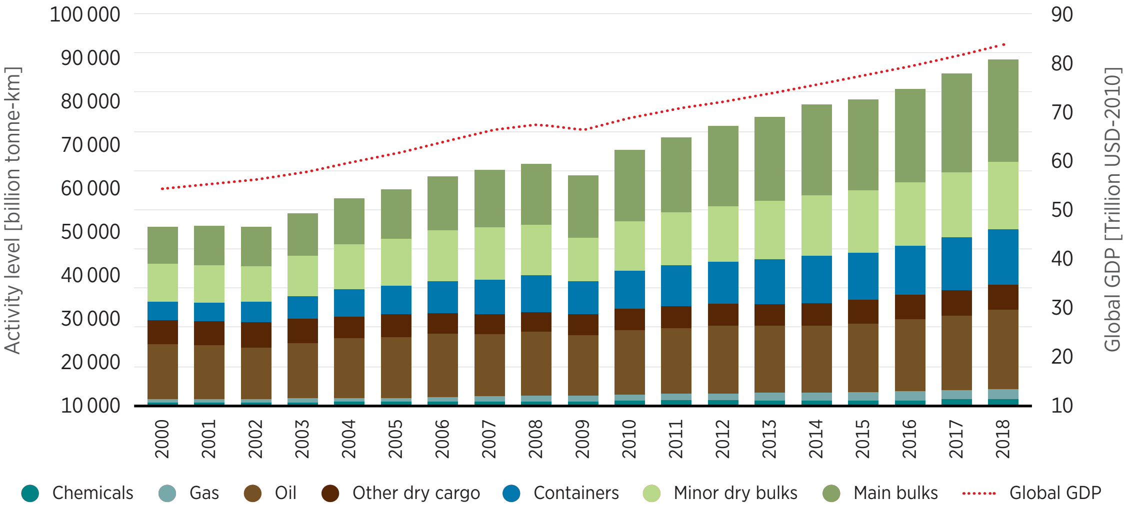
Between 80% and 90% of international trade is enabled through maritime means, *i.e.* bulk and container carriers, as well as oil and chemical tankers. Together, these types of vessels account for 20% of the global fleet, but they are responsible for 85% of the net GHG emissions associated with the shipping sector (IRENA, 2019a). International cargo shipping activity is correlated to a certain extent with the global economy, as it provides a logistical downstream service to the production and allocation of goods and energy vectors. Thus, historical global GDP developments and trade volumes of goods tend to be analysed to estimate the intensity of the nexus of economic growth, maritime trade and subsequent energy needs. Since 2000, global GDP has grown at an average rate of about 3%. However, due to the financial crisis of 2008, between 2008 and 2009, the average growth rate dropped significantly to -1.5%. Thereafter, the economy bounced back (World Bank, 2020).

A closer look at the period from 2017 to 2019 shows a slowdown of the global economy with an annual GDP growth rate varying from 3.1% (2017) to 3.0% (2018) and 2.9% (2019). Over the same period, the economic slowdown was also evident in global industrial production, a key driver of maritime transport services, which registered a growth rate of 3.6% between 2016 and 2017 and then fell to 3.1% between 2017 and 2018. Not surprisingly, global merchandise trade growth (imports and exports) also dropped from 4.5% in 2017 to 2.8% in 2018 (UNCTAD, 2019).

Figure 1 shows that in recent years, the maritime trade of main bulks and trade from tankers grew at a slow pace, while the trade of dry bulks (*i.e.* minor bulks), containerised trade and residual general cargo dominated the global trend. Together, between 2010 and 2018, these key cargo groups presented an average annual growth rate of 3.42%. However, aligned with the performance of the global economy, trade volumes over recent years have grown at a slower pace, from 4.09% in 2017 to 2.70% in 2018. Geopolitical factors such as the trade tensions between some of the largest world economies has been identified as one of the key factors disrupting global maritime trade. Import restrictions and tariff increases involving North African and West Asian countries have also been identified as decelerating factors of maritime trade in recent years. The COVID-19 pandemic has exacerbated these trends where the United Nations Conference on Trade and Development (UNCTAD, 2020a) noted an overall fall of 4.1% in marine transport and trade by the end of 2020.

For 2019 onward, prior to the COVID crisis, the International Monetary Fund (IMF) had projected that between 2019 and 2024 global GDP would grow at an average rate of 3.6%. However, since the pandemic started and the required healthcare measures (isolation, lockdowns and widespread closures) have been adopted worldwide, the global economy has sunk notably. Indeed, IMF indicated that in 2020 the global economy contracted by -3.3%, a much worse performance than that of the 2008-2009 financial crisis.

Figure 1 **Historical activity level of global trade**



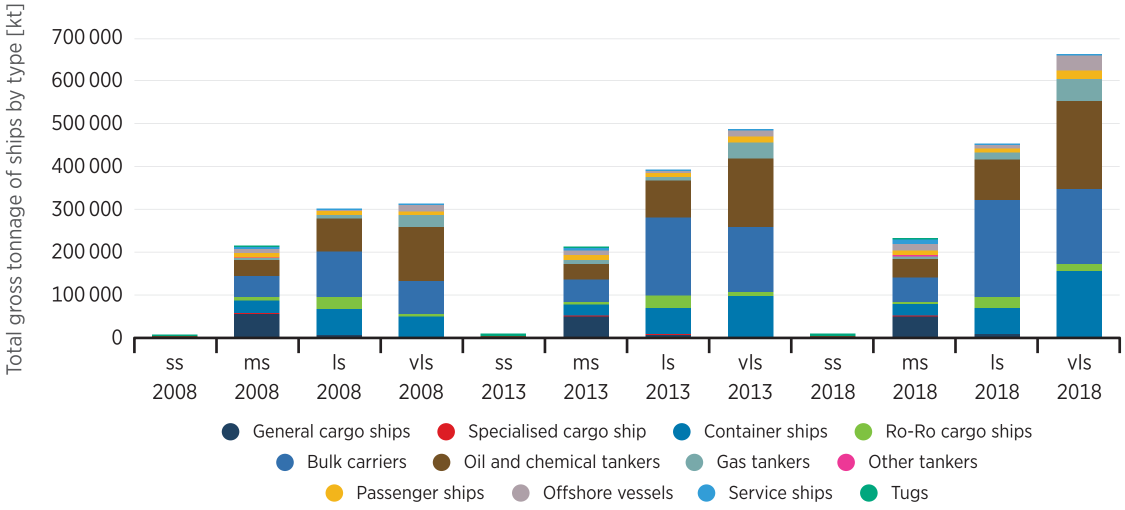
Source: IRENA, 2020d

While the 2008 financial crisis may shed some light on how the economy will perform as the world recovers from the COVID crisis, uncertainty remains about the performance of the global economy post-2020. Assuming adequate and well-focused policy support comes from governments around the world, as economic activity normalises, it is projected that global GDP will grow by 5.8% in 2021 (IMF, 2020). However, it is uncertain how the COVID pandemic will affect the global economy when discussing different future trends. The net impact to the shipping sector, particularly to maritime trade volumes, is also under discussion. If the global economy bounces back at a 5.8% rate in 2021, it is likely that net global maritime trade will follow this trend and continue growing at an annual rate close to about 3.5%. Thus, enabling the use renewable energy fuels and implementing EE measures to avoid a rapid growth in GHG emissions are of prime importance.

INTERNATIONAL MARITIME FLEET

The global maritime fleet comprises 92 251 vessels (Equasis, 2018). Between 2013 and 2018, the total number of vessels increased at an average annual growth rate (a.a.g.r.) of 2.49%. However, data show that vessels including tankers, bulk and container carriers are the faster-growing segments of the fleet. Indeed, in many cases the global fleet of these vessels grew at an a.a.g.r of above 25%, mainly comprising vessels categorised as large ships (LS) and very large ships (VLS).

Figure 2 **Total gross tonnage of ships worldwide, by type, size and year**

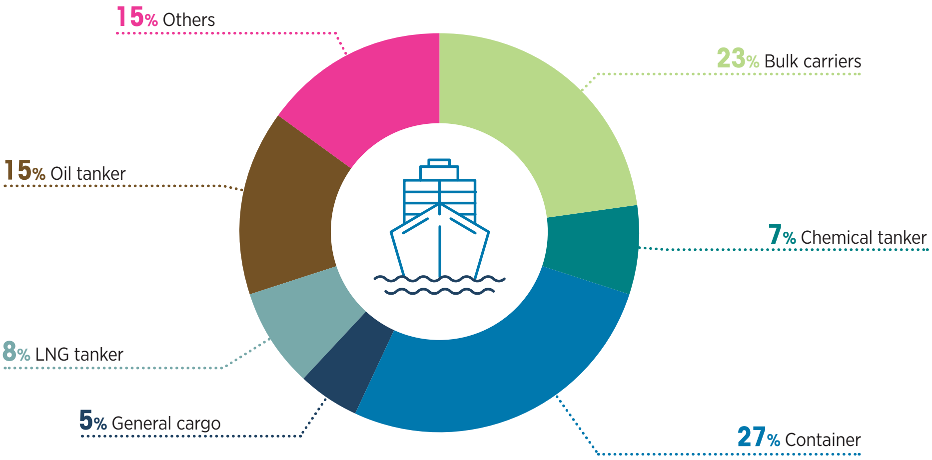


Note: kt = Kilotonne; ss = small ships; ms = medium ships; ls = large ships; vls = very large ships.
Source: UNCTAD (2020d)

Although SS and MS units greatly outnumber the overall number of LS and VLS, the two latter categories (which include bulk and container carriers, as well as oil and chemical tankers) are responsible for transporting 82% of global cargo by weight (Figure 2). Notably, the fuel consumption depends on the amount of cargo moved over time and not just the number of ships. It is therefore advisable that decarbonisation efforts focus on the four above-mentioned types of ships. Indeed, as presented in Figure 3, the *Fourth IMO GHG study* (2020a) noted that six types of vessels were responsible for 85% of the energy consumption associated with international shipping.

Large and very large ships are responsible for about 85% of net GHG emissions associated with the international shipping sector

Figure 3 **Voyage-based allocation of energy consumption for international shipping**



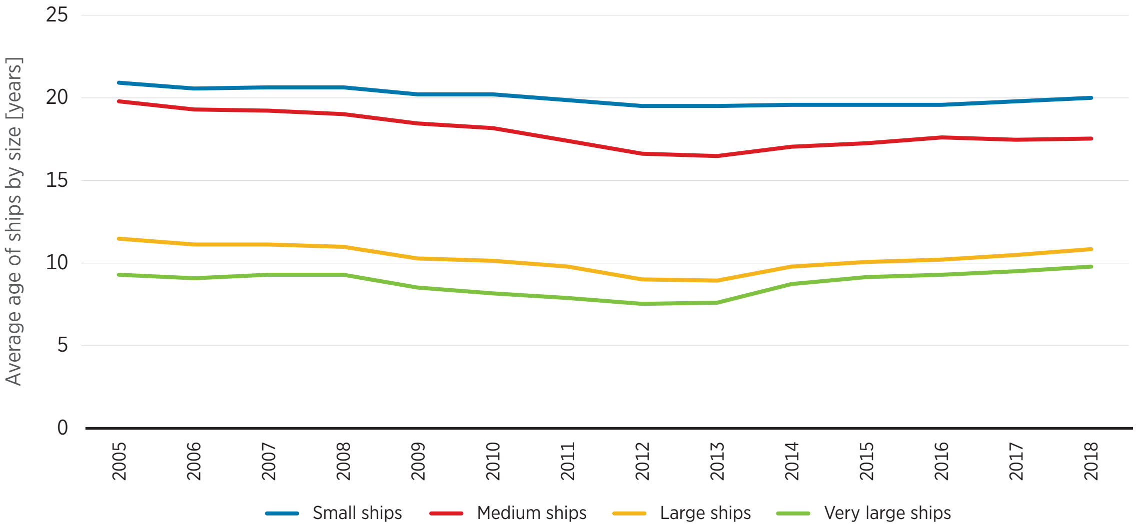
Note: "Others" includes other liquid tankers, ferry-pax only, cruise, ferry-Ro-Pax, refrigerated bulk, ro-ro, vehicle, yacht, service-tug, miscellaneous-fishing, offshore, service-other, miscellaneous-others.

Source: IMO (2020a)

The key motivations for building larger ships greatly depend on the application of the vessel. Larger ships need less energy to move a given amount of freight over a given distance. Therefore, vessel size reflects an economy of scale practice applied by shipping manufacturers and shipowners, thus maximising profits by becoming more efficient. Understanding the average age of the fleet serves as a proxy to estimate when most new-builds will be commissioned. Thus, it indicates the level of urgency needed to develop sustainable shipping alternatives, avoid stranded assets and kick-off the shift to manufacturing net-zero and carbon-zero vessels. A ship's technical lifetime usually ranges from 25 to 30 years. Based on their theoretical lifespan and as illustrated in Figure 4, VLS and LS need to be replaced by 2030. However, to achieve this target, first movers operating on renewable fuels will need to be commissioned much earlier.

A more detailed view of the historical development of the operating number of vessels yields a high a.a.g.r. of 3.3% between 2005 to 2018 and an absolute increase of about 50% over this period. As mentioned, the tendency is primarily seen within bulk carriers, containerships, and oil and chemical carriers (IRENA, 2019a). While the average annual growth of the SS and MS between 2005 and 2018 stands at 3.12% and 2.24%, the average annual growth for LS and VLS is 5.89% and 8.60%. Accordingly, SS and MS mostly comprise old fleets, while LS and VLS tend to be only half as old. Under this observed trend, the number of ships worldwide could triple by 2050 compared to 2018 levels, and LS and VLS would be subject to the highest increase.

Figure 4 **Average age of ships by type**



Source: Equasis (2018)

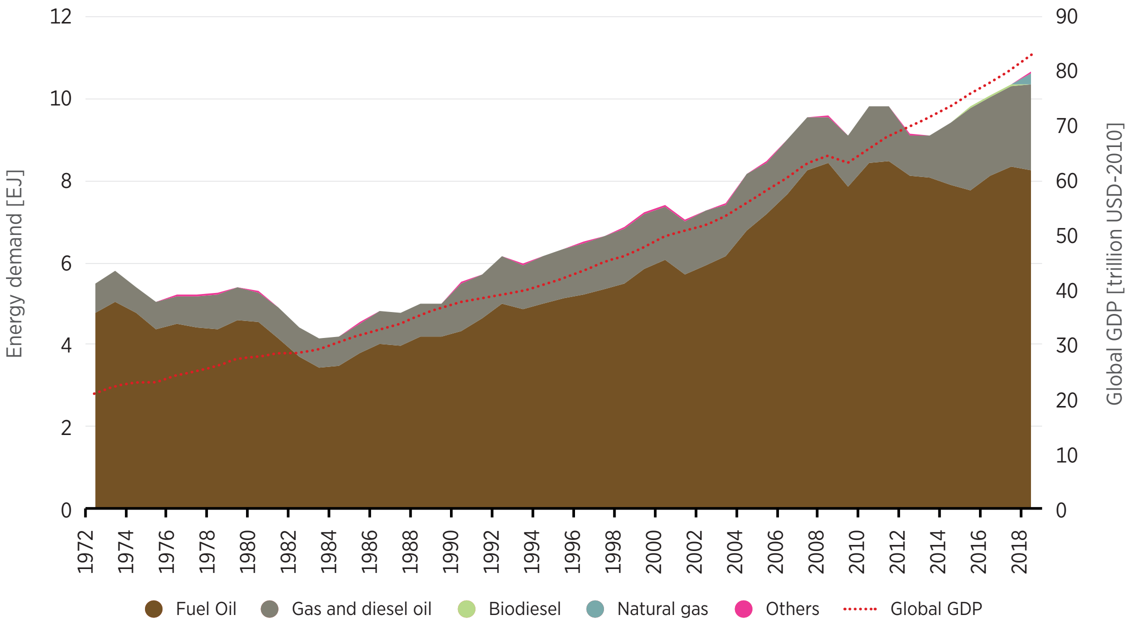
Not surprisingly, although LS and VLS represent around 20% of today's global fleet, together these vessels are responsible for about 85% of net GHG emissions associated with the shipping sector (IRENA, 2019a). In 2018, the fuel mix for international shipping included 79% HFO, 16% MDO, 4% LNG and less than 0.1% methanol. Therefore, this report primarily focuses on the decarbonisation of international maritime shipping, which is mostly composed of LS and VLS.

ENERGY DEMAND AND THE IMPORTANCE OF ENERGY EFFICIENCY

Overview of energy demand dynamics

Since the early 1980s, the demand for marine bunkers has grown at a rapid pace. Between 2005 and 2018, global bunker demand associated with the shipping sector grew by more than 25%, registering an a.a.g.r of 1.77% for this period. With maritime shipping facilitating as much as 80-90% of global trade (UNCTAD, 2018), the linkage between energy demand in the shipping sector and net trade volume is more visible. Indeed, recently global trade has been closely correlated to GDP growth (see Figure 5). Subsequently, global GDP dynamics have tended to impact the final energy use associated with the shipping sector. However, upon disaggregating the GDP components, it is clear that the manufacturing sector added value has been the primary historical driver behind energy demand in the overall shipping sector (*i.e.* international shipping and domestic navigation) (Figure 5). A comprehensive analysis that takes in COVID-19 and the implications of the global pandemic in the short term is presented Chapter 4, which also examines drivers with the potential to shape future energy demand in the international shipping sector.

Figure 5 **Global shipping energy demand and GDP**

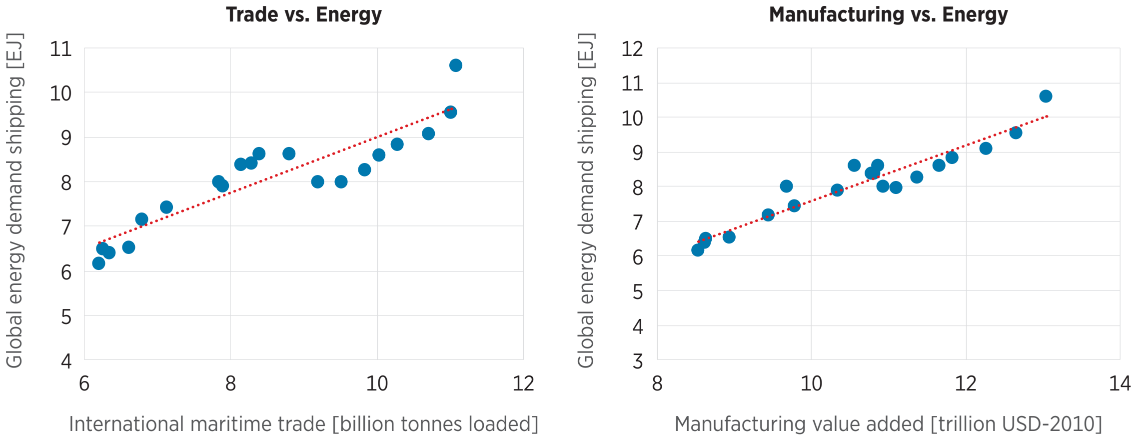


Note: Comprises energy demand from domestic navigation plus international shipping.

Source: IRENA analysis based on DNV GL (2020a), World Bank (2020)

As seen in Figure 5 and Figure 6, factors such as global GDP, trade and manufacturing sector activity have been key drivers shaping energy demand in the international shipping sector. As the adoption of EE measures in international shipping increases, the nexus of GDP, trade and energy demand may decouple progressively. However, given the pivotal role of international shipping in the global economy, the role of EE will obviously have limitations. Renewable energy therefore has a key role to play in decarbonising this sector by mid-century.

Figure 6 **Correlation between trade, manufacturing and energy demand in the shipping sector**



Note: Comprises energy demand from domestic navigation plus international shipping

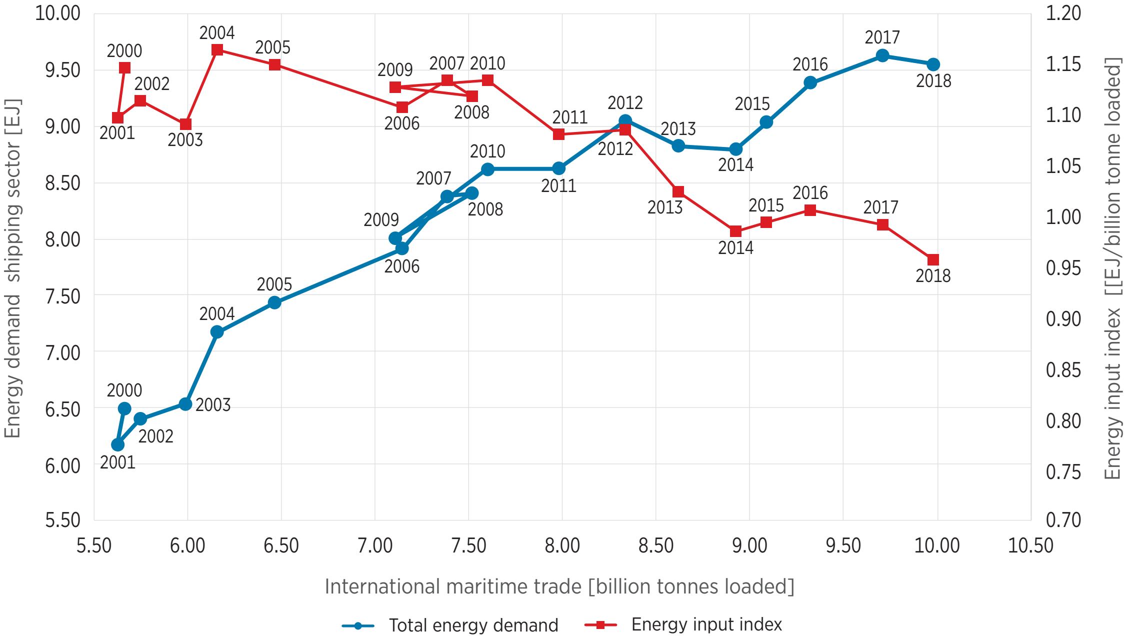
Source: IRENA analysis based on DNV GL (2020a), World Bank (2020), UNCTAD (2020d)

Overall, the global energy performance of the sector can be analysed by comparing the overall energy demand vs. the loaded volume. The ideal trend would be to observe that year by year, energy demand falls while traded volume increases. Nonetheless, as presented in Figure 7, the historical trends show that the actual tendency is the opposite: an increase in trade requires an increase in energy use. While in absolute terms the energy index indicates a more efficient performance, historical trends suggest that this improvement has been mainly driven by the high prices of oil and its derivatives. For instance, by analysing the performance of the sector between 2008-2009 and 2011-2015, it is clear that the sector is well positioned to perform better from an EE standpoint. Between 2008 and 2009, the financial crisis led to a fall in traded volumes, which subsequently resulted in a fall of energy demand. Such behaviour is expected and relatively obvious. In contrast, in 2011-2012, a number of events – including the so-called Arab Spring and disagreements in the Straits of Hormuz – resulted in the oil price jumping from USD 75 (US dollars) to around USD 100 per barrel. Subsequently, shipowners and ship operators appear to have reduced their energy use, but maritime global trade volumes continued rising steadily until 2014 and thereafter.

Oil prices started to fall drastically and hit a record low of around USD 42 to USD 50 between 2014 and 2016. Between 2014 and 2017, the energy input index remained relatively stable, denoting minimal improvement. Thereafter, from 2017 to 2018, there was a clear improvement in terms of EE. However, between these years the oil price increased from around USD 50 to USD 65 per barrel. Hence, as in previous periods, the 2017-2018 EE improvement appears to have been driven by the higher price of oil and its derivatives.

Figure 7 shows that during low oil price periods, the shipping sector pays less attention to its energy usage. Conversely, the sector adapts during periods of high oil prices, increasing its activity while using energy resources more efficiently. The shipping sector balances its use of energy without external market regulations, showing that the sector has the ability to adapt rapidly during times of high oil prices by adjusting operational practices and adopting slow steaming as the primary energy-saving practice.[2]

Figure 7 **Historical analysis of energy demand, maritime trade and net energy input**



Source: IRENA analysis based on DNV GL (2020a), UNCTAD (2020d)

Energy efficiency mandates

To tackle the energy intensity problem, the IMO has developed four mandates focused on improving EE across vessels: i) EEDI (Energy Efficiency Design Index); ii) SEEMP (Ship Energy Efficiency Management Plan); iii) EEXI (Energy Efficiency Existing Ship Index); iv) EEOI (Energy Efficiency Operational Indicator); and v) CII (Carbon Intensity Indicator). The following section provides details on these mandates.

EEDI (Energy Efficiency Design Index)

The IMO mandated the EEDI in 2011 in accordance with the amendments made in the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI (resolution MEPC.203(62)) (MARPOL ANNEX VI, 2013). This index was developed to promote the utilisation of more energy efficient engines and equipment onboard vessels to decrease GHG emissions. A minimum EE is required by vessels to comply with the EEDI mandate, dependent on the size and type of the ship (DNV GL, 2020a). This value is measured in grams (g) of CO_2 per tonne-mile.

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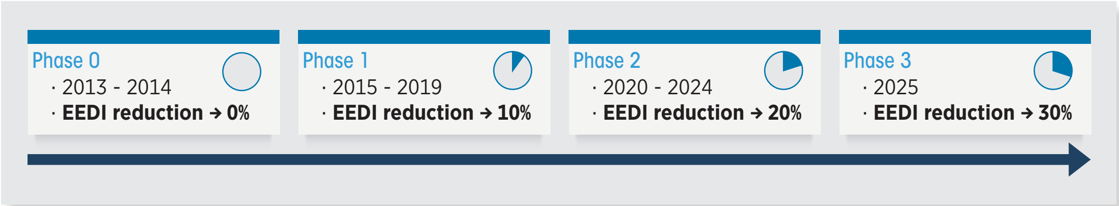
2 "Slow steaming" refers to the fuel-saving practice of operating a vessel at an average speed that is well below its design speed.

EEDI is implemented over different phases, simulating continuous innovation and advancements in EE in a ship starting from its inception. EEDI functions through a performance-based system; therefore, decisions about the type of technology used to achieve the ideal EE in ships are left to the ship designers and builders (MARPOL ANNEX VI, 2013). The first phase involves the reduction of 10% CO_2 levels in ships, which are then further restricted every five years of the vessel's life. This is intended to keep up with the advancements in EE technology. Further reductions are scheduled up to 2025, by which time all applicable ships are required to have a 30% reduction in CO_2 levels in comparison to average efficiency levels for ships built between 2000 and 2010.

EEDI is further broken down into four phases. During Phase 0 (2013-2014), ships were encouraged to start implementing EE measures. Phase 1 (2015-2019) required most cargo carriers to have at least a 10% CO_2 reduction level, with passenger ships having a minimum of 5%. The current stage, Phase 2 (2020-2024), has mandated either a 20% or 15% minimum CO_2 reduction level dependent on the ship type, with most of the large freight vessels required to have 20% CO_2 reduction levels. Phase 3 (from 2025 onward) will require a 30% reduction across all types of vessels (IRCLASS, 2013a).

Figure 8 **EEDI phases, implementation periods and reduction targets**

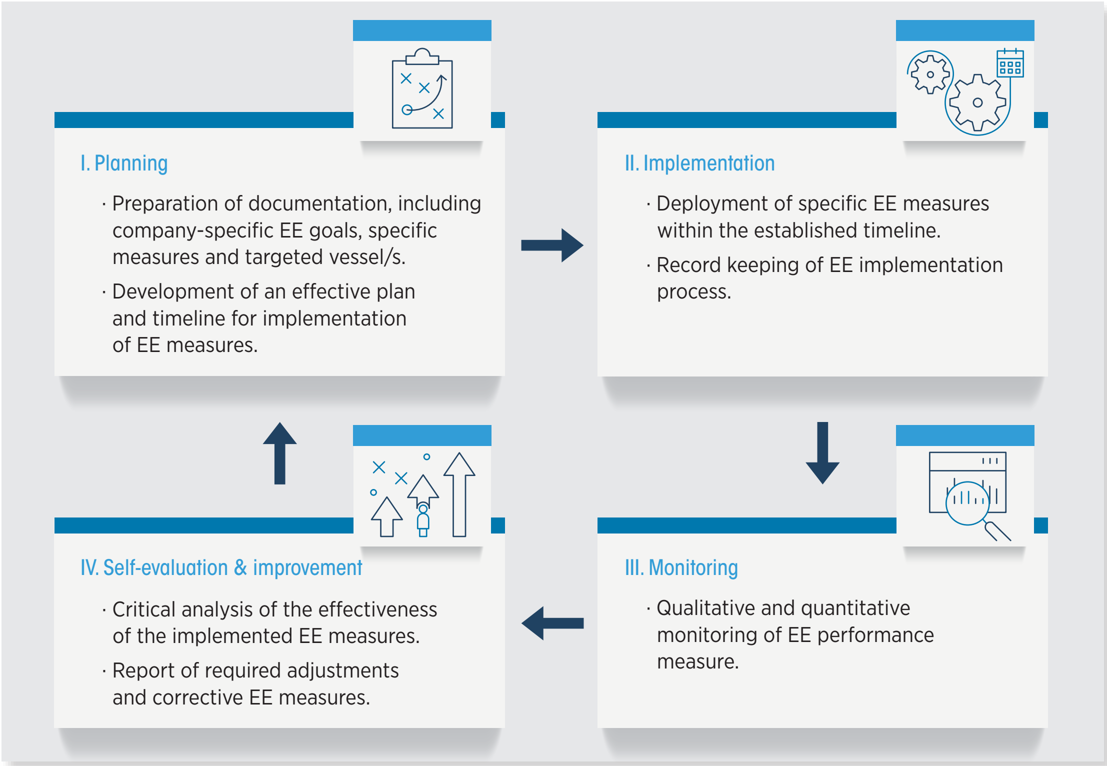


Note: Time period refers to 1 January of the starting year to 31 December of the end year.
EEDI reduction in reference to the baseline year, 2013.
Source: IRENA (2021) based on IRCLASS (2013a)

SEEMP (Ship Energy Efficiency Management Plan)

The SEEMP was implemented in tandem with EEDI to act as the operational measure of ship efficiency in 2013 (IRCLASS, 2013b). This measure provides a mechanism to improve ship efficiency in an economically viable manner (MARPOL ANNEX VI, 2013). It lays out a systematic plan for EE management implementation over a desired time period for individual ships. In 2013, the IMO made it mandatory for all ships above the size of 400 gross-tonnage (GT) to have a vessel-specific SEEMP aboard. The SEEMP tracks the ship's EE and helps smooth out the improvement decision-making process for shipowners and fleet managers (DNV GL, 2020d). Applying the SEEMP mandate is a four-stage, cyclical process: Planning, implementation, monitoring, and self-evaluation and improvement. Given that the SEEMP provides a baseline for energy management of vessels, the application of this mandate is crucial. Figure 9 describes the four-step cycle associated with the SEEMP.

Figure 9 **SEEMP cyclical process**



I. Planning

- Preparation of documentation, including company-specific EE goals, specific measures and targeted vessel/s.
- Development of an effective plan and timeline for implementation of EE measures.

II. Implementation

- Deployment of specific EE measures within the established timeline.
- Record keeping of EE implementation process.

III. Monitoring

- Qualitative and quantitative monitoring of EE performance measure.

IV. Self-evaluation & improvement

- Critical analysis of the effectiveness of the implemented EE measures.
- Report of required adjustments and corrective EE measures.

Source: IRENA (2021) based on IRCLASS (2013b)

EEXI (Energy Efficiency Existing Ship Index)

Japan proposed the EEXI mandate to the IMO in 2019. In February 2020, the seventh session of the Intersessional Meeting of the Working Group on Reduction of GHG Emissions from Ships (ISWG-GHG 7) took place in which a guideline was drafted to incorporate EEXI into MARPOL Annex VI (IMO, 2020b). The IMO currently plans to incorporate EEXI into MARPOL Annex VI in 2023 according to MECP 75, which occurred in November 2020. The EEXI is a technical approach to improving the EE in ships. This index represents the EE of the ship in comparison to the baseline EE when the ship was developed. Under the EEXI, ships are required to meet a specific EE value. This value is based on the required reduction value, which is represented as a percentage relative to the EEDI baseline. The implementation of EEXI is an extension for existing ships related to EEDI. The EEXI is applicable for all vessels above the weight of 400 GT in accordance with MARPOL Annex VI (DNV GL, 2021a).

EEOI (Energy Efficiency Operational Indicator)

The EEOI is an essential tool for managing and monitoring ship and fleet efficiency over a certain timeframe (DNV GL, 2020b). This indicator is a key aspect of the SEEMP monitoring process and was devised with EEDI and the SEEMP in 2011 and introduced in 2013 (MARPOL ANNEX VI, 2013). The EEOI allows ship operators to measure the fuel efficiency of the vessel while in use and to monitor the effect of differing operations to gauge the impact on EE (MARPOL ANNEX VI, 2013). Such operations include improved voyage planning, increased frequency of propeller cleaning, or the addition of technical measures such as installing a new propeller or a heat recovery system (MARPOL ANNEX VI, 2013). The EEOI is expressed in the unit similar to the EEDI value, in CO_2 per tonne mile (FIS, 2020). As opposed to the enforcement of EEDI on vessels, the EEOI is a voluntary measure for shipowners and operators to use to assess performance (FIS, 2020). As ships vary significantly in terms of capacity and EE measures, each EEOI is linked with the individual ship, even with ships that serve similar purposes and share similar technical properties.

CII (Carbon Intensity indicator)

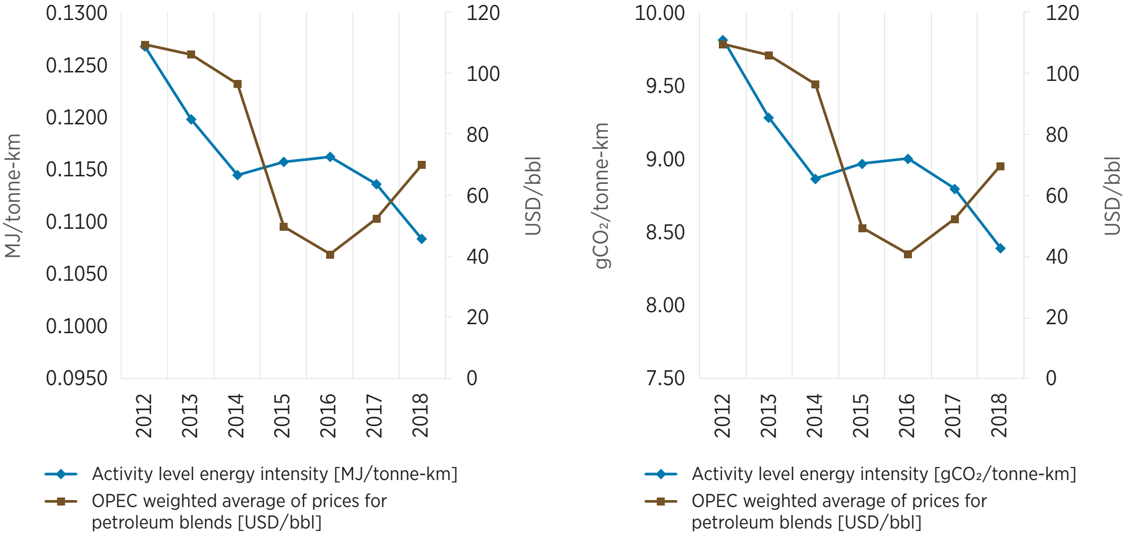
In alignment with the IMO's MEPC 76, which took place in June 2021, starting in 2023 the CII will target all cargo and Ro-Pax vessels, as well as cruise ships above 5 000 GT. For these vessels, the CII indicates the gram of CO_2 per deadweight (dwt)-mile. Eventually, the vessels will be rated from A to E on a yearly basis. However, to secure continual improvement, the rating thresholds will become increasingly stringent by 2030, and accordingly, so will the CII reports on the actual CO_2 emission in operation. In terms of targets and goals, with 2019 as the base year, the CII has to fall by 1% per year between 2020 and 2022 and then fall by 2% per year between 2023 and 2026. Similar to other EE mandates, the CCI and its goals for the period 2027-2030 will be revised and further decided in 2023 (DNV GL, 2021d) (IMO, 2021).

Outline of energy efficiency status and solutions

Since the implementation of EEDI, SEEMP and EEOI in 2013, both energy and carbon intensity in ships have decreased. Indeed, in 2012 the historical global average energy intensity for the international shipping sector was 0.1267 megajoule per tonne-kilometre (MJ/tonne-km). By 2018, this indicator had fallen by 14.5% in comparison to 2012 levels. Displaying a similar trend, international shipping carbon intensity also improved between 2012 and 2018, when this indicator fell from 9.8 gCO_2/tonne-km to 8.39 gCO_2/tonne-km. However, the behaviour of these indicators is inverse to the weighted average of the petroleum blends price. In fact, the lack of improvement in these indicators between 2014 and 2016 indicates that historically, the main driver behind EE performance in the international shipping sector has been the price of fossil fuels.

It is critical to deploy mechanisms which ensure compliance with energy efficiency mandates

Figure 10 **Historical activity level global average energy intensity (left) and carbon intensity (right) for the shipping sector**



Note: bbl = barrel of oil.

Source: IRENA analysis based on IMO (2020a), UNCTAD (2020d), OPEC (2021)

To meet the standards of EE mandated by the IMO's EEDI in 2013, new ship designs are required to apply a variety of structural EE measures. Through the IMO, the push to decarbonise the shipping sector is constantly adapting to the change in technologies over the years. Where operational EE measures are tracked utilising EEOI and SEEMP, EEDI directly targets the design phase of vessels through measures that affect the hull and superstructure of the ship, the propulsion and power systems, machinery technologies integration, and the use of alternative energy sources. Table 1 presents a summary of the various EE design and operational solutions.

Table 1 **Overview of operational and design EE solutions**

EE OPERATIONAL SOLUTIONS	**VOYAGE PERFORMANCE MANAGEMENT**	**Just-in-time arrival**	Just-in-time (JIT) refers to the method whereby a ship optimises and maintains a particular speed to arrive at a port or piloting station in a timeframe that guarantees a berth, throughway or servicing.
		Ship speed optimisation	Optimising speed during a ship's journey is another important EE measure in conserving fuel. This process is applicable to new and existing vessels and is relatively easy to implement.
		Weather routing	Weather plays an important role in ship pathing, and planning a route based on the weather allows for safe voyage and accurate time of arrival.
		Autopilot improvements	To mitigate energy consumption, autopilot software can be used to make calculated decisions about rudder movement to optimise its utilisation.
		Trim, draft, and ballast optimisation	The draft, ballast and trim of a vessel is instrumental in dictating fuel and energy consumption. The trim of the ship dictates the ability of the ship to maintain a maximum speed while keeping the shaft power a constant, thus reducing energy and fuel usage.
	ENERGY MANAGEMENT SYSTEMS	**Reducing onboard power demand**	To increase vessels' EE, the power demand of all onboard machinery and equipment must be reduced.
		Fuel quality and consumption reporting	Fuel consumption is directly linked to vessels' energy demand. Therefore, all ships have a system of fuel consumption monitoring and reporting for bunkering logistics and fleet cost management. Improvements in monitoring these aspects can reduce vessels' fuel consumption.
	VESSEL MAINTENANCE MEASURES	**Hull roughness management**	Hull roughness determines the amount of friction between the ship and the water. Too much frictional force on the ship increases energy demand and fuel consumption. To mitigate this, various methods can be applied to maintain optimum roughness of the hull.
		Propeller roughness management	Propeller roughness is caused by corrosion and fouling from organisms such as those that affect hull roughness. Therefore, shipowners should maintain propellers by polishing and coating them.

EE DESIGN SOLUTIONS	**HULL AND SUPERSTRUCTURE**
	Ship sizing
	Larger capacity ships tend to be more energy efficient due to their ability to transport more cargo at the same speed as smaller vessels while expending less power.
	Principal dimensions
	Designs for new ships should optimise the length/beam ratio by increasing length and decreasing the beam of the vessel while maintaining draft.
	Ship weight
	The structural weight of a vessel impacts a ship's EE and fuel consumption performance. The benefits of a lighter structural weight are proportional to ship size, with larger ships seeing increased efficiencies and reduced fuel consumption.
	Aftbody and forebody optimisation
	Designs integrated into the forebody of the vessel include the design of the bulb, waterline entrance, forward shoulder and the bilge (ABS, 2013). Aftbody optimisation mitigates stern waves, improves flow towards the propeller and avoids the eddy effect.
	PROPULSION SYSTEMS
	Propeller optimisation
	Various forms of high-efficiency propellers exist. Each propeller installation is required to be designed specifically to suit a ship's operational profile and stern hydrodynamics.
	Enhancement of propulsion drives
	These are devices that provide wake equalisation and flow separation alleviation to improve the flow around the hull of a ship through mitigating issues arising from propeller and hull resistance.
	Air lubrication systems
	Air lubrication systems can prove instrumental in mitigating resistances on a vessel, thus improving propulsion. Two forms of air lubrication exist: air cavity systems and micro-bubble systems.
	POWER SYSTEMS
	Main engines
	The use of main engine efficiency measurement instrumentation is a key EE measure to track a ship's fuel consumption and energy demand. This includes shaft power meters, fuel flow meters and engine performance measurement and control.
	Auxiliary equipment
	Improvements to a ship's auxiliary systems in the design stage can boost the vessel's EE. Hybrid auxiliary power generation systems consisting of fuel cells (FCs), diesel/gas generators and batteries can improve ship energy performance.
	Assisted propulsion by wind and solar
	Various measures can be integrated into a ship's design to assist propulsion, such as towing kites, which are common and commercially available. The introduction of solar power to vessels is also currently in development. In vessels, solar photovoltaic (PV) panels can be best used to power auxiliary systems and supplement a vessel's power demand.

Source: Based on Lassesson and Andersson (2009), Hakirevic (2020), ABS (2013), The Motor Ship (2015)

For a more detailed description of the various operational and design EE solutions, refer to Annex B.

NAVIGATION ROUTES AND BUNKERING INFRASTRUCTURE

Ports are essential for the global economy, with 80-90% of trade accounted for in shipping. To mitigate GHG emissions in the shipping sector, it is vital to focus development on the supply chain and logistics infrastructure. As stated by the European Seaports Organisation (ESPO, 2018), there are 12 key types of port infrastructure that are identified through investment. These 12 elements can be further divided into two base infrastructure categories, terminal infrastructure and operational equipment (Table 2).

Table 2 **Main infrastructure in ports**

CATEGORY	INFRASTRUCTURE TYPE/INVESTMENT
Terminal infrastructure	1. Inland waterway connection between the port and the main waterway
	2. Basic port infrastructure, *i.e.* docking areas
	3. Bunkering
	4. Cold ironing[3]
	5. Sites for port-related logistic and manufacturing activities in the port area
	6. Infrastructure for reducing the environmental footprint of port and shipping operations
	7. ICT/digital infrastructure for efficient port and hinterland operations
Operational equipment	1. Road transport connection from port to the main highway
	2. Maritime access, *i.e.* dredging and tugboats
	3. Intermodal/multimodal terminals in the port area and/or dry ports outside the port area
	4. Rail transport connection from port to main line
	5. Infrastructure for smooth transport flows within the port area, *i.e.* cranes

Source: ESPO (2018)

Port location plays an important role in shipping logistics, requiring access to large quantities of land located near a major manufacturing district and/or access to raw materials. Key container ports globally include Los Angeles, Rotterdam, Shanghai and Singapore. The top ten busiest container ports internationally are predominantly based in China, with Shanghai being the leading port (WSC, 2018). In 2018, Shanghai accounted for 42.01 million TEU (twenty-foot equivalent unit)[4] in container trade, followed by Singapore with a total of 36.60 million TEU (WSC, 2018). Furthermore, 20 ports are responsible for 45% of the global container trade (UNCTAD, 2019)

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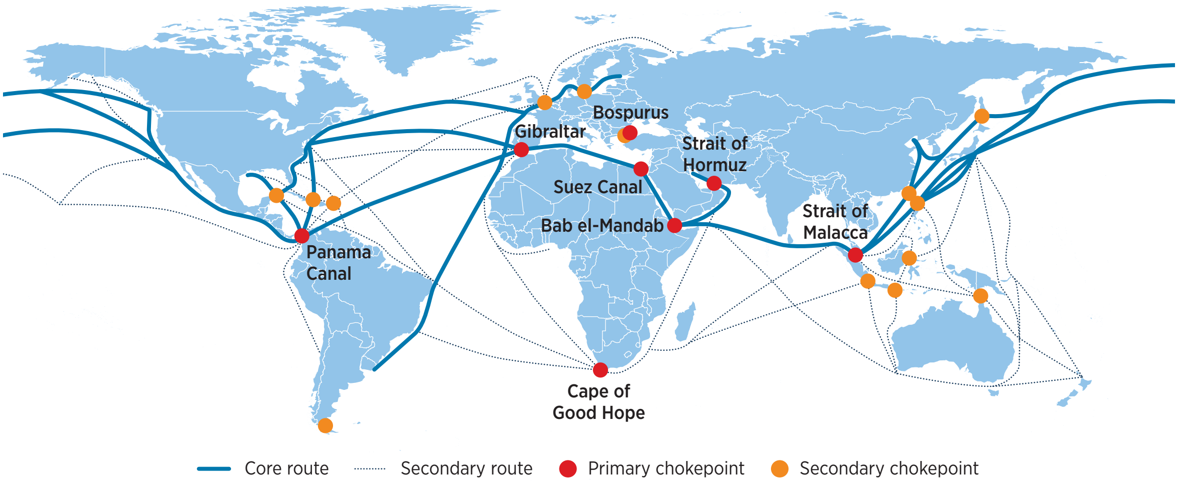
[3] *"Cold ironing" (CI) refers to the practice of turning off a vessel's auxiliary engines during shore-side operations in the port area by plugging the vessel into an electricity source offered by the port authority, thereby reducing airborne emissions during docking periods.*

[4] *"TEU" is a unit typically used in the shipping sector. It denotes a shipping container whose internal dimensions measure about 20 feet long, 8 feet wide and 8 feet tall.*

(UNCTAD, 2020c). Decarbonisation in these key ports can dramatically decrease CO_2 emissions from shipping infrastructure. As with port locations, shipping lanes are vital in optimising trade routes. Geographical boundaries are an important consideration in plotting ship trajectories, and certain key global maritime routes provide access between the international industrial regions globally. The most important global routes are the Panama Canal, the Straits of Malacca and the Suez Canal (see Figure 11).

Figure 11 **Main maritime shipping traffic routes**



Source: Rodrigue (2020)

This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

The Panama Canal provides direct access between the Atlantic and Pacific oceans without circumnavigating Cape Horn. In 2019, the Panama Canal reported 13 785 ship passages and a total of around 229 million tonnes of goods (Georgia Tech, 2020). The Suez Canal is in Egypt, which connects the Mediterranean and the Gulf of Suez. This canal provides a direct route between the Atlantic and Indian oceans, allowing shorter trade routes for Europe and Asia. The Strait of Malacca is an important route that connects the Indian Ocean and the Pacific Ocean. This route is vital for trade between all the island nations in the Pacific and provides a shorter route for trade from the Middle East.

Bunkering infrastructure

Bunkering is a key aspect of port infrastructure that deals with the storage and resupply of fuel to ships. Currently the ports with the highest bunkering capacity globally include Singapore, Fujairah (United Arab Emirates) and Rotterdam (Netherlands), with the latter being the largest bunkering port in Europe (see Figure 12). In this context, the main fuels used by the shipping sector are HFO, MGO and very low-sulphur fuel oil (VLSFO). During 2019, the global shipping fuel supply mostly comprised un-scrubbed high-sulphur fuel oil (HSFO) and MGO, accounting for 71.8% and 20.5% of fuel demand, respectively (IEA, 2019a).

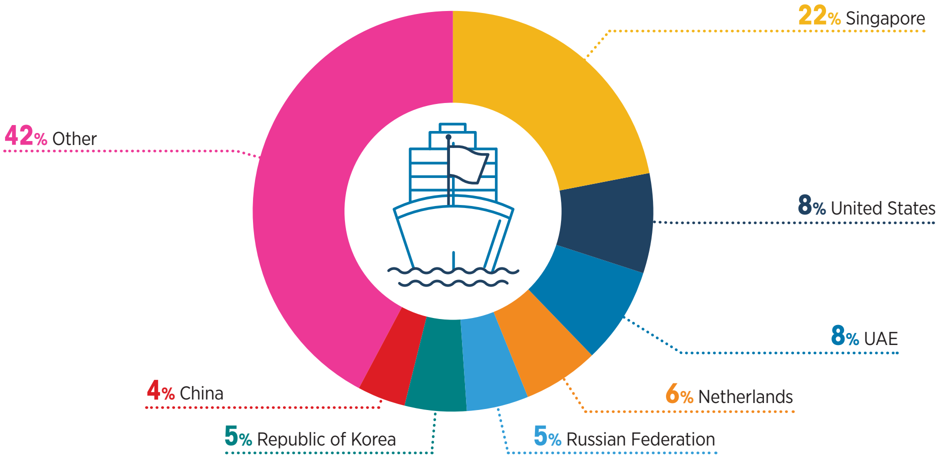
In 2020, the IMO sulphur limits resulted in a significant shift from HFO to VLSFO. However, to mitigate CO_2 and GHG emissions, alternate fuel sources such as advanced biofuels are already being employed, while green hydrogen (H_2)-based fuels are expected to be introduced in the medium term via innovative projects and initiatives. Transitioning between these fuels is a process of utilising the current bunkering infrastructure and adjusting it according to the fuel type.

In consequence of the sulphur emission limitation imposed by IMO and the decarbonisation needs of the shipping sector, LNG has gained momentum in recent years where important infrastructure developments have been completed. As of today, there are nearly 200 ports equipped with LNG bunker facilities across the globe. Europe and Asia register the highest concentration of such infrastructure (DNV GL, 2019a, 2021b). However, expanding this infrastructure further comes with important challenges. For instance, LNG must be stored at cryogenic temperatures, which require extensive retrofits to existing infrastructure. Hence, LNG is considered highly hazardous, and safety precautions are required when handling it. It is also important to note that current LNG engines are subject to a methane slip of between 2% and 5% (Mallouppas and Yfantis, 2021), and the global warming potential (GWP) of methane in a time horizon of 20 years is 56 times higher than the GWP linked to CO_2 (UNFCCC, 2021). The rather low potential of LNG to deeply decarbonise international shipping is emphasised by the fact that on an energy basis, the CO_2 content of LNG is only about 26% lower than that of fuel oil (IPCC, 2019). Accordingly, it is critical to focus efforts on renewable fuels with a representative potential to decarbonise international shipping by 2050 (see chapters 3 and 4). Indeed, LNG's limited potential to decarbonise international shipping at a large scale and thus its restrictive potential to limit global warming to 1.5°C by 2050 signals that if LNG infrastructure continues to expand as it has in the past, it risks becoming stranded. In the context of LNG, it is important to note that liquefied biomethane could be employed as a drop-in fuel solution for LNG vessels. The technological readiness and scalability potential of renewable gaseous fuels is discussed in Chapter 3.

In the race to decarbonise the maritime shipping sector, it is crucial to identify the geographical locations that could fast-forward the energy transition in the shipping sector. This includes paying attention to key trading ports, as well as ports of relevance from a fuel supply point of view (see Figure 12). It will also be important to observe key navigation routes and choke points (see Figure 11). Stakeholders in these locations can play a critical role by monitoring and fostering compliance with EE mandates and by enabling access to renewable bunkering fuels. Clearly, focusing efforts on and facilitating investments in such locations in the years to come will be of critical importance.

It is crucial to identify the geographical locations that could fast-forward the energy transition in the sector

Figure 12 **International shipping bunkering by country, 2017 (TJ/year)**



Note: TJ = terajoule.

Source: Based on IEA (2019b)

In the process of decarbonising the international shipping sector, decarbonisation measures and opportunities at ports need to be acknowledged. For instance, enabling cold ironing (CI) would significantly drive down fossil fuel consumption during docking hours provided the electricity provided is from 100% renewable sources. While CI infrastructure is not widespread across the globe, it is expected that over the coming years several ports will develop shore power infrastructure. In parallel, attention needs to be given to port and terminal handling infrastructure and to port vessels. However, while it is important to address the origin of these emissions, it should be noted that such emissions are not accounted for as international shipping but rather as domestic navigation, potentially making them subject to more stringent measures such as the California Air Resources Board (CARB) restrictions in California. For further detail and information on decarbonisation measures and opportunities at ports, refer to Annex A.

3. RENEWABLE FUELS AND TECHNOLOGY READINESS

KEY MESSAGES:

- In 2019, the average costs of HFO and LNG fluctuated around USD 41 per megawatt hour and USD 19/MWh. Advanced biofuels can be immediately harnessed by the shipping industry; current technological readiness allows for fuel blends of up to 20% without engine modifications, although tests have been conducted using a maximum blend of 30%. Production costs ranges for advanced biofuels are similar among the various alternatives, *i.e.* USD 72/MWh to USD 238/MWh. Avoiding the use of food crops for biofuels is critical. Therefore, the use of waste fats, oils and greases is essential to produce fatty acid methyl ester (FAME) biodiesel and hydrotreated vegetable oils (HVOs) that do not hinder food security or land availability. Bio-methanol from lignocellulosic biomass is another potential option.
- Biomethane production costs are highly dependent on feedstock availability and feedstock market price, leading to wide cost rages, *i.e.* USD 25/MWh to USD 176/MWh Biogas produced via anaerobic digestion for the subsequent production of liquid biogas and compressed biogas has high technological maturity, making it an attractive option for displacing LNG. However, due to scalability and logistical issues, the role of renewable gaseous fuel may be limited. Biogas may be more effective in end-use applications other than for fuelling the shipping sector.
- The direct use of green H_2 via fuel cells (FCs) and internal combustion engines (ICEs) is an option for the shipping sector, but this alternative is more attractive for short sailings, *e.g.* domestic navigation. However, the use of green H_2 for the subsequent production of e-fuels is the centrepiece of international shipping decarbonisation. Current green H_2 production costs vary between USD 66/MWh and USD 154/MWh, but as the costs of electrolysers and renewable energy technology fall, green H_2 costs will become cost-competitive starting in 2030, eventually achieving 2050 costs of around USD 32/MWh-USD 100/MWh.
- Renewable methanol, *i.e.* bio-methanol and renewable e-methanol, requires little to no engine modification and can provide significant carbon emission reductions in comparison to conventional fuels. Renewable e-methanol is of particular interest in the shipping sector, where having access to affordable, renewable CO_2 is an important milestone that needs to be addressed.
- Renewable e-fuels methanol and ammonia are the most promising fuels for decarbonising the sector. Of these, ammonia is more attractive due to the null carbon content on its molecular structure. This exempts ammonia from the cost of carbon capture and storage (CCS) technologies, which add to the final cost of e-methanol. The falling costs of green H_2 coupled with the cost reduction of carbon capture and removal technology will result in the achievement of 2050 production costs around USD 107/MWh to USD 145/MWh for renewable e-methanol.

- Renewable ammonia appears to be the backbone for decarbonising international shipping in the long term. By 2050, production costs for e-ammonia are expected to be between USD 67/MWh and USD 114/MWh. The ammonia engine to be ready in 2023 will be a key milestone in unlocking the use of renewable ammonia. Ammonia is corrosive and highly hazardous if inhaled in high concentrations, but it has been handled for over a century and its hazardous nature and safe handling are manageable challenges.
- From an economic perspective, if compared against LNG; this latter fossil fuel is subjected to very high market price volatility. A clear example is the very high price of natural gas that is currently troubling many countries across the world, particularly in Europe. While renewable fuels production costs are currently high, in the next decades renewable fuels will become competitive, therefore, renewable fuels can shield the shipping sector from the volatility that characterises the fossil fuels market.

The main emphasis in mitigating emissions in the shipping industry is on replacing current fossil fuel sources with alternative fuels. Current fuels used in the sector consist of MGO, LNG, and LSFO, which have low sulphur content in line with regulations dictated by IMO's amendment to MARPOL Annex VI (IMO, 2020b). However, these fuels, as with all fossil fuels, produce vast amounts of CO_2 emissions and are the main source of emissions in the shipping sector. To achieve IMO's goal of reducing CO_2 emissions by 50% by 2050, the shipping sector needs to switch to renewable fuels (IRENA, 2019a). The renewable fuels considered for the shipping industry include biofuel, biogas, methanol, ammonia and H_2. These options each have their own benefits and challenges, which are covered in the sections below. Chapter 4 addresses the timeframes for each of these alternatives to be deployed. Overall, the choice of fuel is highly dependent on factors such as supply, engine technology, net environmental performance and economic viability. With regard to the latter factor, the production costs of renewable fuels and their availability will likely be the decisive factors in the choice of fuel/propulsion technology (IRENA, 2019a). This chapter analyses further the technology readiness and associated production costs of the various renewable fuels considered for the shipping sector.

Other important aspects to consider with regard to renewable fuels are energy density, volumetric density and the temperature of the fuel, because these factors impact each fuel's economic feasibility (IRENA, 2019a). The energy density of the various fuels and the implications in terms of onboard storage are elements that require further analysis. Depending on the fuel of choice and the type and size of a given vessel, cargo capacity and thus cargo revenue could be affected.

Table 3 depicts the differences among the fuels. Liquid ammonia has one-third of the volumetric energy density compared to MGO and two-thirds compared to LNG, and therefore requires more storage to attain the same energy output (IRENA, 2019a). Methanol, for example, can be stored as a liquid at ambient temperatures, whereas LNG has to be stored at -162°C, creating difficulties in terms of infrastructure and transport. Each alternative fuel has advantages and disadvantages in terms of physical characteristics, and therefore it is important to consider logistical, infrastructural and safety aspects when choosing an alternative fuel. The alternative fuels considered for the shipping industry include biofuel, biogas, methanol, ammonia, H_2 and FCs. Each of these fuel options has benefits and challenges, covered in the section below and summarised in Table 4.

Table 3 **Comparison of different marine fuels**

Fuel type	LHV (MJ/kg)	Volumetric energy density (GJ/m³)	Storage pressure (bar)	Storage temperature (°C)
MGO	42.7	36.6	1	120
LNG	50	23.4	1	-162
Methanol	19.9	15.8	1	20
Liquid ammonia	18.6	12.7	1	-34
			8.6	20
Liquid H_2	120	8.5	1	-253
Compressed H_2	120	7.5	700	20

Note: GJ = gigajoules; m³ = cubic metres.

Source: IRENA (2019a)

Table 4 **Readiness level of shipping fuels (🟢 High - 🟡 Medium - 🔴 Low)**

	FUEL TECHNOLOGICAL READINESS	ENGINE TECHNOLOGICAL READINESS	SCALABILITY & TIME TO MARKET	ENERGY DENSITY	GHG REDUCTION	ENGINE TECHNOLOGY	ADVANTAGES	CHALLENGES
Fuel Oil	🟢	🟢	🟢	🟢	🔴	ICE	Already used globally, has high efficiency and is low cost in comparison to alternative fuels.	HFO has high carbon emissions and particulate emissions from production and use in vessels.
LNG	🟢	🟢	🟡	🟢	🔴	ICE	Well-established supply infrastructure, high energy density and is currently used in vessels globally. Has a lower sulphur content than HFO.	LNG has fewer emissions compared with HFO but still significantly more emissions than low-carbon alternative fuels. Uses non-renewable resources.
Advanced Liquid Biofuels	🟢	🟢	🔴	🟢	🟡	ICE	Biofuels have an established infrastructure due to use in multiple sectors. Easy integration into current engines. Can be used as a drop-in fuel.	Growth of feedstock used in biofuel production may affect land use, which could impact global food security. High demand from multiple sectors makes scaling difficult.
Renewable Gaseous Fuels	🟢	🟢	🔴	🟢	🟡	ICE	Bunkering in ports can use LNG infrastructure, making implementation cheaper. Ships that use LNG can switch to liquefied biogas (LBG) as a drop-in fuel.	Limitations with storage capacity required for LBG. Can only be considered for short-distance vessels. Long-distance vessels would require large storage capacity.
Hydrogen	🔴	🔴	🟡	🔴	🟢	ICE FCs	Employing green H_2 would lead to nearly zero carbon emissions. A main option as an energy carrier in FCs. Multiple applications across sectors, which can increase the rate of research.	H_2 production and storage is costly, requiring cryogenic storage. Still an immature technology in the shipping sector but has high potential as an alternative fuel.
Ammonia	🟢	🔴	🟡	🟡	🟢	ICE FCs	Ammonia has existing production and transport infrastructure due to the agricultural industry. Green ammonia is carbon neutral and has one of the highest efficiencies when compared to alternative fuels.	Global demand for ammonia across multiple sectors can cause scalability issues. Ammonia has a high production cost and is highly toxic, requiring special storage and safety measures.
Methanol	🟢	🟢	🟢	🟡	🟢	ICE FCs	Currently used in a multitude of sectors and can be implemented within the shipping sector with relative ease. Using e-methanol and bio-methanol is 100% renewable.	Difficulties in acquiring sustainable and cost-effective carbon sources. Green methanol has high production costs.

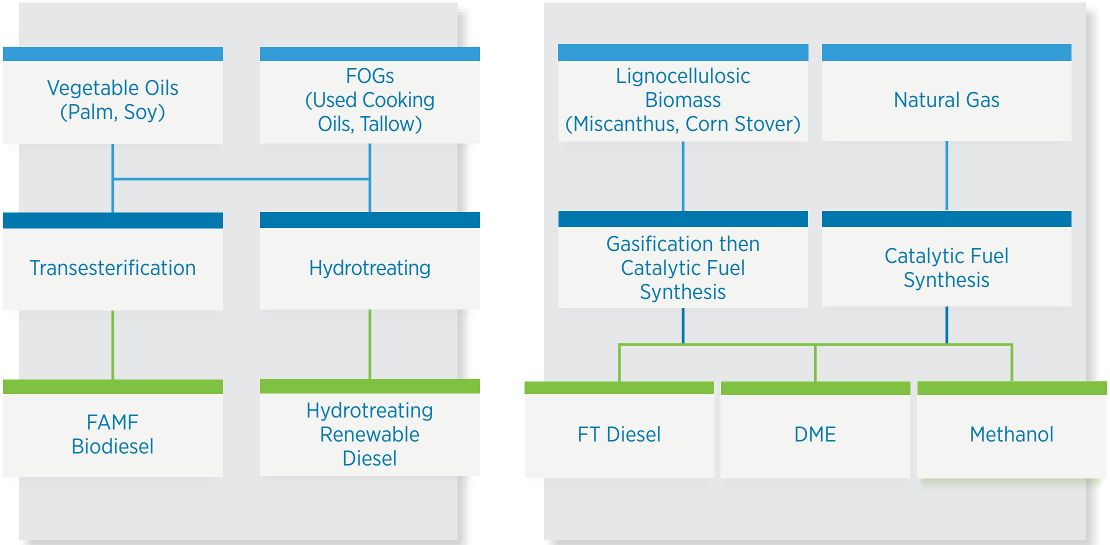
Note: An overview of engine technology, including Otto and Diesel cycles, can be found in Annex C.

LIQUID BIOFUELS

There are two approaches to harnessing liquid biofuels. One requires blending first-generation biofuels with existing fossil fuels to mitigate a percentage of emissions. However, using first-generation biofuels may result in sustainability issues, *e.g.* food and land security issues. The other route involves harnessing second-generation liquid biofuels as a replacement for current conventional shipping fuels because they provide the highest reductions in GHG emissions (Fraunhofer, 2020). The life cycles of liquid biofuels are an important consideration, because certain feedstocks may have the potential to produce similar amounts of GHG emissions as MGO – for example, first-generation feedstocks such as palm and soy oil. Biofuels produced from second-generation feedstock are therefore the optimal alternative, as they have a 70-100% reduction in life cycle GHGs compared with MGO (ICCT, 2020). The International Council on Clean Transportation (2020) has identified five of the most viable liquid biofuels in terms of life cycle GHGs. This has been reiterated by Det Norske Veritas Germanischer Lloyd (DNV GL, 2019b, 2020e). These are fatty acid methyl ester (FAME) biodiesel, hydrotreated vegetable oils (HVOs), Fischer-Tropsch (FT) diesel, dimethyl ether (DME) and bio-methanol (discussed in the section on methanol). Figure 13 depicts the different pathways each liquid biofuel can take in terms of feedstocks and production process.

Biofuels produced from second-generation feedstock are an optimal alternative

Figure 13 **Differences in feedstock and production methods for alternative liquid fuels**



Technological readiness of fuel and engine

FAME is a popular biodiesel due to its shared similar properties with fossil fuel diesel. This form of biofuel is produced from fats, oils and greases (FOGs) that are recycled from waste, which can come from a wide range of sources such as food production waste from factories, restaurants and households, or oil seeds such as rapeseed and palm seed (ETIP, 2020). At the current state of the technological readiness, fuel blends of up to 20% do not require any engine modification in a ship (ICCT, 2020). However, if used as a drop-in fuel,[5] furthermore, additives are required in the fuel system to prevent bacterial growth and lower pour point. To date, only trials have been completed using FAME blends, with a maximum of 30% being used by a vessel funded by the Mediterranean Shipping Company (Biofuels International, 2019). Also important to note that 100% methanol engines are a proven technology; hence, new ships can easily rely 100% on biofuels.

From a current technological standpoint, HVO can be used as a drop-in marine fuel or a blend with zero engine or fuel system modifications (Fraunhofer, 2020) (ICCT, 2020). HVO faces issues similar to those with FAME in terms of having high life cycle emissions from producing HVO from virgin vegetables oils, such as rapeseed. The most viable feedstock option for this type of biofuel is waste FOGs. However, HVO differs in blend capability with the opportunity to fully replace heavy fuel oil. This technology is still in development, so there are limited practical instances where this fuel has been used. HVO requires no modifications to engine systems, making it the ideal drop-in fuel to negate GHG emissions produced by ships.

FT diesel is at a lower level of technological readiness than FAME and HVO because it uses a complex form of production through the FT reaction. The feedstock used by this fuel is lignocellulosic biomass, such as dry plant matter that can be found as an agricultural residue, or naturally found (Van Vliet, Faaij and Turkenburg, 2009). This form of biofuel uses non-food feedstock that is more available than waste FOGs, making this a viable fuel for the longer term. FT diesel can be used as a drop-in fuel mitigating significant emissions and has 100% compatibility with current engines (ICCT, 2020). This technology is still in development, so there are limited practical instances in which this fuel has been used.

DME can be produced either by gasifying solid biomass feedstock to syngas or by reforming biomethane to syngas followed by gas cleaning and catalytic DME synthesis. Another potential for DME production is through the use of electrolysis; however, this method is currently costly and still under research development. DME fuel has been tested on a vessel at a 40% blend, but the ship required specific modifications for the use of DME due to the low flash point. Currently, there are no commercially available examples of DME being used as a marine fuel because the technology is still under development (ICCT, 2020).

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[5] *Drop-in biofuels are alternative biofuels with properties very similar to gasoline, diesel, bunker and jet fuels. They can be blended in very high proportions in these fuels or used neat while meeting fuel specifications. Often, minor engine and fuel system modifications may be required (IRENA, 2016, 2020b).*

Table 5 **Potential biofuels for the shipping industry and their viability**

Fuel	Pathway	Feedstock	Compatibility	Feedstock availability	Cost	Tech. readiness	Industry interest
FAME biodiesel	Transesterification	FOGs	1	1	2	2	2
		Vegetable oils		2	2	2	0
Hydrotreated renewable diesel	Hydrotreating	Waste FOGs	2	1	1	1	2
		Vegetable oils		2			0
FT diesel	Gasification then FT synthesis	Lignocellulosic biomass	2	2	1	1	2
		Natural gas			2	2	0
DME	Gasification then fuel synthesis	Lignocellulosic biomass	1	2	1	1	2
		Natural gas		2	2	2	1
	Electrolysis then fuel synthesis	Renewable electricity and CO_2		1	0	1	2
	Gasification, fuel synthesis, methanol reduction	Natural gas		2	1	1	1
Methanol	Gasification then fuel synthesis	Natural gas Biomethane	1	2	2	2	1
		Lignocellulosic biomass		2	1	1	2
	Electrolysis then fuel synthesis	Renewable electricity and CO_2		1	0	1	2

Key: 2 = Good, 1 = Average, 0 = Poor.

Source: ICCT (2020)

Scalability and infrastructure

Existing commercial-scale second-generation biofuel market data is limited, which in turn severely limits estimations of scalability and supply/demand for FAME. Despite this, the infrastructure required for this alternative fuel can rely on existing HFO bunkering infrastructure, making transitioning to this fuel significantly cheaper (EAFO, 2019a). The use of biofuels for the shipping sector, along with most other alternative fuels, will have to compete with demand from other sectors because multiple sectors will require the fuel for decarbonisation purposes, and production may not meet the required demand (Fraunhofer, 2020). This poses a supply issue. FOGs are a limited resource, and to meet future demand, resource availability increases need to be considered (ICCT, 2020). Estimates indicate that for 2020, global HVO production stood at between 6 and 7 million tonnes (Mt). Furthermore, it has been stated that the European Union (EU) has the potential to produce 12 Mt of HVO per annum (EAFO, 2019a).

Due to HVO demand in multiple sectors, mainly the transport industry, the supply infrastructure requires further development to sustain ample fuel supply to the shipping sector. FT is a viable fuel for future endeavours as this fuel uses non-consumable feedstock that is more widely available than other biofuel feedstocks (DNV GL, 2019c). This process can also use natural gas (NG) as a feedstock. However, this would nullify all carbon reductions achieved by this process, thus making NG unfeasible (ICCT, 2020). Supply would suffer from the same issues that HVO and FAME biofuels have, wherein the demand across multiple sectors could possibly be higher than a feasible supply output. DME is commonly used to replace propane in liquefied petroleum gas (LPG), so current LPG shipping infrastructure can be used for DME (EAFO, 2019b).

Box 1 Ocean Network Express conducts successful trial of sustainable biofuel for decarbonisation

Biofuel storage

Source: GoodFuels (2021)

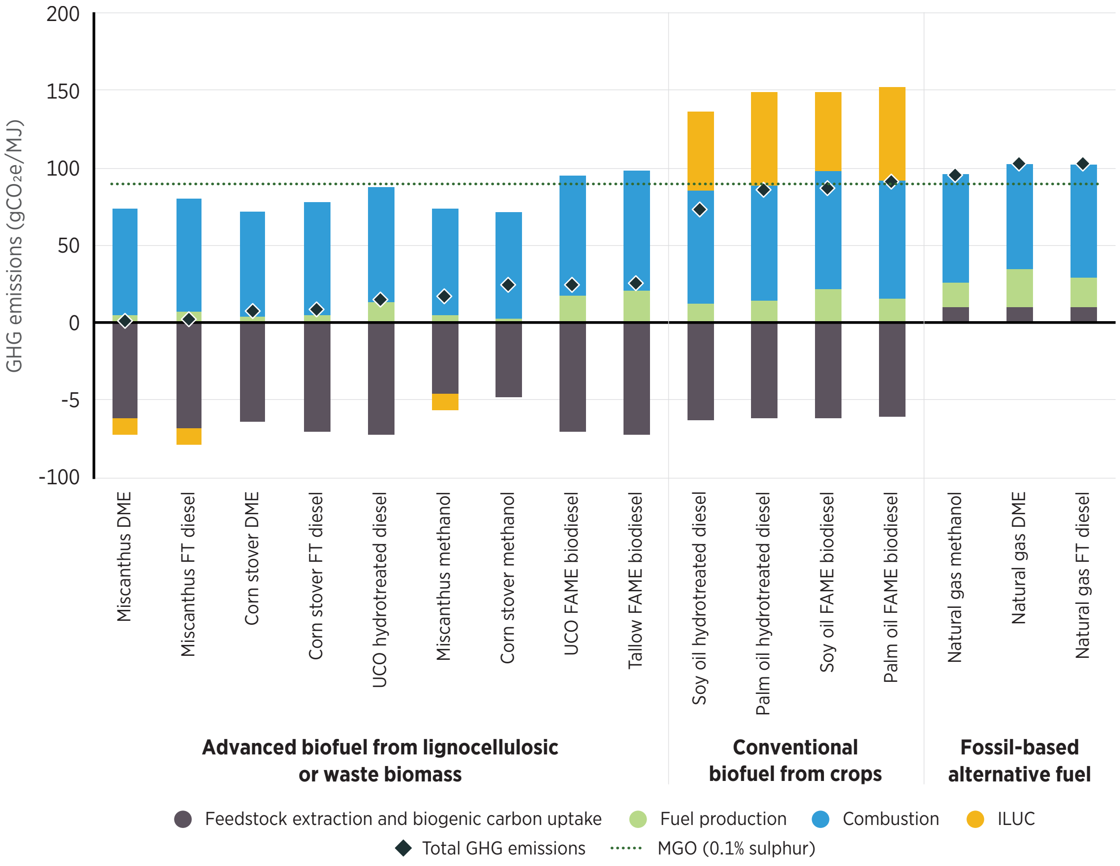
On 7 February 2020, Ocean Network Express announced the completion of a successful trial using biofuel to power a vessel called the M/V MOL Experience. The trial involved the ship bunkering in the Port of Rotterdam in November 2020 and travelling from Europe to the United States across the Atlantic Ocean (GoodFuels, 2021). The project was a collaboration between the shipowners, Mitsui O.S.K Lines, and sustainable biofuel producer GoodFuels. The biofuel used was blended with conventional fuel, allowing the vessel to make the long journey across the Atlantic (GoodFuels, 2021). This is a significant endeavour that proves the viability of sustainable biofuels as a fuel alternative for the shipping sector. The biofuel used, developed by GoodFuels, is essentially free from sulphur oxides (SOx) and has an 80-90% reduction in life cycle CO_2 in comparison to conventional fossil fuel equivalents. Various countries in Asia are supporting research into biofuel use in ships and bunkering solutions. For instance, the Maritime Port Authority of Singapore in 2017 supported a biofuel pilot study being carried out by the United Kingdom-Australian mining company BHP (Argus Media, 2020a).

Fuel characteristics and other key considerations

FAME diesel has an estimated energy density ratio of 90% compared with fossil diesel, making it a viable choice as a fuel alternative (ETIP, 2020). FAME diesel derived from oil seeds is not feasible because the seeds undermine emissions savings due to indirect land-use change (ILUC) effects. This makes FAME diesel from FOGs the more viable choice. In comparison, HVO has reduced nitrogen oxide (NO_X) emissions than those of FAME biodiesel (Biofuels International, 2020). FT diesel is considered a lower carbon emission fuel that has minimal to zero life cycle impacts from land use (ICCT, 2020). FAME's energy density is equivalent to 32.7 gigajoules (GJ)/m^3, which is marginally lower than MGO at 36.6 GJ/m^3 (TFZ, 2020). HVO on the other hand has a slightly higher density at 33.8 GJ/m^3, with FT diesel sharing the same energy density (Neste, 2020a, 2020b). DME is currently produced using NG, which has a higher potential for GHG emissions than MGO. To nullify GHG emissions, lignocellulosic feedstocks are used instead of NG, making DME a potential alternative shipping fuel (ICCT, 2020).

However, DME has the lowest energy density in comparison with other liquid biofuels at 21.24 GJ/m^3. Among biofuels, there are various degrees of emissions released dependent on which feedstocks are used. Figure 14 shows that advanced biofuels (those that use second-generation feedstocks) produce overall lower life cycle emissions than first-generation feedstock biofuels. Indeed, all biofuels negate emissions compared with conventional fuels such as HFO, LNG and MGO, while FAME, HVO and FT have similar energy densities to these fuels.

Figure 14 **Comparison of life cycle GHG emissions associated with different biofuels**



Note: gCO$_2$: grams of CO$_2$ equivalent

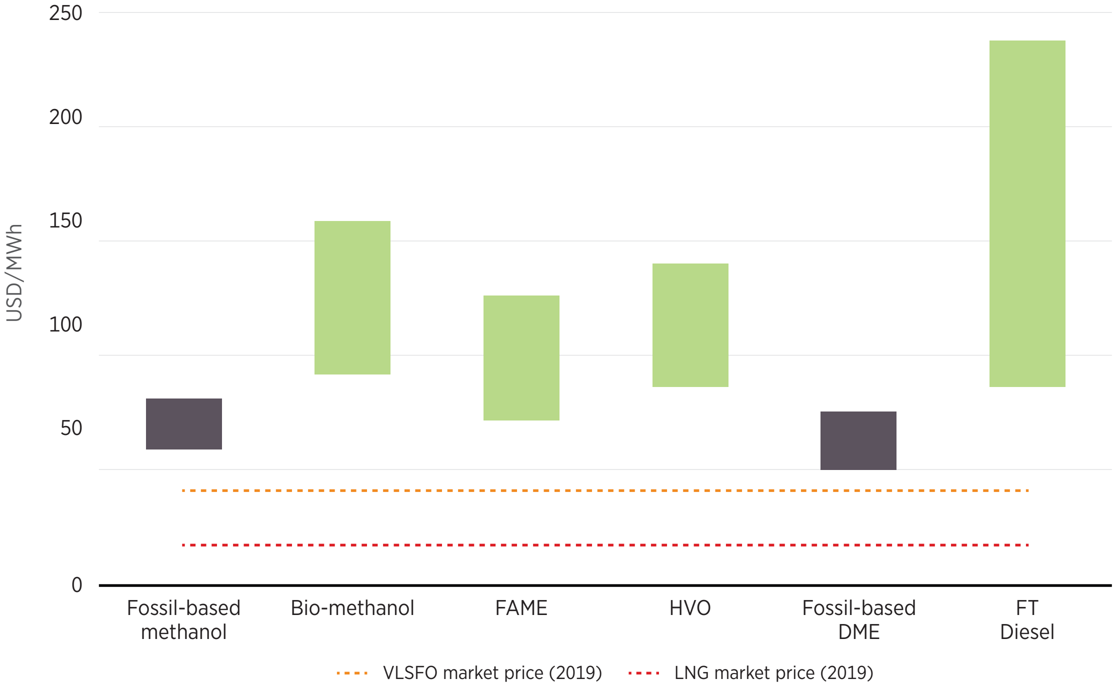
Source: ICCT (2020)

Costs

A recent analysis from ICCT (2020) indicated that current costs for advanced biofuels vary widely. FT diesel costs between USD 86.5/MWh and USD 237.6/MWh, whereas FAME biodiesel fluctuates depending on the location and feedstock end price. Overall, FAME biodiesel production costs are between USD 72/MWh and USD 126/MWh. The latter cost range compares with HVO costs, *i.e.* between USD 86.40/MWh and USD 140.40/MWh, and bio-methanol, *i.e.* USD 57.89/MWh and USD 139.30/MWh (IRENA, 2021). Most biofuels fall between similar ranges, with the exception of FT diesel because of its relatively new technological status.

Biofuel costs are highly reliant on the feedstock used, its availability and the eventual size of the biofuel plant. In contrast to the renewable liquid fuel options, DME appears to be cost competitive, ranging from USD 50.40/MWh to USD 75.60/MWh (ICCT, 2020). However, current DME production is predominantly dependent on NG and coal. Therefore, while DME costs are low, they are environmentally unsuitable, and there is a significant lack of costing data for 100% renewable DME.

Figure 15 **Cost comparison of advanced biofuels**

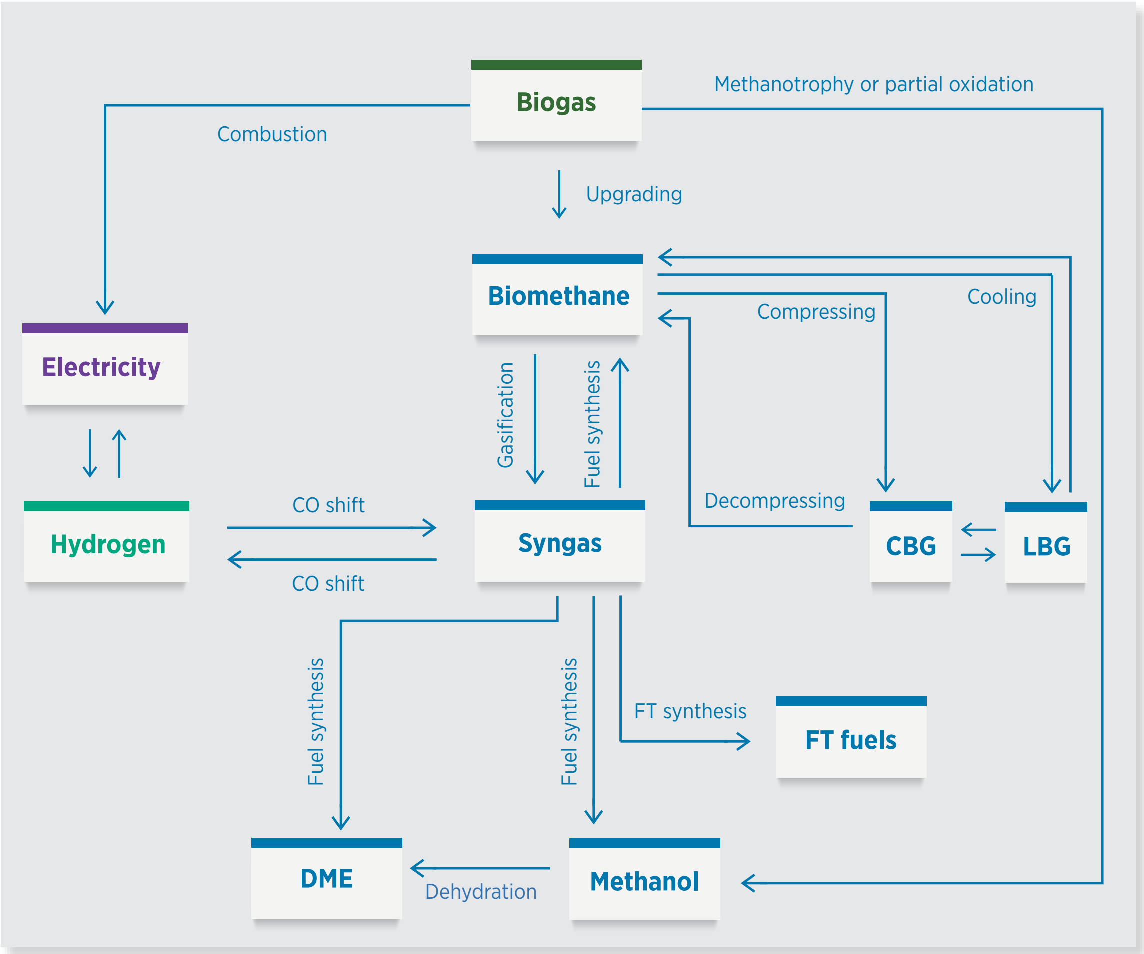


Note: Figure refers to the cost of fuel production. The total cost of ownership (*e.g.* machinery, storage and other) is not captured.
Source: Bio-methanol: IRENA (2021); FAME, HVO, DME, FT diesel: ICCT (2020)

RENEWABLE GASEOUS FUELS

The main forms of renewable gaseous fuels that can be used as ship fuels are compressed biogas (CBG), liquefied biogas (LBG) and synthetic methane from methanation (Dahlgren, 2020). The growth of LNG usage as fuel has increased over recent years due to its wide availability. However, global decarbonisation goals require enormous reductions in CO_2 emissions, and integrating LBG and other renewable gaseous fuels into shipping is necessary to mitigate mass GHG production (IMO, 2020c-d). These fuels are synthesised by upgrading biogas into biomethane and then either cooling or compressing to achieve LBG and CBG. Biogas is primarily produced through anaerobic digestion, which uses waste and biomass from agriculture and livestock. Thereafter, this biogas can be purified, liquefied and used as a blend with LNG, reducing life cycle emissions from the fuel (ITF, 2020). Another potential for renewable gaseous fuel production is the methanation of CO_2 into methane through hydrogenation, which could avoid using biomass as a feedstock.

Figure 16 **Fuels produced from biogas through various methods**



Source: Dahlgren (2020)

Technological readiness of fuel and engine

CBG is made of 97% methane. This fuel is produced by compressing biomethane to 200 bar pressure. CBG requires no modifications to gas engine LNG distribution systems (DNV GL, 2019c), making it a viable drop-in fuel. It can also be blended with compressed natural gas (CNG) (ITF, 2020). LBG is produced by cooling biomethane to -162°C, thus turning the gas into a liquid. Ships that use LNG can switch to LBG as a drop-in fuel with no modifications needed for the fuel and engine systems (ITF, 2020). Both LBG and CBG are produced through biogas from anaerobic digestion of organic matter such as food waste. This method of biogas production is at a high level of technological readiness but is hindered by scalability issues.

Another option is methanation, which comprises the hydrogenation of carbon dioxide and carbon monoxide, resulting in methane. Methane can be used to produce various alternative fuels for shipping, and synthetic methane can be used as a drop-in fuel. Although this option is promising, it is important to note that this technology is still in early experimental stages.

Scalability and infrastructure

CBG has been used in the transport industry in the form of small road transport vehicles and could be viable for vessels travelling shorter distances. This is due to CBG's storage volume being quite large, requiring frequent refuelling stops (Hansson *et al.,* 2019). Compressed biogas at its current stage is viable for use in vessels that travel short distances, but not for deep sea shipping. Limitations on scaling LBG technology into the shipping industry are attributed to the lack of infrastructure required for LBG refuelling (Dahlgren, 2020). Currently, Sweden is one of the largest producers of LBG globally, with the Port of Gothenburg providing LBG bunkering (Offshore Energy, 2019). Moreover, ESL Shipping, based in Finland, introduced the first 100% renewable LBG dry bulk carrier to its fleet (Bioenergy Insight, 2020). Limitations on CBG and LBG occur from the spread availability of organic feedstock, causing supply chain issues. Furthermore, high costs related to the transport of fuels from spread locations reduce the cost effectiveness of CBG and LBG for the shipping sector, making it more economically beneficial for biogas producers to supply biogas for local district heating. The process of methanation on the other hand has higher scalability, as it does not require biomass feedstock, but the need for CO_2 as a feedstock could hinder its practical application. Its low technological readiness is another barrier for this alternative. Therefore, LBG and CBG will have limited potential in the international shipping sector, yet, it will be useful in certain maritime situations. Similarly, methanation may also be subject to scalability issues due to its CO_2 feedstock needs.

Box 2 *Viikki* bulk carrier utilising 100% renewable LBG

One example of LBG use in the shipping industry is the maiden voyage of the *Viikki* carrier using 100% renewable LBG (European Commission, 2020). Produced as a co-project between Sweden and Finland with the aim of decarbonising the shipping sector, the ship is mainly used to transport iron ore for SSAB, a Sweden-based steel company (European Commission, 2020). The *Viikki* was originally designed to use LNG but with limited modifications was fuelled with 100% renewably sourced liquid biogas from Finland-based Gasum biogas manufacturers. The ship, developed by ESL Shipping Oy, is a 25 500 dwt bulk carrier fuelled in Raahe, Finland. ESL estimates that the fuel used in the trial reduced around 85% of life cycle CO_2 emissions in comparison to fossil fuels (Jiang, 2020). The *Viikki* is part of ESL's drive to reduce emissions in the shipping industry with a goal of reaching 50% reduction in CO_2 by 2050 (Jiang, 2020). SSAB appears as a frontrunner in the adoption of biogas in steel manufacturing by 2026, with plans to be fossil free by 2045.

Fuel characteristics and other key considerations

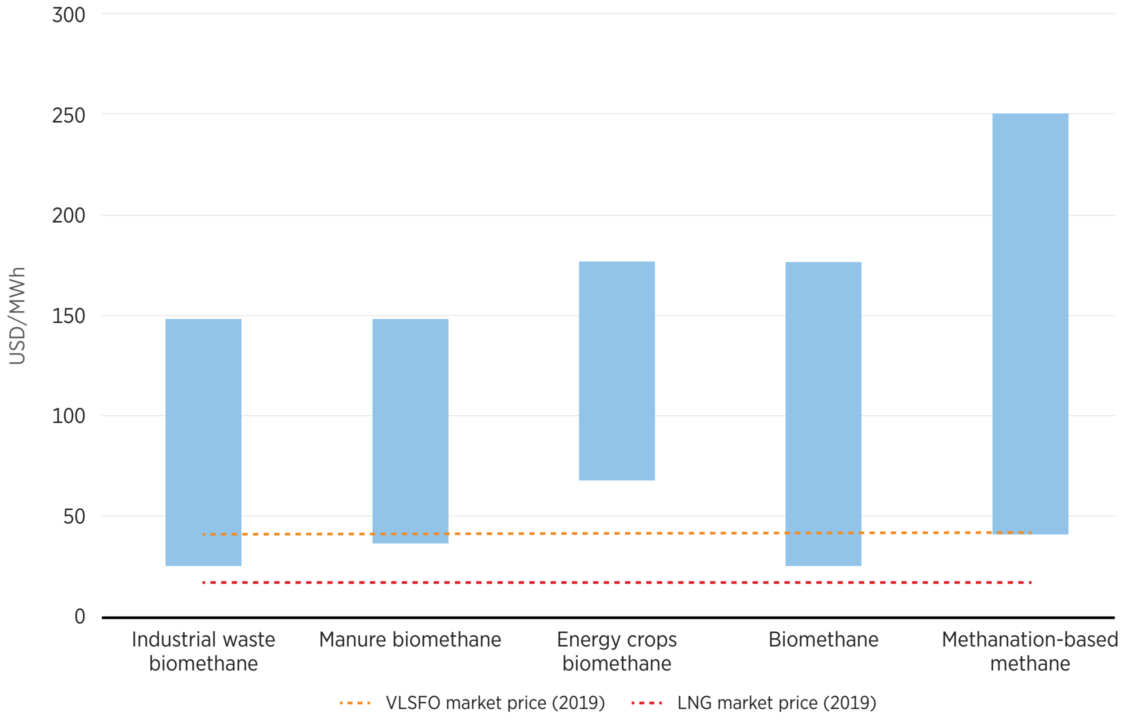
CBG is a replacement for CNG, with a much lower GHG life cycle and net-zero sulphur emissions (ITF, 2020). CBG has an energy density of 7.2 GJ/m^3 in comparison to conventional MGO, which has an energy density of 36.6 GJ/m^3 (Dahlgren, 2020). With the current trend leaning towards using LNG as a replacement for HFO, a further step in decarbonising the shipping industry would be to replace LNG with LBG, as it would mitigate GHG emissions to almost zero (IRENA, 2018). In comparison to other biogas products, LBG has an energy density of 21.2 GJ/m^3.

Methane, on the other hand, has an energy density in a liquefied state of 23 GJ/m^3, making methane the most energy dense of all the gaseous fuels. Methane and LBG have similar energy densities, making them more viable as fuels for long-distance transport in ships. Furthermore, as with biofuels, implementing bioenergy with carbon capture and storage (BECCS) system would help to mitigate further emissions from renewable gaseous fuels.

Costs

Biomethane production from energy crops is estimated at between USD 68.18/MWh and USD 176.36/MWh. Manure biomethane production costs are estimated to be between USD 36.36/MWh and USD 148.18/MWh, and the cost of producing biomethane from industrial waste is between USD 25.45/MWh and USD 148.18/MWh (IRENA, 2018). Production costs are expected to decrease as the demand for more renewable gaseous fuels increases and renewable gaseous fuels are subjected to highly localised costings due to infrastructure, land and feedstock availability. Overall, it is clear that biomethane produced from industrial waste and from manure has a low-cost range that reaches below VLSFO market price, but its utilisation in the shipping sector may be challenged due scalability challenges. Methane produced from methanation is another alternative that may help to tackle scalability issues, but methanation is in the research and development (R&D) phase, and thus there are very few cost estimates for it. Cost estimates range from USD 40.99/MWh (if electricity costs are not considered) to USD 249.88/MWh (at electricity costs of USD 121/MWh). These estimations are based on a continuous operation plant mode throughout the year (Gorre, Ortloff and van Leeuwen, 2019).

Figure 17 **Cost comparison of renewable gaseous fuels**



Note: Figure refers to the cost of fuel production. The total cost of ownership (*e.g.* machinery, storage and other) is not captured.

Source: Biomethane: IRENA (2018); methanation: Gorre, Ortloff and van Leeuwen (2019)

HYDROGEN

As a potential option for alternative fuel for the shipping sector in line with IMO's emission reduction goals, hydrogen (H_2) is one of the most viable fuels in the long term. H_2 can be used in two forms, either in FCs or in ICEs (McKinlay, Turnock and Hudson, 2020). Currently, H_2 FCs are being used across the transport industry, especially in public transport such as buses. For example, in London, Transport for London has begun operating H_2-fuelled double decker buses (GOV.UK, 2020). Since 2009, China has been looking at the use of H_2-fuelled vehicles. In 2016, Foshan City began operating H_2-powered public transport in the first deployment of H_2 infrastructure and vehicles in China (Kendall *et al.,* 2017). H_2 FCs and engines have not yet been scaled up for merchant vessels and are still currently in the development stage, but they were successfully tested for maritime use in 2016 (Shell, 2017).

Globally, H_2 is mainly produced through reforming NG, which produces high quantities of CO_2. This method is known as steam methane reforming, which produces grey H_2. When the CO_2 is captured, it is called blue H_2. Green H_2 produced from renewable energy through the process of electrolysis is the only viable option as an alternative shipping fuel, as it produces net-zero life cycle emissions (DNV GL, 2019c). Avoiding the use of grey H_2 is essential because it is not in line with sustainability goals, it uses non-renewable resources and it is not carbon neutral (IRENA, 2020a-b).

Table 6 **H_2 production methods**

Fossil-based H_2	**Fossil-based H_2 + CCUS**	**Electricity-driven pyrolysis**	**Renewable H_2**
Split NG into H_2 and CO_2 or Produce from coal via partial oxidation combined with carbon monoxide water-gas shift reaction		Use electricity-driven pyrolysis to split methane	Split water into H_2 by hydrolysis powered by renewable energy sources
CO_2 emitted to the atmosphere	CO_2 stored or reused	Solid carbon is produced, not CO_2	No CO_2 emitted

Source: Aurelia (2019)

Technological readiness of fuel and engine

Due to the early design phase for H_2 FCs, current applications can be considered for smaller vessels, such as ferries or passenger ships. Applications have not been scaled for larger merchant vessels (McKinlay, Turnock and Hudson, 2020). H_2 used in an ICE is less mature than FC technology with no established practical examples and is currently in testing levels. Blending H_2 is possible, but the costs of implementing the storage for fuel make it unfeasible for use as a blend (McKinlay, Turnock and Hudson, 2020). Furthermore, using H_2 as a fuel would require a complete refit of ship fuel and engine systems, making its use as a drop-in fuel also unfeasible (McKinlay, Turnock and Hudson, 2020). H_2 as a fuel is more efficient when used in FCs with efficiency levels between 50% and 60%, whereas harnessing H_2 in modified ICEs can result in efficiency levels between 40% and 50% (DNV GL, 2019c). FC technology is currently available, but because the required space for a system is significantly larger than other alternatives, it is best suited to small to medium-sized vessels.

Scalability and infrastructure

Currently, H_2 is used globally mainly to produce ammonia, which is used in the agricultural sector. About 55% of total H_2 usage is accounted for in this process. Therefore, if H_2 and ammonia are to be used as fuel for the transport sector, a significant scaling-up of production levels is required. Some estimates predict a scale-up of three times the current production of H_2 is needed to supply the shipping sector alone with fuel. H_2 has not yet been used commercially in the shipping industry, but there are plans to start using compressed and liquid H_2 in vessels (McKinlay, Turnock and Hudson, 2020). H_2 will play a significant role in the shipping sector in the near future through indirect use, which allows for the development of renewable fuels from green H_2. Direct use through H_2 FCs and ICEs will play a minor role in deep-sea shipping, but there are opportunities to use H_2 in short-distance shipping.

Box 3 Fuel cells

FCs can be used with various fuels, particularly with alternative shipping fuels such as methanol, ammonia and H_2. FCs have the potential to emit zero GHG emissions dependent on the source of electricity used to supply them and the type of carrier fuel used in the FC (EMSA, 2017). Currently, electrical power is used in auxiliary systems on vessels, but the use of electric propulsion has received more interest in recent years. In principle, FCs directly convert chemical potential energy to electrical energy. Unlike conventional engines, FCs are modular in nature, and therefore they can be scaled or descaled depending on a vessel's energy demand (Van Biert *et al.,* 2016). There are several issues to consider with FC use in maritime shipping. However, there are several issues to consider with FC use in maritime shipping. The current early state of FC technology means that compared with other alternative shipping fuel sources, FC volumetric energy density is much lower (EMSA, 2017). Therefore, FCs can be used in short to medium-distance vessels but cannot currently be considered for deep-sea freight. Advancements in this technology could result in efficiency improvements, making FCs a viable option for widescale implementation across the shipping sector, particularly H_2-based FC (Shell, 2017).

There are several different types of FC that have undergone significant research. The most relevant cells for shipping are proton exchange membrane fuel cell (PEMFC), methanol fuel cell (DMFC), molten carbonate fuel cell (MCFC), and solid oxide fuel cell (SOFC) (EMSA, 2017). Among all the different FC types, efficiencies range, on average, between 50% and 60%. However, certain FCs can achieve up to 85% efficiency if heat recovery is introduced into the system (EMSA, 2017). When installing FCs in a vessel, a full overhaul of the engine and fuel systems is required, making it a costly endeavour.

The current aim of the FC industry has been mainly targeted at land freight and the transport sector, with H_2 FC-powered buses operating in various cities, including London (GOV.UK, 2020). In terms of the shipping sector, there has been very limited FC introduction, but various initiatives have been developed with companies such Ballard (Ballard, 2019). FC projects include FLAGSHIPS, which aims to develop and operate two H_2 FC vessels in France and Norway; H2PORTS, which aims to use H_2 FC as an alternative to heavy-duty port equipment; HFC Marine; Shipping Lab Project; and HySeas III project (Ballard, 2019). There is no existing infrastructure for FC in shipping, so significant investment is needed in order to be competitive with other alternative fuels. Furthermore, as FCs use fuel sources such as H_2 and ammonia, scaling this technology is directly impacted by the scaling of the other fuel technologies (EMSA, 2017). However, to be more competitive with other fuel sources, reductions in costs and increases in efficiencies are required.

As there is currently no demand for H_2 in the shipping sector, infrastructure and bunkering for H_2 has not been developed. With future demand expected to grow, there are various plans for green H_2 developments in Australia, Chile, Morocco and Norway (IRENA, 2019b). Furthermore, H_2 production can be scaled up with the increase of renewable energy globally, as excess renewable energy can be electrolysed into H_2. Morocco's potential as a bunkering hub is a vital development in the bunkering of H_2 fuels. This is due to Morocco's vast potential for renewable energy development in the form of solar energy and its strategic location, with access to the Atlantic Ocean and the Mediterranean Sea.

Box 4 Kawasaki Heavy aims to replicate LNG supply chain with H_2

A team led by Japan-based Kawasaki Heavy Industries is developing a pilot project to be the first to ship liquefied H_2 from Australia to Japan. The project, which began operations in March 2021, is backed by the Japanese and Australian governments and has received investments of USD 390 million. This is the first of many H_2 carriers that Kawasaki intends to develop. The company's goal is to have 80 H_2 carriers by 2050 and 2 commercial carriers by 2030 (Obayashi and Shimizu, 2021). In all, 75 tonnes of H_2 will be transported from Australia, the equivalent of filling 15 000 FC vehicles. The H_2 will be frozen at -253°C and will be compressed to 1-800th of its gaseous volume. The major concern of this project is the costs involved. Kawasaki plans to decrease H_2 supply costs by 2030 (Obayashi and Shimizu, 2021).

Fuel characteristics and other key considerations

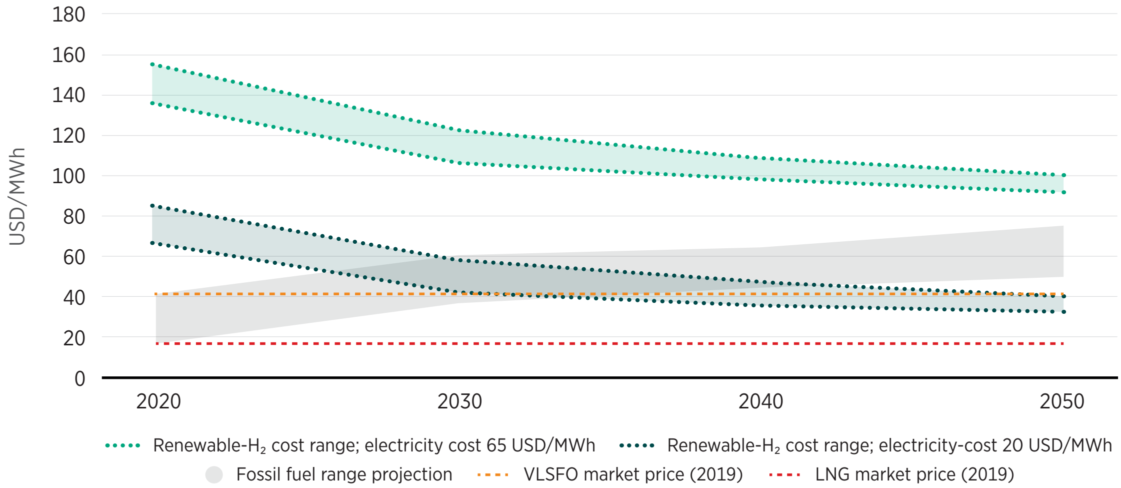
Currently the main method for producing H_2 is through the use of fossil fuels such as coal and NG. To mitigate the emissions from this process, carbon capture, utilisation and storage (CCUS) is employed to extract CO_2 before it can enter the atmosphere (NRCNAE, 2004). Although introducing CCUS to current H_2 production decreases emissions significantly, to reach fully sustainable green production of H_2, water electrolysis powered by renewable energy is the ideal production method for H_2 synthesis. The production of green H_2 through electrolysis differs significantly from the production of H_2 from fossil fuels. Electrolysis uses electricity to separate H_2 and oxygen (O_2) from water, while fossil fuels undergo thermochemical processes such as steam methane reforming (SMR) and autothermal reforming (ATR) (Energy.Gov, 2020a-e). Overall, the production of H_2 via renewable energy sources coupled with water electrolysis appears to be the most suitable path for producing carbon-zero H_2. For more detailed information regarding H_2 and H_2 feedstocks, refer to the IRENA report *Green hydrogen cost reduction: scaling-up electrolysers to meet the 1.5°C climate goal* (2020a).

H_2 as a shipping fuel can be stored either as compressed gas or as a cryogenic liquid, or it can be used to produce e-fuels, *e.g.* e-ammonia or e-methanol. These storage options are expensive and hazardous to maintain because H_2 is easily ignitable and so poses a flammability risk. Specially designed storage options are required for H_2 fuel on ships, as other fuels do not have compatible storage options (McKinlay, Turnock and Hudson, 2020). Storing liquefied H_2 requires temperatures of -240°C at a pressure of 13 bar; where the volumetric energy density of hydrogen is 8.5 GJ per m^3 in liquid state (DNV GL, 2018). Fuel tanks for storing H_2 as a cryogenic liquid would have to be stronger and heavier, taking up more space in a ship and decreasing cargo capacity.

Costs

The main issues with using H_2 as a fuel for ships are the costs associated with engine retrofits, storage on ships and bunkering of H_2 (McKinlay, Turnock and Hudson, 2020). Current green H_2 production costs are estimated at between USD 66/MWh and USD 85/MWh if electricity prices equate to USD 20/MWh. Electrolyser costs are between USD 650/kW and USD 1 000/kW (DNV GL, 2019b-c) (IRENA, 2020a). Considering an electricity price of USD 65/MWh, the cost of green H_2 production was between USD 135/MWh and USD 154/MWh in 2020 (IRENA, 2020a). This cost is relatively high in comparison to the market price of conventional fossil-based fuels. However, IRENA analysis shows that green H_2 production costs will fall progressively. Indeed, the lowest cost range for green H_2 could become more competitive than LNG and VLSFO by 2030. Despite the future competitive costs, green H_2 as a fuel has a lower energy density in comparison to other alternatives, such as ammonia. Furthermore, harnessing H_2 as a shipping fuel requires cryogenic onboard storage and would therefore require additional investment and thorough attention from a safety perspective. Nonetheless, the prospect of cost-competitive green H_2 would result in falling production costs for its derivative fuels, *e.g.* renewable ammonia and methanol.

Figure 18 **Green H_2 cost projections**



Note: Figure refers to the cost of fuel production. The total cost of ownership (*e.g.* machinery, storage and other) is not captured.
Source: H_2: IRENA (2020a); fossil fuel cost projections: Lloyd's Register (2019)

METHANOL

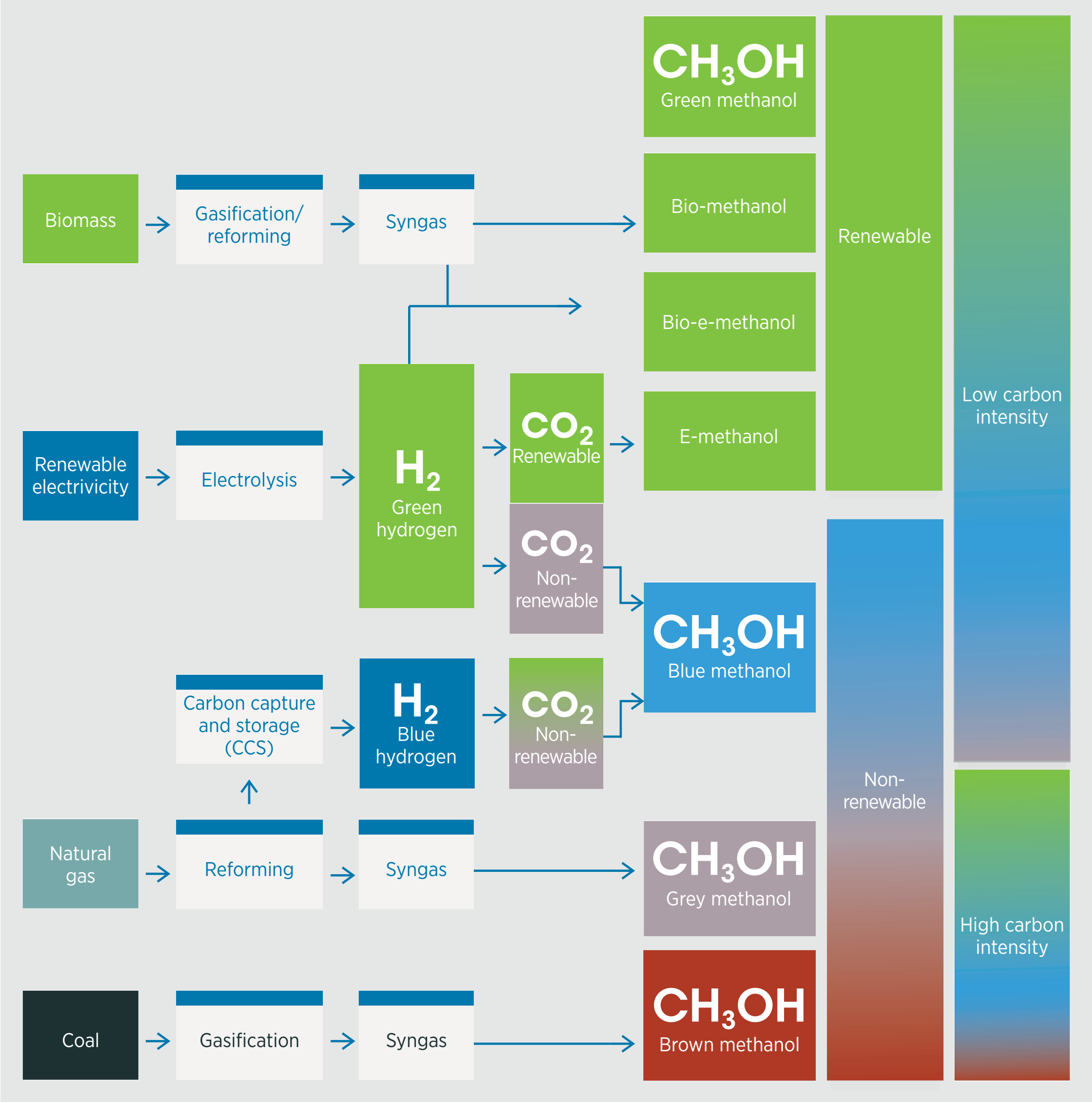
Methanol, widely known as an alternative fuel for shipping, has seen rising interest in recent years. This alcohol has one of the lowest carbon and highest H_2 contents compared to other fuels. Furthermore, methanol reduces emissions of sulphur oxide (SOx), and NOx by up to 60% in comparison to HFO (ITF, 2018), including reductions in particulate matter emissions of 95% (Methanex, 2020).

Currently, most methanol is produced from coal or NG, but methanol can also be produced from lignocellulosic feedstocks such as agricultural waste, from biomass collected from sustainable managed forests to produce bio-methanol, or from gasification of municipal solid waste. Another method is to employ biomethane as a substitute for fossil NG in the production of methanol. Bio-methanol produced from biomethane as feedstock can be certified under the International Sustainability and Carbon Certification (ISCC) scheme. Methanol can also be produced utilising CO_2 acquired through CCS and the use of renewable energy supplied electricity, but it is still not renewable as it requires NG (ICCT, 2020). As with most alternative shipping fuels, methanol can be used in two forms, in an ICE or as a H_2 carrier for FCs. Utilising methanol as a maritime fuel source benefits from an existing infrastructure for transport and storage (Methanex, 2020). In comparison to HFO, methanol produced from NG is estimated to emit 25% less CO_2. However, when considering the life cycle of both HFO and methanol from NG, methanol is estimated to have 10% higher GHG emissions than HFO (Balcombe *et al.,* 2019). Therefore, it is imperative to introduce green methanol production to produce e-methanol and bio-methanol, which are fully renewable and the most sustainable options.

Technological readiness of fuel and engine

Methanol can be used today as a ship fuel in an ICE. Currently, methanol can be used in two types of ICEs, in four-stroke and two-stroke engines, and this technology is quite well developed (DNV GL, 2019b). Many commercial ships have been retrofitted with methanol engines. These engines have been installed in eleven new chemical tankers operated by Waterfront Shipping, Marinvest and MOL, with another eleven on order. These vessels are dual-fuel methanol engines with 10 megawatts (MW) of total power. Other commercial examples include Stena Lines' *Stena Germanica*, which was retrofitted with a dual methanol/diesel engine and has a total energy output of 24 MW (Ming Liu, 2019). In total, there are nine examples of commercial methanol-fuelled ships globally (ICCT, 2020). Further research is being conducted, and the expansion of a methanol-fuelled fleet is planned in the near future to target GHG emission reduction goals by 2050 (Balcombe *et al.,* 2019). Despite the success of using methanol fuel in ship engines and its commercial availability, the technology is still in development (Ming Liu, 2019), and existing vessels are required to replace fuel injectors and the fuel supply system. In terms of the engine itself, newly developed two-stroke engines made by well-known engine manufacturers can operate perfectly with methanol.

Figure 19 **The methanol production process**



Source: IRENA (2021a)

In the production of methanol, there are multiple pathways. The current method of producing methanol uses coal, which is referred to as brown methanol, and NG, referred to as grey methanol (IRENA, 2021a). These production methods are the most carbon intensive and are not sustainable for the future of methanol production. The ideal production method for methanol is green methanol production, which is split between e-methanol and bio-methanol. E-methanol is produced from sourcing H_2 from electrolysis powered by renewables and utilising renewably sourced CO_2 from BECCS and direct air capture (DAC) (IRENA, 2021a). Bio-methanol is produced using biomass gasification and reformation. The feedstock for this method is usually forestry and agricultural waste and by-products, biogas from landfill, sewage, municipal solid waste, and black liquor from the pulp and paper industry (IRENA, 2021a).

Scalability and infrastructure

Current estimates calculate that the methanol produced globally equates to 98 Mt across over 90 different methanol plants (IRENA, 2021a). This industry is well established and is estimated to generate USD 55 billion in economic activity per annum (Methanol Institute, 2020). The current uses for methanol are mainly for formaldehyde synthesis, which accounts for 25% of global methanol usage (DNV GL, 2019b). Other uses for methanol include the production of olefins used in making plastic products, methyl tert-butyl ether/methyl tert-amyl ether (MTBE/TAME), fuel production such as blending for gasoline, and DME (IHS Markit, 2019). With increasing amounts of methanol fuel being introduced to the shipping industry, supply will likely increase to achieve this rising demand (ICCT, 2020). According to Ming Leu *et al.,* (2019), if methanol was used to replace 50% of the world bunker demand, 328.9 Mt of global methanol production would be required, about triple the current global production of methanol. This is a massive scale-up from current production levels, which would require about 22.6 million hectares of agricultural land equivalent to 0.46% of total global agricultural land use (Ming Liu, 2019). This would require major scaling of the methanol production industry to meet demand for methanol across various sectors, including transport other than shipping.

Utilising methanol as a shipping fuel benefits from a well-established transportation and distribution infrastructure. Furthermore, methanol bunkering does not require special storage, as the fuel is compatible with fossil liquid fuels, and methanol is a liquid at ambient pressure and temperature. However, one of the main issues with methanol scalability is the acquisition of cheap and renewable carbon sources for the production of e-methanol. From a technical standpoint, e-methanol is a feasible fuel for the shipping sector due to the limited engine modifications required. However, there are challenges from an economic standpoint. From an operating expense perspective, the feedstock of renewable electricity is the main challenge, and from a capital expenditure perspective, the investment linked to the electrolysis itself is a challenge. Yet these latter factors represent a challenge for all renewable e-fuels. Particularly in the case of e-methanol, the key challenge is acquiring sustainable carbon capture, which is costly and adds to the final costs of e-methanol. Bio-methanol on the other hand relies on mature gasification technology but may be limited by the availability of biomass resources and the ability to scale-up production via this thermochemical route. Despite these challenges, it is important to mention that key players in the shipping industry including Maersk are devoting important resources to and testing the potential of renewable methanol via a pilot project with one of the first renewable methanol vessels, expected to be ready in 2023.

Using methanol as a shipping fuel benefits from a well-established transportation and distribution infrastructure

Fuel characteristics and other key considerations

Methanol's storage temperature varies between -93°C to 65°C, making it significantly cheaper to store and transport than other fuels such as H_2, ammonia and LNG. Energy density is a main concern with methanol as it has a volumetric energy density of 15.8 GJ/m^3. In comparison, LNG has a density value of 23.4 GJ/m^3 and MGO has more than double the energy density of methanol at 36.6 GJ/m^3 (Ming Liu, 2019). Due to this, storage options and fuel tanks for methanol are about 2.5 times larger than MGO (DNV GL, 2019c). Therefore, when using methanol as a fuel, ships are required to double their fuel storage volume, which limits the space that can be used for cargo (Ming Liu, 2019). However, in comparison to fuels that require onboard cryogenic storage, methanol provides more flexibility because it requires a single storage tank. Methanol can use slop tanks, ballast tanks and double hulled bottoms (ABS, 2021). Indeed, despite methanol possessing a lower energy density compared with other fuels, it benefits from one of the highest EE rates, 70%, in the production stage of the fuel. When storing methanol fuel onboard, additional monitoring systems are required that conventional fuel storage systems do not require. Fire detection systems are required, because when methanol is ignited, its invisible flame poses a possible risk (IMO, 2016). Safety considerations when employing methanol onboard comprise methanol tank location and its protection, methanol tank venting, spill containment, and vapor and fire detection (ABS, 2021).

Box 5 Maersk aims for first carbon-neutral container ship in two years

As the world's largest container shipping company, Maersk has a goal of being carbon neutral by 2050. A key project in development is the production of three carbon-neutral container vessels that will be powered by zero-carbon methanol. These vessels are estimated to be completed by 2023, seven years ahead of schedule (Milne, 2021). These vessels will be capable of carrying two thousand 20-foot containers and will be able to run on most carbon-neutral fuels, particularly e-methanol and bio-methanol. The push for carbon-neutral fuels and vessels capable of utilising these fuels comes from pressure on the shipping industry to cut emissions by 2050 (Milne, 2021). According to Maersk Chief Executive Soren Skou, this goal requires that the first carbon-free vessels to be operational by 2030 (Milne, 2021).

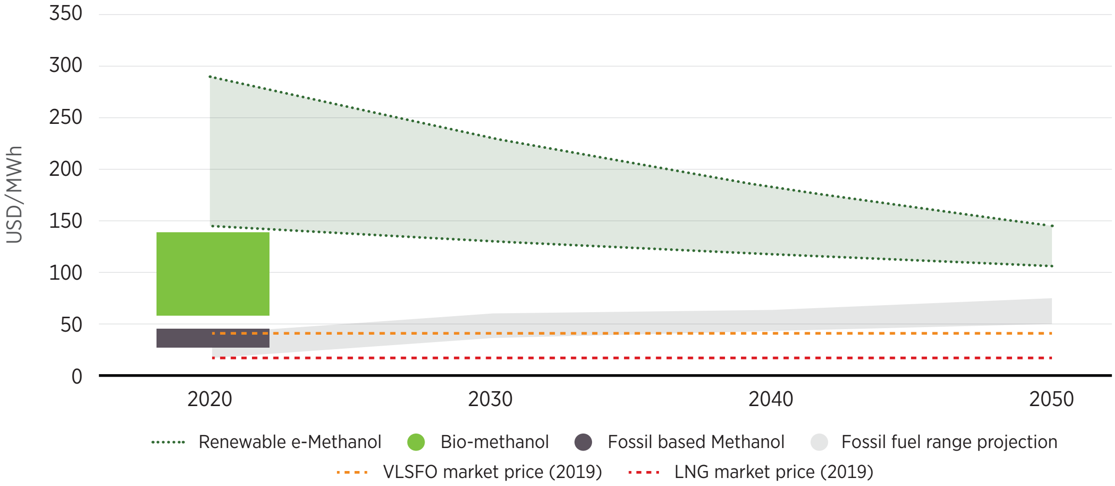
Maersk container Ship

Source: Shutterstock

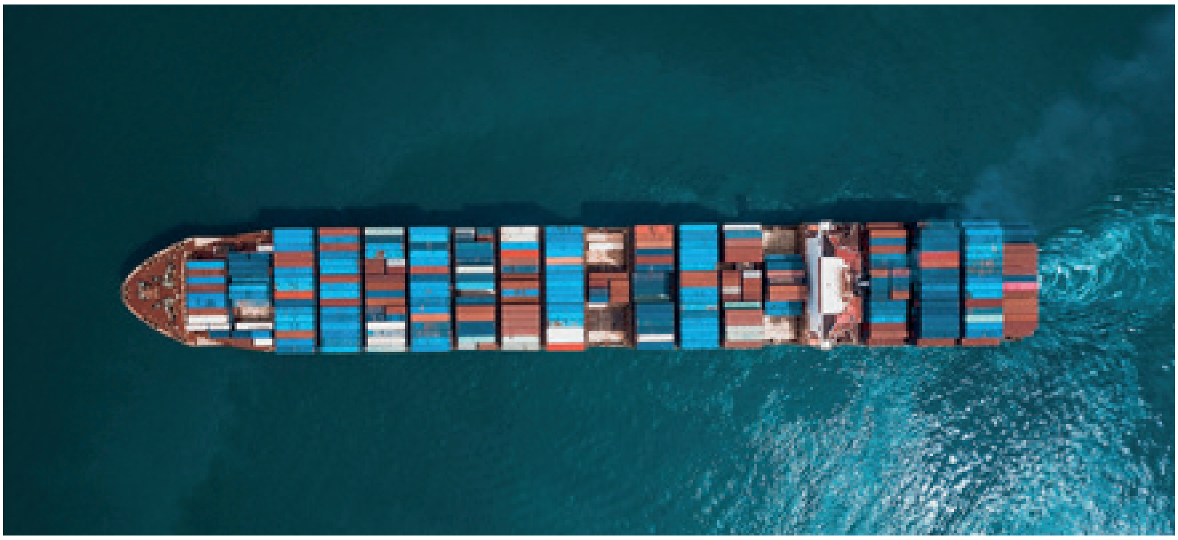
Costs

With the current state of bunkering infrastructure, minimal investment is required to retrofit fuel oil infrastructure to store methanol fuel (Dias *et al.,* 2020). Fossil-based methanol production costs range between USD 18.09/MWh and USD 45.23/MWh, with bio-methanol estimated at USD 57.89/MWh to USD 139.30/MWh, and green e-methanol combined with BECCS estimated at USD 144.72/MWh to USD 289.45/MWh (IRENA, 2021a). While green e-methanol is significantly more expensive than the fossil fuel options, the cost of green e-methanol is expected to fall progressively, eventually achieving a 2050 cost of between USD 107/MWh and USD 145/MWh. The eventual feasibility of deploying e-methanol as a shipping fuel at a large scale is reliant on the development of cheaper production technology for bio-methanol and e-methanol. One of the challenges, particularly with e-methanol, is the need for an external carbon source. Therefore, compared to other e-fuel options, *e.g.* e-ammonia, the future competitiveness of e-methanol depends on the costs of carbon capture and removal technologies.

Figure 20 **Methanol cost projections**



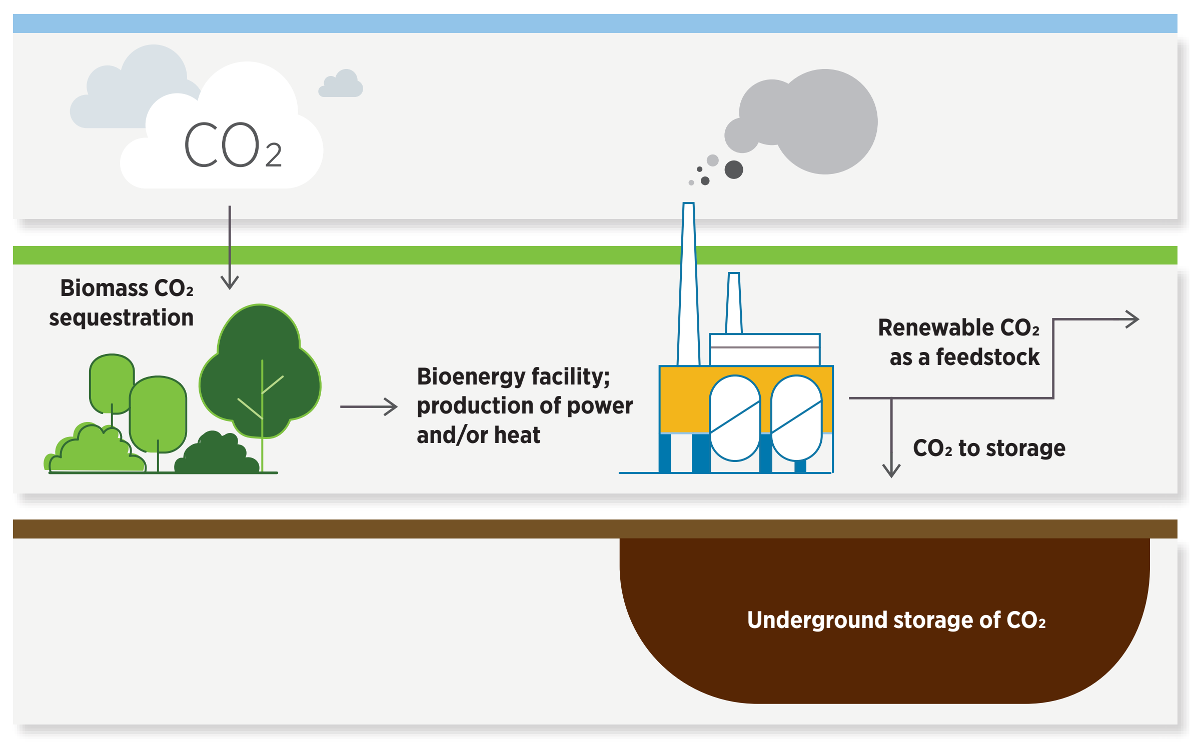
Note: Figure refers to the cost of fuel production. The total cost of ownership (*e.g.* machinery, storage and other) is not captured.
Source: Methanol costs: IRENA (2021); fossil fuel cost projections: Lloyd's Register (2019)



Box 6 Acquiring carbon as a feedstock

The production of 100% renewable methanol is highly dependent on having access to renewable CO_2 sources. In this aspect, CO_2 can be obtained from carbon-intensive industries or the energy transformation process via CO_2 removal measures, including CCUS. Another option is acquiring carbon via DAC. This path involves the capture of atmospheric CO_2, which is then stored and used in different processes. However, DAC requires high amounts of energy to sequester carbon compared to other carbon capture methods. Another route, and indeed the most promising source of carbon, is Bioenergy Carbon Capture and Storage (BECCS). BECCS refers to different technologies under the broader scope of CCUS. This process involves the direct capture and storage of CO_2 during the conversion of biomass into power and heat. Overall, BECCS stands as the most suitable route for acquiring renewable CO_2 and therefore for producing 100% renewable e-methanol. The utilisation of renewable methanol as a fuel in what are considered hard-to-decarbonise sectors, including shipping, will depend on having access to carbon-zero CO_2; hence the relevance of BECCS in the context of producing 100% renewable methanol. Figure 21 shows the most suitable route for acquiring CO_2 for its further utilisation as a feedstock for producing renewable methanol.

Figure 21 **Biomass sequestration combined with bioenergy production plus carbon storage and utilisation**



In the broader global context and as presented in IRENA's *World Energy Transitions Outlook* (2021b), BECCS is expected to play a pivotal role in achieving the Paris Agreement goals and halting the pace of climate change by transforming the global energy landscape.

AMMONIA

One of the most promising alternative shipping fuels is carbon-free ammonia ("green ammonia"), widely touted as a means to achieve IMO's GHG emission goals (Kim *et al.,* 2020). Recent studies have shown that ammonia produced through electrolysis sourced by renewable energy will be highly beneficial in the efforts to achieve deep decarbonisation of the shipping sector. However, vessel engines operating on renewable energy ammonia still require small amounts of a pilot fuel to combust, so it is important that the pilot fuel also be carbon zero (Ash, 2019).

Ammonia has various advantages compared to other alternative fuels. These include an existing logistical infrastructure with no need for cryogenic storage. In addition, ammonia is more energy dense in liquid form than other green fuels (Ash, 2019).

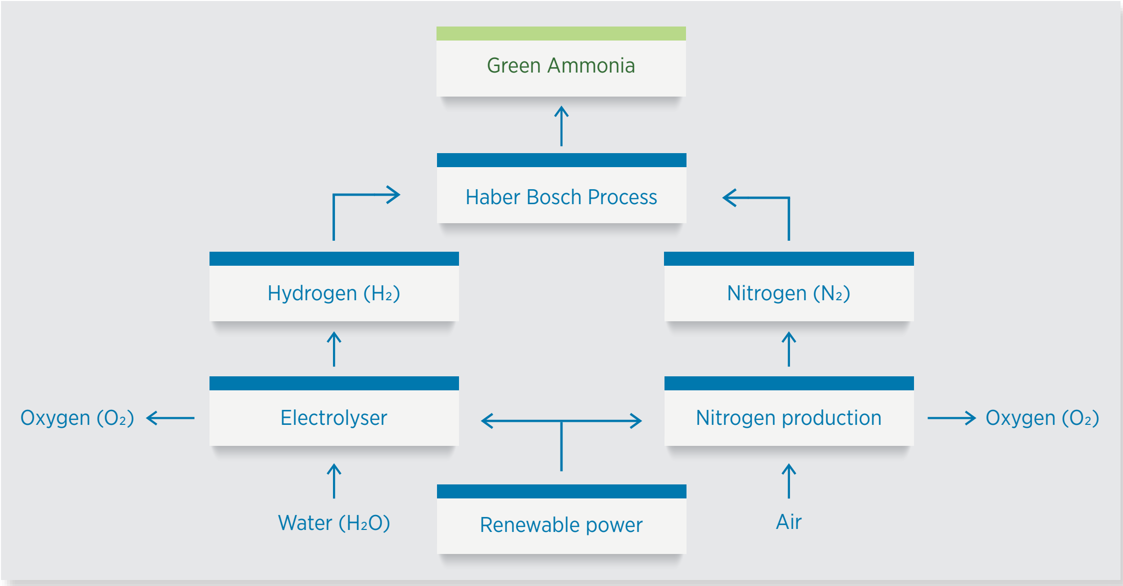
Currently, ammonia is produced through the use of NG, producing large quantities GHG emissions throughout its life cycle. Therefore, employing renewables is the only viable option for producing carbon-free ammonia (Lewis, 2018). Ammonia is created through the Haber-Bosch process, which uses H_2, and is further used as a feedstock for agricultural products, mainly fertiliser (Siemens Energy, 2020). Future planning has begun to scale-up ammonia production to supply the transport sector with fuel. However, with high demand for ammonia, scaling-up faces difficulties. Ammonia becomes liquid at a more ambient temperature than H_{2-} fuel (ammonia becomes liquid at -32°C while H_2 fuel becomes liquid at -253°C) and therefore is easier to store and transport. As with H_2, there are two ways of utilising ammonia as a fuel, in a FC or in an ICE (DNV GL, 2019c). Similarly, production of ammonia through the use of NG with CCS can provide reduced emissions. However, this is not as effective in mitigation as producing ammonia through renewable energy input (Ash, 2019).

Technological readiness of fuel and engine

Current technology levels of both ammonia fuel applications, FCs and ICE, are still in the development and research stages, with few real-world applications in the shipping industry at present (Siemens Energy, 2020). However, the technology for creating ammonia through the use of the Haber-Bosch process is well established (DNV GL, 2019c), including the integration of electrolysers for utilising renewable energies in ammonia synthesis. In terms of ICE, current testing is undergoing in organisations such as MAN Energy solutions, Wärtsilä, Japan Engine Corporation (J-ENG), IHI, CSIRO and Siemens Energy with positive results (Ash, 2019). Another example of ammonia propulsion is direct combustion in a gas turbine, but gas turbines in ships tend to operate at lower efficiencies compared with ICE engines (Ash, 2019). Engine and fuel system modifications are also necessary if using ammonia (DNV GL, 2019c) (Ash, 2019).

Japan and South Korea have a high interest in the development of ammonia-based engines. J-ENG worked in tandem with the National Maritime Research Institute during the second half of 2019 to research ammonia-based engines, including H_2 options. In South Korea, companies such as Daewoo Shipbuilding & Marine Engineering Co., Ltd have devoted significant R&D to developing ammonia engines, as well as Hyundai Mipo Dockyard (Brown, 2019) (Hellenic Shipping, 2020b). Future developments of ammonia engines will see widescale deployment in the forms of dual-fuel and ignition-based engines in the effort to decarbonise the shipping sector.

Figure 22 **Renewable e-ammonia production process via Haber-Bosch process**



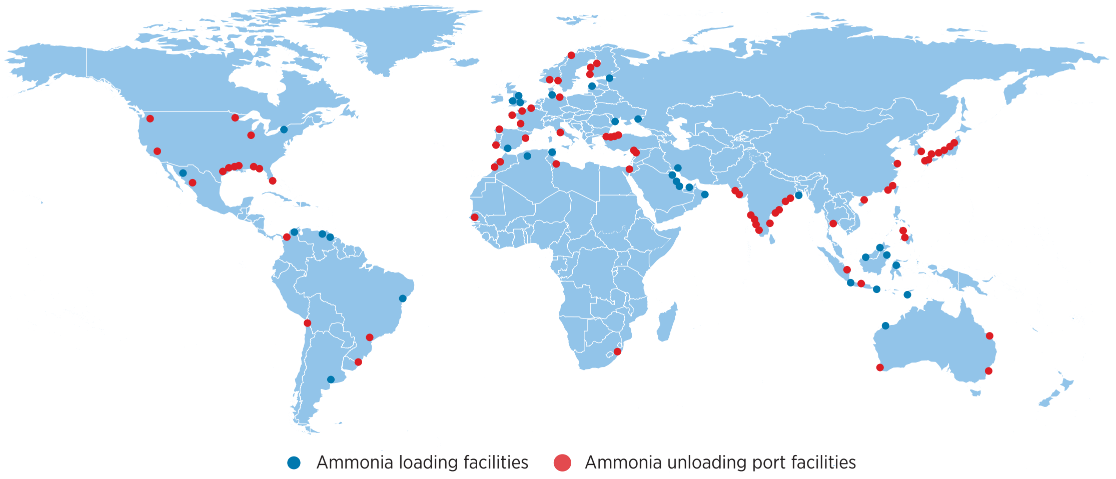
The current and future technology of ammonia fuel exists in three generations (MacFarlane *et al.,* 2020). Generation 1 ammonia production refers to the use of CCS, or carbon sequestration, to lower the overall carbon emissions to net zero. This is commonly referred to as “blue ammonia” as it still uses NG, and is therefore considered a transitional generation to establish supply and demand for ammonia fuel (MacFarlane *et al.,* 2020). Generation 2 ammonia refers to using renewable energy to supply green H_2 for the Haber-Bosch process, and thus it does not result in any carbon emissions throughout its life cycle. This is a long-scope generation in terms of the ammonia economy, which is hindered by current investment in production and long development times for the necessary facilities (MacFarlane *et al.,* 2020). This is the current ideal source of ammonia fuel for the shipping industry, and its process is portrayed in Figure 22. Generation 3 ammonia technology is currently under research. It does not use the Haber-Bosch process, but rather uses the method of electroreduction of nitrogen into ammonia. The production of ammonia through the use of electrochemical nitrogen reduction reaction has the potential for higher EE than Generation 2 production (MacFarlane *et al.,* 2020). Both Generation 2 and 3 ammonia production are considered green; therefore, both are viable options for the future of the ammonia economy.

Scalability and infrastructure

The global ammonia industry produces an estimated 180 Mt of ammonia annually (Argus Media, 2020b), of which 80% is used by the agricultural sector for fertiliser (DNV GL, 2019c). Current production of ammonia is mainly based in China, Eastern Europe, Southwest Asia and North America, with China producing the largest amount of ammonia at 32% (DNV GL, 2019c) (IHS Markit, 2020). In China, the main resource used for ammonia production is coal, whereas NG is used in the rest of the world. Currently, there are no commercial applications for ammonia as a fuel in the shipping sector. There is however great interest in its potential as an alternative fuel, with large investments from South Korea totalling USD 870 million going toward developing greener shipping solutions with a focus on ammonia (The Maritime Executive, 2020a). Ammonia has existing infrastructure in terms of transport and handling, lending it an advantage over other alternative fuels such as H_2 (Lewis, 2018). Furthermore, there are established ammonia terminals across the world, with infrastructure in Japan, the United States, Europe and along the predominant maritime routes, as seen in Figure 23.

As with H_2 fuel, ammonia production can be scaled with the use of renewable energy globally, allowing renewable energy to supply ammonia production. Furthermore, as ammonia production through the Haber-Bosch process is well known, ports with ammonia bunkers have the potential to produce their own fuel if adequate energy is available, either from grid-supplied renewable energy or off-grid renewable energy (DNV GL, 2019c) (Ash, 2019). The forthcoming IRENA report *Renewable ammonia: Production, market status and future prospects* (2021) presents a comprehensive list of the upcoming renewable ammonia projects across the world. Indeed, the IRENA report finds that announced projects for renewable ammonia will total 17 Mt of ammonia per year by 2030 – around 9% of the current global ammonia production of around 183 Mt produced per year. Such a finding denotes important momentum in the industry in moving towards scaling-up renewable ammonia production.

Figure 23 **Ammonia shipping infrastructure including a heat map of liquid ammonia carriers and ammonia loading and unloading facilities**



Source: Rodrigue (2020)

This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Morocco has vast potentials to become a bunkering hub for green H_2, and therefore for renewable ammonia too. Due to its strategic location in the Strait of Gibraltar, it could become a central bunkering hub of global relevance. Furthermore, Morocco has vast potential for renewable energy, with abundant solar and wind sources, and some established hydropower production. Other areas that have significant investment in ammonia projects include Australia, Chile, Denmark, the Netherlands and New Zealand, which use solar, wind or a mix of renewable energy sources.

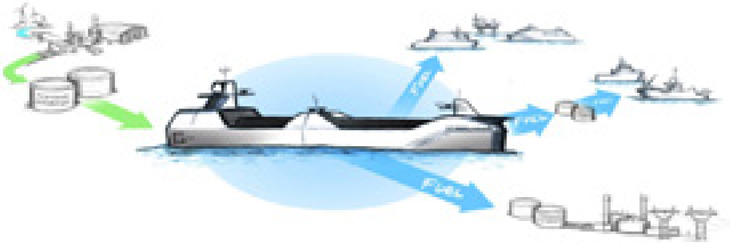
Box 7 Projects advancing ammonia use in the shipping sector

Japan pushes ahead with ammonia as a shipping fuel of the future

Japan plans to use ammonia commercially as a fuel for shipping to achieve its decarbonisation goals by 2050 (Ovcina, 2020). This is in addition to the country's use of ammonia as a fuel mix for thermal power generation. Ryo Minami, director-general of oil, gas and mineral resources at the Ministry of Economy, Trade and Industry, expects ammonia to be used as a commercial fuel for the shipping and thermal power generation sectors in the late 2020s and to be in widespread use by 2030 (Ovcina, 2020). Japan's plans involve collaboration with resource-rich countries such as Australia as producers of H_2 and the use of this H_2 in ammonia production (Harding, 2020).

Wärtsilä and Grieg to build ground-breaking green ammonia tanker

In the framework of the Zero Emission Energy Distribution at Sea (ZEEDS) initiative, Wärtsilä and Grieg Edge are running a joint project aimed at developing the first green ammonia tanker to produce no GHG emissions by 2024. This project has support from the Norwegian government in the form of USD 5.34 million. The ammonia is expected to be supplied by a planned green ammonia plant in Berlevåg, Norway (Wärtsilä, 2020a, 2020b). Norway has the largest number of vessels capable of using alternative fuels and high volumes of renewable energy sources, providing the perfect conditions to produce the world's first green ammonia market, according to Vidar Lundberg, chief business development officer at Grieg Star Group (Wärtsilä, 2020a, 2020b).



Proposed ammonia vessel
Source: Wärtsilä (2020a)

NYK and China Merchants launch initiatives to commercialise ammonia

Further initiatives for the advancement of ammonia in shipping come from a Japanese group led by NYK that intends to speed up the commercialisation of ammonia in the shipping industry by developing an ammonia-fuelled ammonia gas carrier (The Maritime Executive, 2020b). The other companies involved in this initiative are Japan Marine United Corporation and ClassNK. This project also includes the development of ammonia floating storage and a regasification barge (Offshore Energy, 2019). In China, the China Merchants Industry has brokered an agreement with the Italian Classification Society and the China Classification Society to focus research efforts into maritime energy sources such as H_2 and ammonia (The Maritime Executive, 2020b).

Fuel characteristics and other key considerations

Ammonia as a fuel has many characteristics that make it one of the most viable alternative shipping fuels. Ammonia requires higher cryogenic temperatures to liquefy at -33°C than H_2 at -253°C (Kim *et al.,* 2020), and the transportation and storage of ammonia is drastically simpler and more affordable. Furthermore, ammonia is estimated to be almost 50% more energy dense per volume than liquid H_2 at a density of 12.7 GJ/m^3 (MKC, 2017). A study conducted by Kim *et al.,* (2020) discussed four proposed propulsion systems that were fuelled by ammonia, utilising differing power systems. The study stated that ammonia-fuelled ships would require between 1.6 and 2.3 times the volume of fuel compared to conventional HFO ships. However, it is estimated that reductions of life-cycle GHG emission were between 83.71 and 92.1%. Ammonia-fuelled ships need pilot fuels to trigger combustion in an ICE, although this pilot fuel can be H_2, cracked from the ammonia on-board. Using ammonia comes with safety challenges – such low flammability, corrosion and toxicity – but an established infrastructure for handling and transporting ammonia exists and can apply the necessary safety measures (Kim *et al*., 2020). Indeed, ammonia has been handled in various applications for over a century and thus its hazardous nature and safe handling is a manageable challenge (Thorson Solvi and Ruhlman, 2020).

Box 8 Nitrogen as feedstock for ammonia fuel

Nitrogen is abundant in the atmosphere, constituting around 78% of air volume. With nitrogen highly available globally, production locations can be flexible, and the need for complex and costly chemical processes is avoided (Generon, 2020). Currently, commercial-scale nitrogen production facilities use cryogenic separation, pressure swing adsorption (PSA), or polymeric membrane methods (Tianmiao *et al.,* 2018). All these methods use ambient air as the main component of the process. The process used to produce nitrogen is similar to carbon air extraction and uses the same principles, while being carbon neutral (Tianmiao *et al.,* 2018). Overall, nitrogen production from air is mature and fully commercialised globally. Currently, cryogenic separation is one of the main technologies used for large-scale nitrogen production and has the ability to produce high purity nitrogen at 99.99% (Tianmiao *et al.,* 2018) (Ivanova and Lewis, 2012). Despite this, PSA and polymeric membrane methods have become popular, but they are more suitable for small to medium-scale production (Tianmiao *et al.,* 2018).

Cryogenic air separation, also known as cryogenic distillation, requires ambient air extraction into a compression chamber. The air is then cooled and run through various filters to remove pollutants, moisture and water vapor. Once this process is complete, the air is funnelled through a heat exchanger into an expansion engine, which rapidly expands the gas. This decreases the temperature, which liquefies the various gases, and high-purity nitrogen is distilled with by-products of pure O_2, argon and other gases,

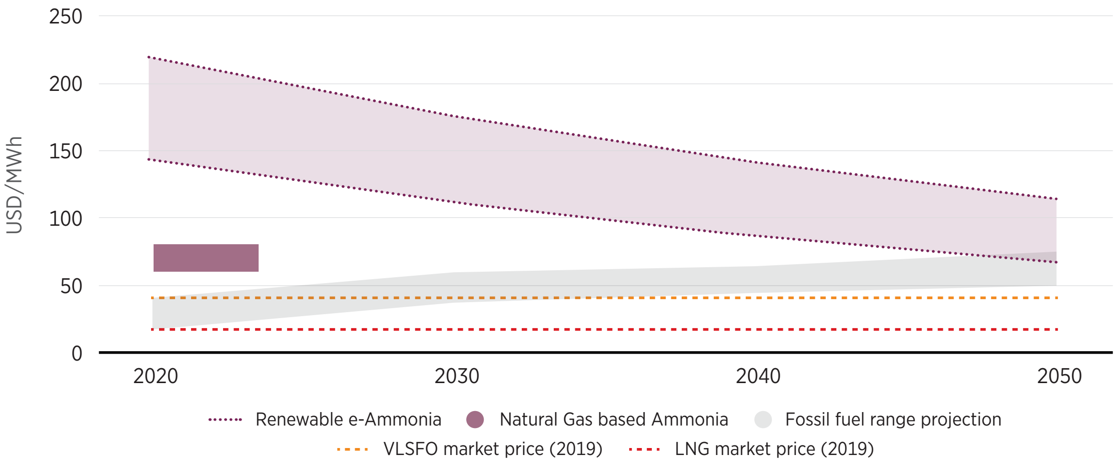
The PSA method is based on adsorption and desorption principles that occur simultaneously (Ivanova and Lewis, 2012). Air passes through a variety of filters, as with the cryogenic method, removing oil and water. The air then passes through one of the two adsorption components, which are filled with carbon molecular sieves (CMSs), which absorb residual moisture and CO_2 at the entrance of the adsorption process (Ivanova and Lewis, 2012). Air is then highly pressurised, allowing the CMS to absorb O_2 and allow nitrogen to pass through the system. Simultaneously, while the first adsorption vessel produces nitrogen, the second adsorption vessel is depressurised, which releases the absorbed O_2 into the atmosphere (Ivanova and Lewis, 2012). The benefit of this method is that the cyclic nature of the adsorption vessels allows for continuous nitrogen production. Further details on nitrogen production including technology readiness and costs are presented in Annex D.

Costs

As with most alternative fuels for shipping, the costs for producing and employing ammonia are high in comparison to fossil fuel alternatives with no emission abatement. The capital costs for investment in an ammonia plant are significant, with 60% of the cost related to the electrolysers. Another significant cost to consider regarding ammonia is the installation of bunkering facilities, because ammonia is not compatible with existing bunkering infrastructure (Ash, 2019). The production cost of NG-based ammonia is currently between USD 21.29/MWh and USD 65.81/MWh (IRENA & AEA, forthcoming). The current cost of production of renewable e-ammonia is estimated to be between USD 143/MWh and USD 219/MWh (IRENA, forthcoming). However, these costs would decrease significantly by 2050, *i.e.* USD 67/MWh to USD 114/MWh, making the lower cost estimates cheaper than the VLSFO market price. In comparison to H_2, the production costs of ammonia are higher due to a more complex method of production. However, due to much lower costs for the storage and distribution of ammonia, the delivered cost of ammonia fuel may be significantly lower than H_2 fuel (Dias *et al.,* 2020). While costs are not currently competitive, as the cost of renewables continues to fall and the costs electrolysers and H_2 storage fall progressively, renewable ammonia could be a very attractive option for the decarbonisation of international shipping in the medium and long term.

The upcoming development of the ammonia engine by renowned engine manufacturers by 2023 will have a very positive impact on the sector and unlock an attractive market for renewable ammonia producers. The scale-up in production would also result in falling costs for renewable ammonia. Ammonia is indeed the preferred alternative for the shipping sector as it has more similarity to conventional fossil fuel sources in terms of physical characteristics, is simple to store and transport, and as opposed to e-methanol, the production cost of e-ammonia does not depend on the costs associated with carbon capture and removal technology.

Figure 24 **Ammonia cost projections**



Note: Figure refers to the cost of fuel production. The total cost of ownership (*e.g.* machinery, storage and other) is not captured.

Source: Ammonia: IRENA (forthcoming), IRENA & AEA (forthcoming); fossil fuel cost projections: Lloyd's Register (2019)

4. DECARBONISATION PATHWAY

KEY MESSAGES:

- IRENA's analysis includes four energy scenarios for 2050. The primary focus comprised the analysis of a 1.5°C Scenario.[6] This chapter builds on IRENA's REmap methodological approach, in which scenarios are aligned with IRENA's *World Energy Transitions Outlook* (2021b), and analyses a mitigation pathway to limit global temperature rise to 1.5°C.
- The active adoption of energy efficiency (EE) measures will be critical to reduce energy demand and thus CO_2 emissions in the immediate term. In comparison to 2018 levels, a Base Energy Scenario (BES) and Planned Energy Scenario (PES) imply a net energy demand of 12.4 exajoules (EJ) and 11.8 EJ, respectively, by 2050. The IRENA 1.5°C Scenario pathway comprises a lower demand for maritime transport services combined with the successful adoption of EE measures, resulting in a final demand about 1.5 times less, *i.e.* 7.9 EJ, by 2050.
- In the short term, advanced biofuels will play a key role in the reduction of CO_2 emissions. IRENA 1.5°C Scenario implies that demand for advanced biofuels in international shipping needs to grow at an a.a.g.r. of about 9%, eventually reaching a participation of nearly 10% of the total mix in 2050.
- In the medium to long term, green H_2-based fuels will be at the core of the drive to decarbonise international shipping. Green H_2 required for this sector for 2050 stands at 46 Mt, *i.e.* 74% for e-ammonia, 16% for e-methanol and the remaining 10% to be employed directly as green H_2 through FCs or combusted through ICEs.
- Renewable ammonia forms the backbone of the decarbonisation of the shipping sector. Renewable ammonia could represent as much as 43% of the mix in 2050, which would imply about 183 Mt of renewable ammonia for international shipping alone, an amount comparable to today's global ammonia production.
- Given the relevance that powerfuels[7] are expected to have in the decarbonisation of this sector, it is important to note that the production of e-methanol and e-ammonia for 2050 implies demand for 55 Mt of renewable CO_2 and 155 Mt of nitrogen.
- The IRENA 1.5°C Scenario pathway presents clear advantages over other possible scenarios. While BES and PES would result in 930 Mt and 746 Mt of CO_2 in 2050, IRENA 1.5°C Scenario implies 144 Mt of CO_2. The net gain is further observed in the avoided cumulative emissions between 2020 and 2050. 1.5°C Scenario enables the avoidance of 12.5 and 9.5 billion tonnes of CO_2 in comparison to BES and PES.

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[6] *The 1.5°C Scenario refers to IRENA's proposed pathway, which would enable the limitation of global temperature rise to 1.5°C and bring CO_2 emissions closer to net zero by mid-century.*

[7] *Powerfuels are renewable and climate-friendly synthetic gaseous or liquid non-biofuels that draw their energy content from renewable electricity. Powerfuels can be used as energy carriers and feedstock (Global Alliance Powerfuels, 2021)*

ESTABLISHMENT OF ENERGY SCENARIOS 2050

IMO forecasts that maritime trade could increase between 40% and 115% by 2050 in comparison to 2020 levels. About 99% of energy demand from the international shipping sector is met by fossil fuels, with fuel oil and marine gas oil comprising as much as 95% of total demand (IMO, 2020a). IMO warned that in the absence of suitable mitigation policies, GHG emissions associated with the shipping sector could grow between 50% and 250% by 2050. As mentioned earlier, this broad range presented by IMO illustrates the level of uncertainty in terms of how the sector will evolve over the next 30 years, but even the lower band increase would undermine efforts to limit global warming. To reduce the level of uncertainty, it is critical to plan in advance and analyse pathways to decarbonise the international shipping sector by 2050.

Table 7 **IRENA shipping energy scenarios**

Base Energy Scenario (BES)	**Planned Energy Scenario (PES)**	**Transforming Energy Scenario (TES)**	**IRENA 1.5°C Scenario (1.5-S)**
Base climate scenario RCP 4.5 – SSP5	**Base climate scenario** RCP 4.5 – SSP2	**Base climate scenario** RCP 2.6 – SSP1	**Base climate scenario** RCP 1.9 – SSP1
Energy scenario narrative	**Energy scenario narrative**	**Energy scenario narrative**	**Energy scenario narrative**
Socio-economic and technological development are primarily based on harnessing fossil fuels. Future energy demand and supply in the shipping sector follow the historical trend. HFO, VLSFO and MGO continue as the dominant fuels by 2050. EE measures are not embraced.	Primary reference case. Moderate decarbonisation by the shipping sector. Actions comprise a "dash-for-gas" dynamic. The use of HFO, VLSFO and MGO is replaced by LNG, which characterises the sector. EE measures are vaguely embraced.	Decarbonisation ambition increases. LNG is the primary fuel displacing the use of HFO, VLSFO and MGO. Energy demand in the shipping sector is well diversified. Renewable fuels, including advanced biofuels and powerfuels, are employed at considerable levels. EE measures are embraced	The shipping sector embarks on a deep decarbonisation path in the years leading up to 2050. The utilisation of renewable fuels and the adoption of EE measures characterise the future of the maritime sector. While energy intensity levels improve significantly, the use of green H_2-based fuels outweigh the use of fossil fuels.

Note: RCP: Representative Concentration Pathway | SSP: Shared Socio-economic Pathway

Based on the Organisation for Economic Co-operation and Development's (OECD's) long-term projections presented in the *Fourth IMO GHG Study 2020*[8] (IMO, 2020a), IRENA analysed four energy scenarios. The primary focus of this report comprises the analysis of an energy transition pathway aligned with the 1.5°C climate ambition. Accordingly, IRENA 1.5°C Scenario is based on a climate scenario RCP 1.9 (see Table 7), representing a mitigation pathway to limit global temperature rise to 1.5°C and bring CO_2 emissions closer to net zero by mid-century.

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[8] *The Fourth IMO GHG Study 2020 Transport Work Projections section outlines several transport work scenarios, considering GDP growth projections (or Shared Socioeconomic Pathways), population, transport work and energy consumption. From the two methods used to project transport work (logistic and gravity model), IRENA's analysis uses the non-energy transport work's projection derived from OECD's long-term GDP projection using the logistical model (OECD_L) (IMO, 2020)*

For this purpose, the development of scenarios presented in this report builds on IRENA's REmap (Renewable Energy Roadmap) methodological approach (IRENA, n.d.). Hence, all four scenarios are aligned with IRENA's *World energy transitions outlook* (2021b). Table 7 provides details on foundations and the narratives considered within the scenarios explored in this study.

While the activity level growth varies among the various scenarios being explored by different organisations, most scenarios coincide in presenting that containerised and dry bulk trade will be the main cargo characterising trade by 2050. Other cargo facilitated by chemical and gas tankers is also expected to grow at a rapid rate, but on net terms container and dry bulk carriers are the vessels characterising the activity level matrix in the short and long term. Table 8 and Table 9 present several factors that will play a role in shaping the future of energy demand and supply in the shipping sector.

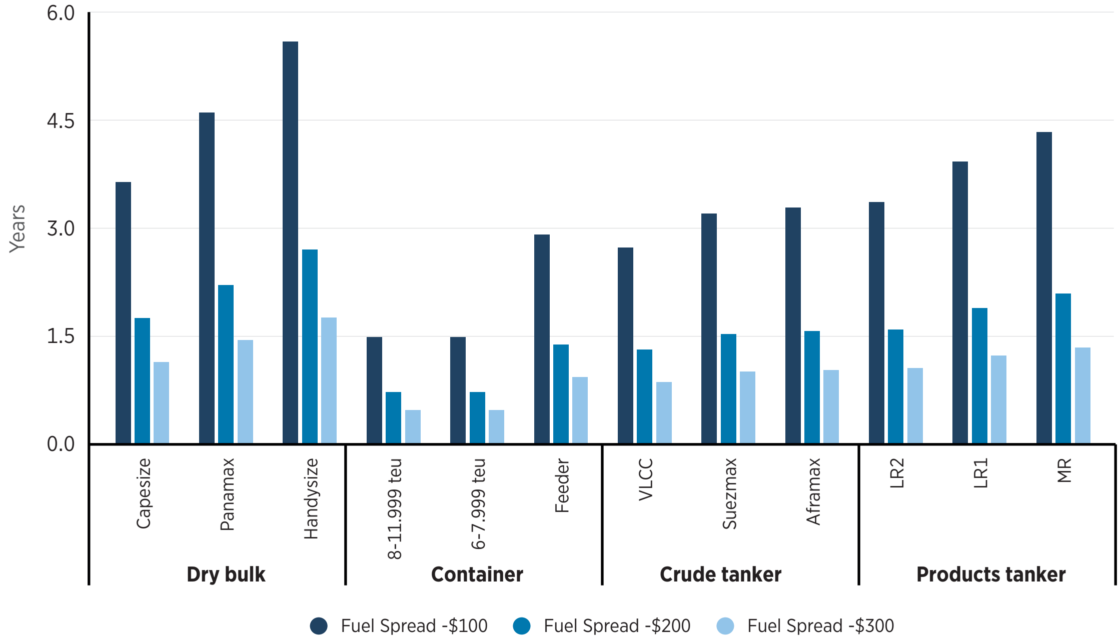
Given the key role that international shipping has in the global economy by facilitating overall trade and enabling the transport of energy commodities around the world, the future activity level of maritime transport is subject to a number of complex dynamics, particularly when developing long-term projections.

In the short term, it is clear that the global pandemic will shape future activity levels and thus final energy demand. According to IMF (2021), by the end of 2020 global GDP fell by 3.3% but by the end of 2021 the global economy is expected to recover, registering a GDP growth of 6% (IMF, 2021). In 2020, OECD expected a deeper economic contraction in which global GDP would fall between 4.3% and 4.5% at the close of 2020 and then recover by 4.1% to 5% by the end of 2021 (OECD, 2020). Although there is some level of uncertainty about the precise recovery of the global economy post-COVID, it is clear that beginning in the first quarter of 2020, the shipping sector experienced an important deceleration. For instance, between January and mid-April, 232 east-west sailings of container ships were cancelled (Danish Ship Finance, 2020). Simultaneously, the economic slowdown was fuelled by lockdown measures, resulting in global energy demand falling by 3.8% over the first quarter of 2020 and the demand for fossil energy commodities declining significantly (IEA, 2020). Around this time, an oversupply of crude oil resulted in many oil tankers acting as stationary storage. For instance, by the end of April 2020, Singapore's coastline was packed with several oil tankers serving as anchor storage (Low, 2020). The decline in activity was also strong in passenger carrier vessels, *i.e.* between 17% and 69%, while overall it was expected to fall between 7% and 9% in 2020 in comparison to 2019 levels. Depending on the cargo type, the reduction rate varied from 2% to 8% (UNCTAD, 2020a-b).

At a regulatory level, IMO MARPOL Annex VI, which limited SOx emissions by 0.50% starting in January 2020, had an important impact on global bunker fuel demand in terms of volumes and fuel of choice. The payback periods linked to the installation of SOx scrubbers (Figure 25) will certainly influence the fuel of choice and the price of low-sulphur fuel oil (LSFO) and MGO, and the availability of these fuels will also influence the fuel choice decision from shipowners. On this matter, the availability of low-sulphur fuel oil will mainly depend on the ability of the refineries to produce such bunker fuels. New refineries in Asia and the Middle East may be able to rapidly shift their production towards low and ultra-low sulphur fuel oil, but shifting production for old refineries in Europe will be more challenging. Similarly, the availability of LNG is also expected to play an important role in shaping energy demand on the shipping sector in the short-term. LNG is only available in selected ports, so only vessels with specific routes could choose such an option.

Eventually, in the short term, the choice of complying with IMO MARPOL Annex VI by shipowners will depend on the added weight from the scrubber, reduced cargo capacity, and additional operational costs vs. the fuel price difference between high-sulphur and low-sulphur oils. Based on these factors, the installation of scrubbers, which come at a cost of USD 2 million to USD 6 million (Danish Ship Finance, 2018), is more attractive for larger vessels with high fuel consumption.

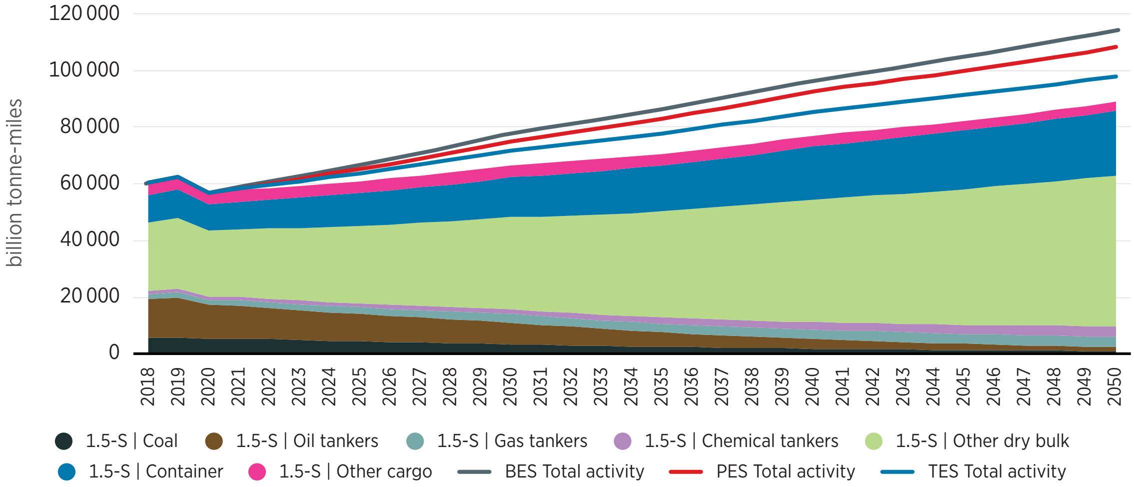
Figure 25 **Scrubber payback period depending on the type and capacity of vessels**



Source: Danish Ship Finance (2018)

In the short term, energy demand by the shipping sector could also be affected by geopolitical factors. For instance, the trade dispute between North America and the Far East will play a role in limiting maritime trade, particularly trade of dry bulks. In the very short term, maritime shipping activity may fall, with the consequence that the immediate energy demand associated with this key sector of the economy will fall accordingly. Figure 26 presents the activity level projections considered for the present analysis.

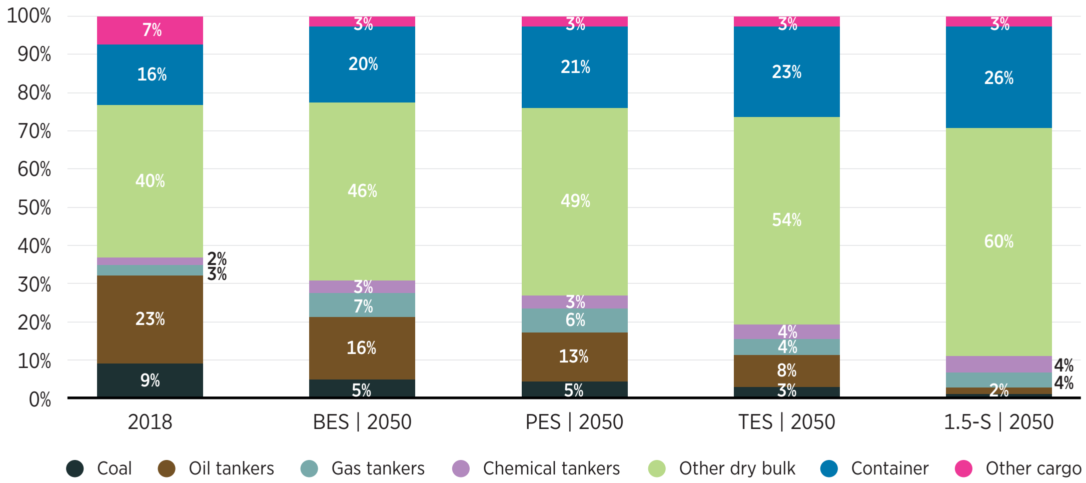
Figure 26 **Activity level projection**



Source: IMO (2020a)

For 2018, the reported activity level stood at 60 414 billion tonne-miles. Under a BES behaviour that follows a historical trend, it is expected that activity levels by 2050 would grow by about 90% in comparison to 2018 levels, while for PES and TES scenarios, activity levels would grow by about 80% and 62%, respectively. In contrast, the 1.5°C scenario considers a growth of about 56% in comparison to 2018 levels. Having presented activity level projections results, it is important to note that in the long term there are several complex drivers influencing final activity levels of the shipping sector and thus energy demand. For instance, large trade initiatives such as China's Silk Road Economic Belt, also known as the One Belt One Road (OBOR), will influence the future dynamics of the shipping sector. Simultaneously, as the world embarks on a total decarbonisation of the economy, the activity and energy demand from oil and gas (O&G) tankers will decline. Circular economy principles and consumers favouring locally produced goods will also lead to a decline in the activity level of the shipping sector and thus less energy demand.

Figure 27 **Projected disaggregation of activity level depending on cargo type**



Source: Based on activity level projections from IMO (2020a)

Indeed, the OBOR is expected to spark global sea trading, particularly across Asia, Europe and Africa. The initiative, focused on promoting economic prosperity, green development and regional economic co-operation, will lead to the investment of more than USD 1 trillion on infrastructure. This includes the development of power plants, power lines, development of hinterland infrastructure, and the expansion of ports, among other transport projects which would imply an incremental need for steel, *i.e.* about 150 Mt of steel will be required over the next ten years. Therefore, it is expected that activity from marine dry bulk carriers and thus energy demand linked to these vessels will increase. In general, the development of infrastructure linked to the OBOR initiative is expected to foster trade at all levels, cascading across the entire shipping sector (Kuo and Kommenda, 2020).

On the other hand, the decarbonisation of the global economy would imply the electrification of end-use sectors, including land transport sector, and therefore less trade of crude oil and its derivatives. Overall, it is expected that as countries continue to embrace the clean energy transition, international trade of fossil fuel commodities will fall and so will the energy demand from O&G tankers and dry bulk carriers transporting coal. Also linked to the energy sector, in the coming years most refinery expansions will occur close to O&G production sites, *e.g.* the Middle East and Africa, as well as Latin America. Therefore, large sailings carrying crude oil are likely to fall accordingly, reducing energy use by oil tankers. Figure 27 portrays the activity level share depending on the nature of the cargo by 2050.

ENERGY DEMAND PROJECTIONS

The clean energy transition will result in fewer vessels transporting fossil fuels, but as the world works on deploying more renewable energy, increased trade in renewable energy equipment and parts is expected. Trade of primary resources for battery storage manufacturing would also increase, *e.g.* trade of energy storage equipment. The trade dynamics of fossil fuels will also affect sectoral activity levels and thus final energy demand. In parallel, the electrification of end-use sectors is expected to boost the trade of primary materials and end products to support the development of transmission and distribution (T&D) infrastructure. Other factors with the potential to increase final energy demand in the shipping sector include the economic growth in emerging economies and low interest rates. Low interest rates imply the existence of more disposable income, and therefore increasing activity from container carriers trading non-critical goods. Together, all these factors describe how international shipping is affected by various factors that add uncertainty to this sector's future activity levels and energy demand. Table 8 presents the most relevant factors with the potential to increase final energy demand in the shipping sector.

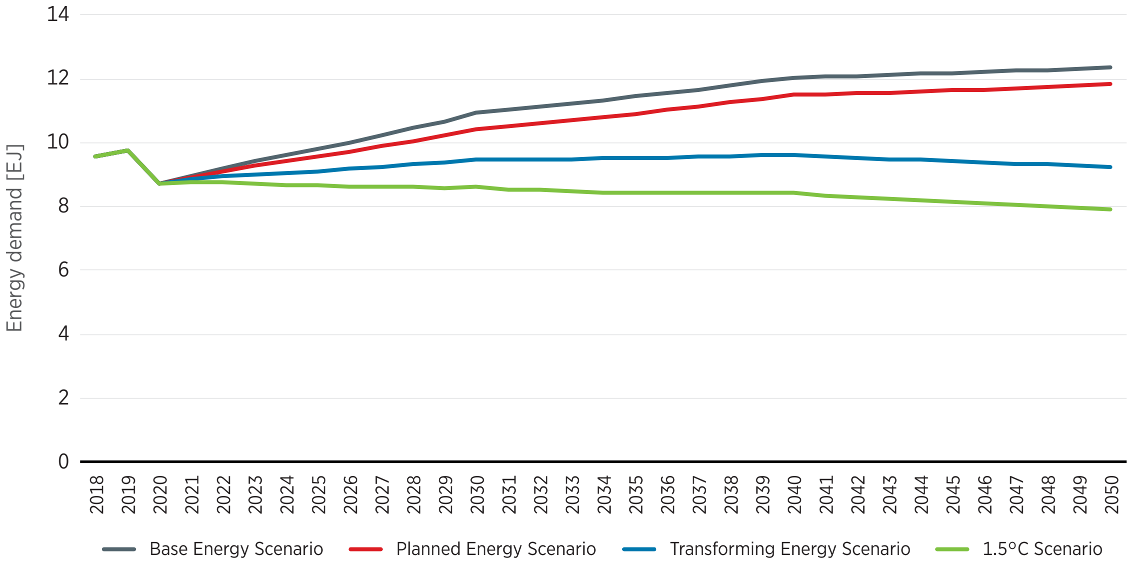
Table 8 **Key drivers with the potential to increase final energy demand in the shipping sector**

	Driver	Main vessel implicated	Description
1	**Global economic growth**	O&G tankers Dry bulk carriers Container carriers	Continuous global economic growth may spur demand for shipments of energy products and other goods.
2	**Economic growth in emerging markets**	O&G tankers Container carriers	Growth in the manufacturing and industry sectors and improved socio-economic standards in emerging markets may increase demand for goods.
3	**Shift towards cleaner cooking fuels**	Dry bulk carriers	LPG could see higher demand if domestic users switch from charcoal and other dirty-burning fuels to LPG
4	**Strong growth in the petrochemical sector**	Petrochemical tankers Oil tankers	If the demand for naphtha as a feedstock in the petrochemical sector continues to increase, seaborne demand will also increase.
5	**Regional trade agreements - One Belt One Road (OBOR)**	Dry bulk carriers	The development of support infrastructure around OBOR projects could represent an increase of activity from dry bulk carriers.
6	**Clean energy transition**	Dry bulk carriers Container carriers	Decarbonisation of the global energy supply will increase demand for renewable energy equipment and related parts.
			Increasing battery use for vehicles and energy storage may boost demand for metals such as lithium and copper and support bulk de-mand.
			The adoption of renewable and alternative fuels will result in incremental trade of green H_2 and its derivatives, including ammonia and methanol.

Source: Danish Ship Finance (2020)

While economic growth and the intensification of international trade would result in an increase in final energy demand, the clean energy transition beyond the shipping sector appears to be one of the main drivers with the potential to curb final energy demand. An initial "dash-for-gas" behaviour by various countries, especially China, would result in less demand for coal, leading to reduced activity from dry bulk vessels and increased activity from NG tankers. Yet, as the renewable energy transition and the Paris Agreement commitments move forward – accelerating the deployment of renewable energies coupled with an increase in the adoption of EE measures – final energy demand in the shipping sector is likely to fall under a TES and 1.5C-S. Figure 28 presents a final energy demand projection for the different scenarios developed within this report.

Figure 28 **Final energy demand projections, 2018-2050**



If energy demand policies do not focus on improving EE in international maritime transport, in comparison to 2018 levels, business-as-usual behaviour represented under the BES would imply an overall growth of 30% in energy demand by 2050. Similarly, for the PES, final energy demand would increase by 24%. In contrast, for the TES and 1.5°C Scenario, final energy demand could decrease by 3% and 17%, respectively. However, achieving negative energy demand growth and its associated benefits (*e.g.* fuel savings and avoided GHG emissions) depends on the successful implementation of the MARPOL 73/78, IMO's pollution prevention treaty and further adoption of EE mandates and practices (see the "Energy efficiency" section of Chapter 2). Indeed, in comparison to 2018 levels, a BES and PES imply a net energy demand of 12.4 EJ and 11.8 EJ. In contrast, the lower transport demand combined with the successful adoption of EE measures – a pathway analysed in IRENA 1.5°C Scenario – results in a final demand of about 1.5 times lower, *i.e.* about 7.93 EJ by 2050.

The full compliance with mandates such the EEDI (Energy Efficiency Design Index), EEOI (Energy Efficiency Operational Indicator) and SEEMP (Ship Energy Efficiency Management Plan) has been a key driver in reducing fuel usage since 2013 (IMO, 2020). To progress and further prioritise decarbonisation in the shipping sector, policies such as the EEXI (Energy Efficiency Existing Ship Index) and a mandatory CII (Carbon Intensity Indicator) are in development and are scheduled to be implemented in 2023 (IMO, 2020). As vessels continue integrating EE technologies and strategies within their daily operation, and while international control bodies with the support of port authorities enforce the compliance of EE mandates, final energy use will present negative average annual growth. Furthermore, the widespread adoption of circular economy principles and more localised production, as well as the global energy transition and further vehicle efficiency gains within road transport, among other factors, are expected to result in final energy demand falling by 2050. Table 9 portrays the key drivers with the potential to reduce final energy demand in the shipping sector in the long term.

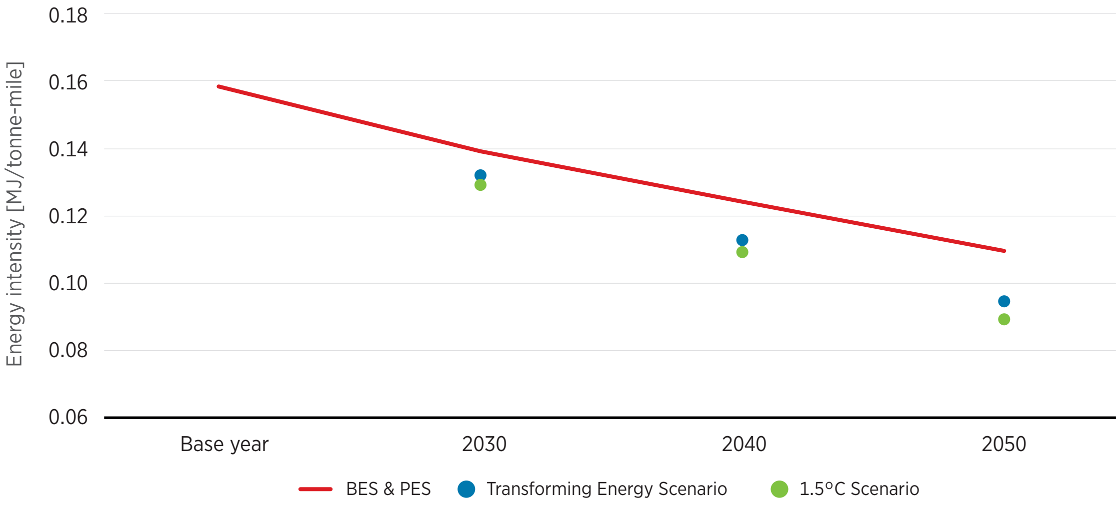
Table 9 **Key drivers with the potential to decrease final energy demand in the shipping sector**

	Driver	Main vessel implicated	Description
1	**The clean energy transition**	Oil and petrochemical tankers Gas tankers Dry bulk carriers	Demand for O&G will fall in the long term as renewable energy becomes cost competitive and energy storage and infrastructure are improved.
			The drive to reduce carbon emissions will result in a rejection of the use of coal as a fuel and decrease demand for goods transported by sea.
2	**Cost of energy**	Gas tankers	Affordable renewable energy will outcompete LNG in the future energy mix.
3	**Vehicle fuel efficiency gains**	Oil and petrochemical tankers	Demand for O&G products will be curbed as fuel usage efficiency accelerates.
4	**Dash for gas dynamics**	Oil tankers Dry bulk carriers	Demand for gas will spike as efforts to decarbonise power generation ramp up. This demand will be short lived because the Paris Agreement limits generation from gas by 2040.
5	**Refinery capacity expansion**	O&G tankers	The Middle East and Africa will add almost half of new refinery capacity up to 2023. Extra capacity near wellheads could lower crude oil exports and demand enabled by crude tankers.
			Oil product imports from the United States could decline as a result of plans, particularly by the Mexican and Brazilian governments, to expand the refinery industry in Latin America.
6	**Circular economic principles and changing consumer habits**	Dry bulk	Dry bulk demand will decline due to an increasing share of recycled, reused or remanufactured materials and reduced demand for raw materials.
		Petrochemical tankers	Consumer demand for petrochemical products is declining as governments ban plastic products like straws, cutlery, cotton buds and tax plastic bags.
7	**Regionalisation of production**	Container carriers	Production nearer to end markets will shorten supply chains and reduce container lift length.
8	**Geopolitical tensions and protectionism**	Container carriers	Trade tensions and protectionism are slowing the globalisation process, leading to disrupted supply chains and reduced container demand.
9		Crude tankers	The global economy and eventually crude oil demand will be negatively impacted by deteriorating global free trade conditions and the ongoing East-West trade tensions.

Source: Danish Ship Finance (2020)

The overall performance of the various scenarios in terms of final energy demand is measured by comparing the global average energy intensity (see Figure 29). As EE measures are adopted by the global fleet and specific fuel consumption (SFC) falls, the correlation between economic growth and final energy demand will become less evident. In fact, the energy intensity indicator across the BES, PES, TES and 1.5°C Scenario is expected to fall between 32% and 44% in comparison to 2018 levels. The full adoption of EE mandates could result in a significant gain in which an energy intensity value of below 0.09 MJ/tonne-mile could be achieved by 2050.

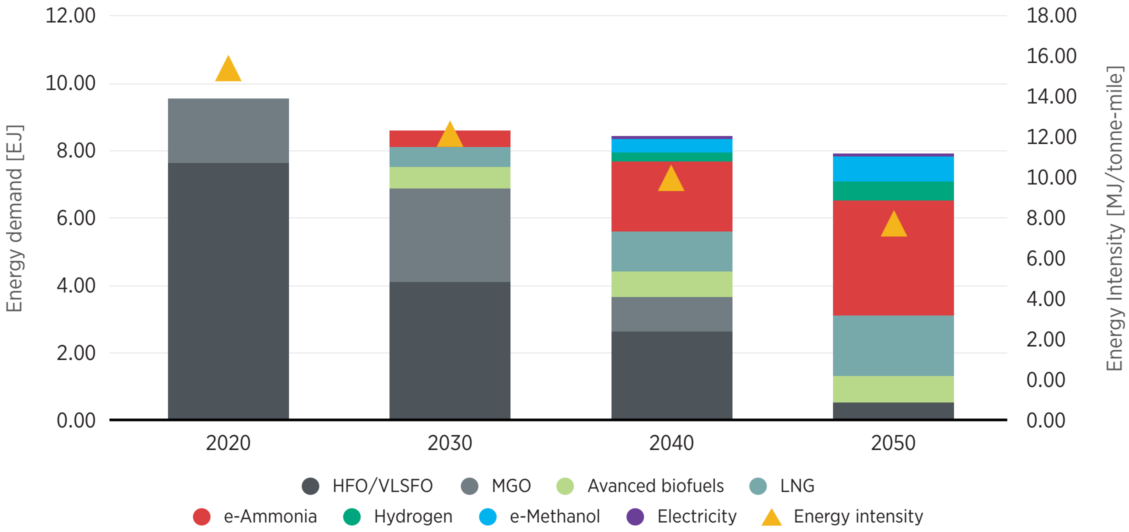
Figure 29 **Energy intensity global average for the shipping sector, 2018-2050**



Regarding the specific type of fuels that will shape the shipping sector's future energy demand, regulations imposing a carbon levy would greatly support a shift towards the use of renewable fuels, including green H_2-based fuels and biofuels. Fuel price and availability will also be decisive factors in the choice of renewable fuel/propulsion technology. Other key decisive factors will include the infrastructural adaptation costs of ships and ports, technological maturity and sustainability issues (*e.g.* food security). The willingness and ability of shipping companies to pay a premium price for low-carbon products will also be decisive (IRENA, 2019b).

While the BES scenario implies that the inclusion of renewable fuels by 2050 is practically null with fuel oil and MGO being dominant, the PES scenario explores a pathway in which LNG becomes the fuel of choice by 2050. In parallel, TES considers a more balanced picture where the inclusion of renewable fuels represents about 40% of the share by 2050. In contrast, the 1.5°C Scenario pathway presents a total renewable fuel share of 70% and limited participation of LNG. In the latter scenario, green H_2-based fuel is expected to play a major role, particularly green ammonia. The overall transition from 2018 to 2050 from a carbon-intensive sector, currently predominantly based on the use of fuel oil and MGO, to a decarbonised sector in 2050 with a high inclusion of renewable fuels is illustrated in Figure 30.

Figure 30 **1.5°C Scenario energy pathway, 2018-2050**



Box 9 Uncertainties in the shipping sector

The future of the shipping sector is one of major uncertainty due to the development of alternative fuels and the required investments in infrastructure, retrofitting of ships and upscaling of R&D activities. In the broader global context and as presented in IRENA's *World Energy Transitions Outlook* (2021b), BECCS is expected to play a pivotal role in achieving the Paris Agreement goals and halting the pace of climate change by transforming the global energy landscape.

Fossil LNG vs. Renewables – Some studies and scenarios point out the very limited role that LNG should have by 2050, *e.g.* Englert *et al.,* (2021). In practice, the international shipping sector's LNG consumption grew at an average annual growth rate of 4.4% between 2012 and 2018. IMO's (2020) latest official statistics show that between 2017 and 2018, LNG consumption grew by as much as 15%. Such dynamics signal that in the years to come, LNG may gain further space, but LNG should not be perceived as the path to decarbonise the shipping sector. The 2050 participation of LNG vs. renewable fuels depends on the type of policies deployed in the upcoming years and how cost competitive renewable fuels become in comparison with LNG. As mentioned in previous chapters, while renewable fuels production costs are currently high, in the next decades renewable fuels will become competitive, therefore, renewable fuels can shield the shipping sector from the volatility that characterises the fossil fuels market.

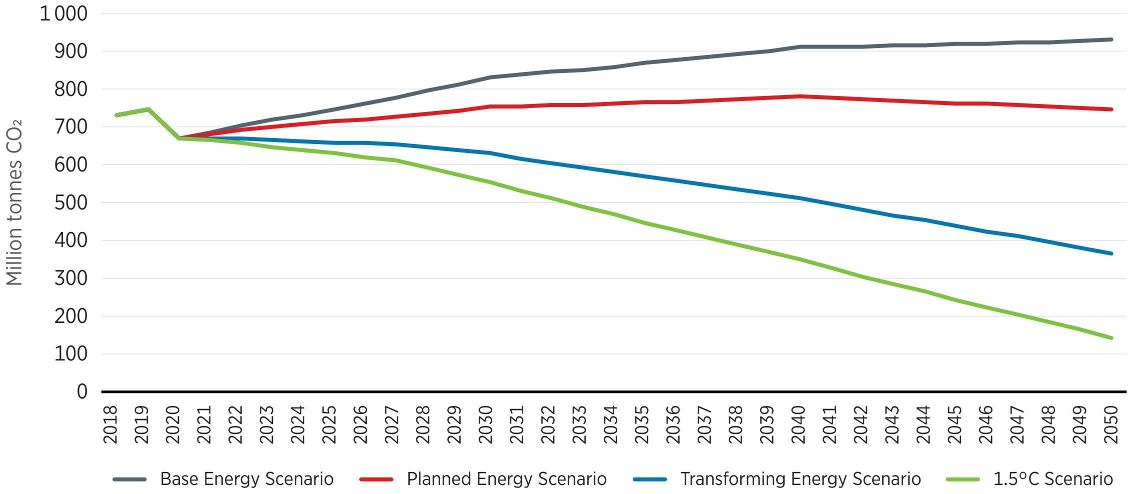
Chapter 5 proposes a number of supportive policy actions and enabling measures to raise the decarbonisation ambition beyond the 1.5°C Scenario goals.

Renewable ammonia and methanol – IRENA scenarios explored the potential of these two renewable fuels in the international shipping sector and the role that each may have in the path to a decarbonised sector in 2050. However, IRENA 1.5°C Scenario presents renewable ammonia as having a participation 4.5 times more significant than that of renewable methanol. Unlike ammonia, the utilisation of methanol requires little engine modifications, a clear advantage of this renewable fuel. However, the production of renewable methanol requires CO_2-free carbon as feedstock. The costs linked to CO_2 as a feedstock result in a higher cost of e-methanol when compared to e-ammonia. However, if DAC and BECCS technology costs fall significantly in the next decade, it could be possible that methanol rather than ammonia will become the fuel of choice.

DECARBONISATION ANALYSIS

Figure 31 clearly depicts that significant efforts will be needed to foster the use of renewable fuels, including biofuels, green H_2, methanol and particularly green ammonia, in the decarbonisation pathway leading up to 2050. In the short term, LNG is expected to play a role in curbing the use of fuel oil and MGO, but biofuels are also expected to play a key role. In 2020, the share of biofuel in the energy share was below 1%. However, in recent years the use in biofuel has flourished, with an average increase of about 30% per year. Overall, the 1.5°C Scenario implies that from now until 2050, the use of advanced biofuels in the shipping sector would have to grow at an a.a.g.r. of about 9%, thereby reaching an end use of around 1 EJ in 2050.

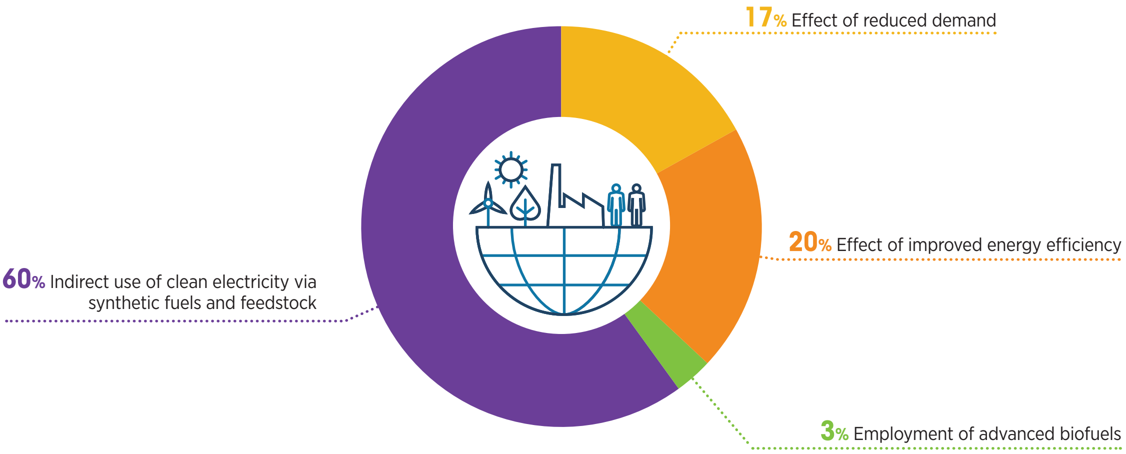
Figure 31 **Comparison of CO_2 emissions associated with each scenario, 2018-2050**



LNG will likely have a role in reducing sulphur emissions and, to some extent, reducing carbon emissions associated with the shipping sector. However, results from PES indicate that an LNG pathway would result in as much as 746 Mt of CO_2 by 2050. In contrast, the 1.5°C Scenario, which proposes a pathway with a 70% share of renewable fuels, would result in 144 Mt of $CO_{2,}$ thoroughly supporting the decarbonisation of international shipping by achieving an emission reduction of 80% in comparison to 2018 levels (see Figure 31). Overall, the decarbonisation pathway analysed in this report would be achieved by four key measures: i) indirect electrification by employing powerfuels; ii) employment of advanced biofuels; iii) improvement of vessels' EE performance; and iv) reduction of sectoral demand due systemic changes in global trade dynamics. Figure 32 displays the estimated roles of these four emission reduction measures.

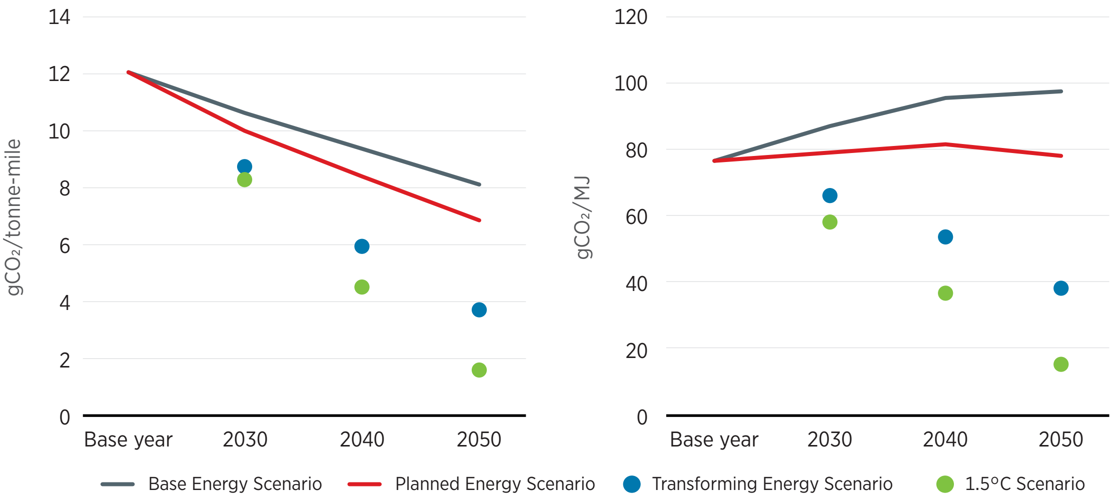
As part of the decarbonisation analysis, it is also relevant to revise the carbon intensity. The EEDI is a suitable key performance indicator (KPI) for the sector. An EE mandate was introduced in 2011 by IMO and thereafter amended in 2013 as per MARPOL Annex VI (resolution MEPC.203(62)) (see Chapter 2). While technical compliance with the EEDI is evaluated on a per-vessel basis, Figure 33 (left) represents a global average of carbon intensity on an activity-level basis.

Figure 32 **Estimated roles of key CO_2 emission reduction measures associated with IRENA 1.5°C Scenario**



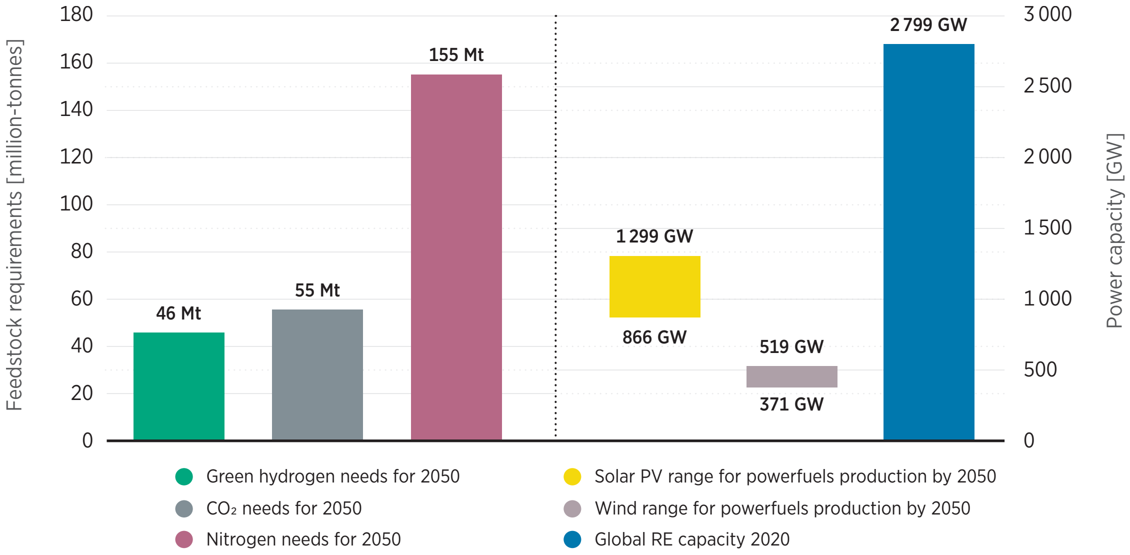
Clearly, the performance of this indicator is strongly influenced by the chosen climate scenario. Note that the decreasing trend presented by BES and PES does not imply progressive decarbonisation of the sector. The reduced carbon intensity for these two scenarios (in gCO_2/tonne-mile) is heavily influenced by the higher activity level considered for BES and PES, *i.e.* 29% and 22%, respectively, higher in comparison to the 1.5°C Scenario for 2050. To complete the decarbonisation analysis, Figure 33 (right) compares the carbon intensity on an energy basis, showing clearly that BES and PES perform badly. Indeed, the 1.5°C Scenario, which comprises a 70% inclusion of renewable fuels, would enable the achievement of a carbon intensity of 15 gCO_2/MJ, performing about 2.5 times better than TES, which implies approximately 40% inclusion of renewable fuels.

Figure 33 **Activity-level carbon intensity (left) and energy-basis carbon intensity (right)**



Considering the relevance that green H_2-based fuels are expected to have in the decarbonisation of the shipping sector, Figure 34 establishes the feedstock requirements and estimates renewable energy ranges that would be required to satisfy the demand of powerfuels for the 1.5°C Scenario by 2050. As indicated below, the overall requirement for green H_2 for 2050 stands at 46 Mt. Of this amount, 74% would be required for the production of ammonia, 16% for methanol and the remaining 10% would be directly employed as green H_2.

Figure 34 **Feedstock requirements and range of renewable energy deployment associated with the inclusion of powerfuels in the 1.5°C Scenario by 2050**



Note: The estimated solar PV capacity and wind capacity are mutually exclusive and cumulative.

Figure 34 also presents the estimated ranges of solar and wind power that would be required to meet the required levels of green H_2. However, several factors will dictate the precise capacity of renewable energy to be deployed up to 2050. The renewable power technology of choice and average capacity factors associated with each renewable energy plant supporting the production of green H_2 will play a role in the final energy capacity. Accordingly, in the years to come it will be fundamental to choose the geographical locations with the most renewable energy resources to ensure cost-effective investments that subsequently result in a competitive cost for powerfuels. As described in Figure 34, this report emphasises the importance of indirectly electrifying the shipping sector by employing green H_2-based fuels.

5. ENABLING ACTIONS TO RAISE THE DECARBONISATION AMBITION

KEY MESSAGES:

- The IRENA 1.5°C-Scenario represents a mitigation pathway to limit global temperature rise to 1.5°C and bring CO_2 emissions closer to net zero by 2050. However, moving from nearly zero CO_2 emissions to net zero requires a 100% renewable energy mix by 2050. Decarbonisation can be accelerated and ambition can be raised beyond the climate goals by adopting relevant and timely co-ordinated international policy measures. Stakeholders must establish strategic partnerships and develop new business models in energy-intensive industries, as well as power suppliers and the petrochemical sector.
- EE mandates must be tightened and suitable mechanisms developed for monitoring and enforcing the adoption of EE measures. Mandates and policies should be comprehensive, of high technical level and provide minimum standards in terms of vessel design and operation.
- It is critical to enable a level playing field by establishing a realistic carbon levy. Each fuel must have a carbon price that may be adjustable over time as the market becomes more favourable towards renewable fuels. Taking early action will not only foster the deployment of renewable fuels but also prevent investments in fossil fuel infrastructure that risk becoming stranded.
- Stakeholders in the international shipping sector and beyond need to prompt R&D institutions to analyse the upstream dynamics of renewable fuel production for shipping. This analysis must include the GHG life cycle of the different renewable fuels, as well as the potential and production limits of renewable fuels, *i.e.* biofuels and green H_2-based fuels.
- The decarbonisation of international shipping needs to be fuelled by investment in an efficient, safe, reliable and affordable supply of renewable fuels for the shipping sector via sector coupling mechanisms among bunkering service companies, port authorities, utilities and the renewable energy sector.
- It is critical to devote efforts to develop least-cost renewable power plants for the production of green H_2-based fuel, understand the disaggregation of such costs and propose sustainable configurations that enable the production of powerfuels at competitive costs for the maritime shipping sector.

IRENA 1.5°C Scenario represents a mitigation pathway to limit global temperature rise to 1.5°C and bring CO_2 emissions closer to net zero by 2050. Moving from nearly zero CO_2 emissions to net zero requires a 100% renewable energy mix by 2050. Achieving such a condition is uncertain due to scalability issues including the ability to deploy sufficient renewable infrastructure such as renewable power plants, biorefineries and e-fuel production plants (*i.e.* ammonia and methanol). Furthermore, end-use sectors besides shipping also have ambitious CO_2 reduction targets. Accordingly, end-use sectors risk competing with each other as they try to meet their increasing demand for renewable fuels. For instance, the shipping, aviation and road freight transport sectors are likely to compete with each other on the task of acquiring green H_2-based fuels, but the aviation and road transport sectors have a higher payment capacity than the shipping sector.

Uncertainty about the shipping sector's ability to reach zero CO_2 emissions by 2050 can be reduced. Starting now, EE needs to be promoted and effectively embraced. This will not only result in an immediate reduction of carbon emissions, but also can potentially result in important fuel savings and thus increase monetary revenue for shipowners and operators. From a technological perspective, renewable energies are competitive. Indeed, renewable energy costs have been falling at an accelerated rate. For renewable energy-derived fuels to become the prime choice of propulsion, further cost declines are needed, particularly in renewable energy supportive technologies (*e.g.* electrolysers and hydrogen storage). In this context, sectoral decarbonisation can be accelerated and ambition can be raised beyond the climate goals by fostering investment in the production of renewable fuels. For this purpose, adopting relevant and timely co-ordinated international policy measures is greatly needed. It also requires stakeholders to develop broader business models and establish strategic partnerships involving energy-intensive industries, as well as power suppliers and the petrochemical sector.

The actions listed below can raise the decarbonisation ambition beyond the 1.5°C Scenario goals. These actions are divided into four categories:

Multi-stakeholder synergies

a. **Fully map out and engage stakeholders associated with the shipping sector, and ensure they are working towards the establishment of strategic partnerships and common goals.** Policy makers, shipowners, ship operators, port authorities, renewable energy developers and utilities should work in parallel and with a common decarbonisation goal. Governing bodies regulating the international shipping sector need to develop integral and participative planning exercises, establishing step-by-step short, medium and long-term actions for reaching zero GHG emissions by 2050.

b. **Seek synergies and enhance international collaboration among all stakeholders involved in the field of powerfuels: shipping, aviation and energy-intensive industries (*e.g.* cements, iron and steel), as well as power suppliers and the petrochemical sector.** Given the promising decarbonisation path offered by powerfuels, it is of prime importance to raise awareness and acceptance of powerfuels as a missing link to reach global climate targets within the transport sector and energy-intensive industries. In these discussions, the expert advice and involvement of technology developers, academia, non-governmental organisations (NGOs), think tanks and governments will be highly relevant.

c. **Liaise with civil society.** Civil society has to be made aware of and informed about environmental impacts, particularly those related to climate change, and presented with potential decarbonisation solutions. It is likely that promotion of the availability of sustainably shipped goods will increase as a result.

Policy-driven actions

d. **Enable a level playing field by establishing a realistic carbon levy. Each fuel must have an implied carbon price that may be adjustable over time as the market becomes more favourable for renewable energy fuels.** Taking early action will not only foster the deployment of renewable fuels but also prevent investment in fossil fuel infrastructure becoming stranded. For this purpose, the successful implementation of a carbon levy is required to **inform stakeholders and promote among them the relevance of a carbon levy system, negotiate and agree on the terms and conditions associated with such a mechanism focused on discouraging the use of fossil fuels while making use of cost-competitive renewable fuels.**

e. **Immediately tighten energy efficiency mandates and develop suitable mechanisms for monitoring and enforcing the adoption of energy efficiency measures.** Mandates and policies should be comprehensive, of high technical level and provide minimum standards in terms of vessel design and operation. EE vessel design mandates should address the i) enhancement of hull and superstructures; ii) improvement of power systems and optimisation of propulsion systems; and iii) the adequacy of lubrications systems. In parallel, EE operational mandates must iv) ensure periodical maintenance of vessels; v) include energy management systems; and vi) continually apply voyage management best practices.

f. **Promote strict local regulations to limit airborne emissions at ports and inland waterways, and make cold-ironing (CI) at ports compulsory wherever available.** Accordingly, enforce turning off vessels' auxiliary engines during shore-side operations in port areas by plugging the vessels into a renewable electricity source offered by the port authority, thus reducing the emission of airborne pollutants and GHG during docking periods. The net gains from CI depend on the port's source of the electricity, so establishing mechanisms and incentives focused on equipping ports with a reliable renewable power supply and the deployment of distributed renewable energy systems directly installed onsite are highly attractive options.

g. **Establish a mandate comprising the progressive increase of renewable fuels within bunkering fuel blends. Start immediately with advanced liquid biofuels and biomethane and follow with the implementation of effective incentives to encourage vessel fleets to shift to green H_2-based fuels.** Liquid biofuels produced from second-generation feedstock have high technological readiness and, coupled with compressed biomethane, can be immediately harnessed as a drop-in fuel. In parallel, to prepare for the development of an ammonia engine by 2023, ammonia production should be scaled up. This depends heavily on the establishment of effective incentives such as excise tax reductions for renewable fuels.

h. **Develop sustainability certifications and suitable schemes such as guarantees of origin (GO) to guarantee ship operators of the renewability index[9] of a given fuel and its 100% sustainable origin.** Such efforts must go together with fit-for-purpose regulatory systems focused on ensuring that increased powerfuel production is aligned with renewable power capacity additions and/or suitable schemes harnessing renewable power curtailed by the grid for green H_2 based fuels production.

i. **Anticipate the upcoming demand for sustainable goods from end-consumers by implementing a relevant labelling system for such a purpose.** This should be driven by the shipping sector with the successful engagement of civil society and suitable instruments. Such a labelling system will enable end-consumers to make well-informed purchase decisions on a daily basis. This task will be important to encourage businesses to demand sustainable shipping options from cargo companies and offer civil society the possibility of purchasing sustainable shipped goods.

Research, development and innovation

j. **Prompt R&D institutions to analyse the upstream dynamics of renewable fuel production for shipping, including the GHG life cycle analysis of the different renewable fuels**, as well as the potential and production limits of renewable fuels, *i.e.* biofuels and green H_2-based fuels. Such an analysis needs to be **comprehensive and result in technical advice regarding the availability, fuel costs implications and alternative routes associated with the supply of feedstocks required for the production of the different renewable fuels, *e.g.* green H_2 and sustainable CO_2.**

k. **Continue devoting efforts to the development of sectoral strategies that clearly define the volume of renewable fuels required to decarbonise the shipping sector and ensure the necessary deployment of renewable power.** Accordingly, it will be crucial to work closely with countries with high renewable energy potential and promote the development of long-term energy planning processes. In addition, develop least-cost energy scenarios that aim not only to meet future national and regional energy demand but also to meet the increasing energy demand from international end-use

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[9] *The renewable energy index refers to the net utilisation of renewable energies sources in the production process of a given fuel.*

sectors for green H_2-derived fuels, and plan renewable energy investments accordingly. This will also result in an opportunity for renewable energy plant owners and operators. Renewable energy from the grid can be used for green H_2 production, while excess heat and O_2 from powerfuel plants can be commercialised, increasing the overall profitability of renewable energy and powerfuel plant investments.

l. **Boost efforts and ensure adequate levels of resources focused on the development of engine technology capable of harnessing green H_2-based fuels, thereby ensuring that technology is well advanced and ready to be deployed and scaled up by 2025.** Indeed, green H_2 produced through renewable-powered electrolysis is projected to grow rapidly, and green H_2-derived fuels are expected to be the backbone of a decarbonised maritime shipping sector. Hence the need to boost R&D and investment centred on the development of engines capable of harnessing green H_2-based fuels, primarily green ammonia.

Invest in renewables and energy efficiency

m. **Enable affordable lines of credit and introduce incentives to foster the development of carbon-zero new vessels and financing of retrofits in existing vessels.** Subsequently, encourage shipowners to progressively place orders for carbon-zero vessels, as well as to complete retrofits that enable the employment of renewable energy fuel, as well as retrofits centred on enhancing EE performance in existing vessels. Such financing should be primarily available for large and very large vessels, which together account for about 85% of energy use in the international shipping sector.

n. **Allocate national resources to support the identification of geographical areas with high renewable energy potential and devote significant efforts to understanding the production costs of renewable powerfuels in the short and long term.** Make this information available to the global shipping sector by nominating an international entity to lead the planning of the shipping sector. This entity would also act as a bridge between countries and the shipping sector and consolidate data for investment planning. In this task it will be critical to propose least-cost power plant designs, understand the disaggregation of such costs and propose sustainable configurations that enable the production of powerfuels at competitive costs for the maritime shipping sector.

o. **Invest in an efficient, safe and reliable supply of renewable fuels for the shipping sector via sector coupling mechanisms among bunkering service companies, port authorities, utilities and the renewable energy sector.** Accordingly, the primary focus should be on the identification of key investments across strategic ports and the allocation of funds for the upcoming development of renewable fuel infrastructure. Ensuring that the market forces associated with the supply and demand of renewable fuels for the shipping sector are well balanced will lead to an affordable, competitive and stable price of carbon-zero energy commodities for the shipping sector.

6. OVERVIEW AND OUTLOOK

The international shipping sector is characterised by its high dependency on fossil fuels. As much as 99% of the energy demand from this end-use sector is met by fossil fuels, with fuel oil and MGO comprising as much as 95% of total demand. Consequently, international shipping is responsible for around 3% of annual global GHG emissions on a CO_2-equivalent basis. Indeed, if the international shipping sector was a country, it would be the sixth- to seventh-largest CO_2 emitter, comparable to Germany's current CO_2 emission levels. IMO warns that if no actions are taken, carbon emissions linked to international shipping will grow substantially.

In the long term, complex drivers influence the final activity levels and thus the energy demand of international shipping. Economic development will continue to foster global trade as well as local shipping activity. In parallel, the electrification of end-use sectors anticipates a trade boost of materials to support the enhancement of T&D infrastructure. On the other hand, as the world embarks on total decarbonisation, activity and energy demand for tankers and some dry bulk carriers are likely to decline. Circular economy principles and consumers favouring locally produced goods may also result in a decline in energy demand.

Since 2011, various EE mandates have been introduced to the shipping sector. However, historical trends show that during low oil price periods, the shipping sector pays less attention its energy usage. However, during high oil prices periods, the shipping sector tends to adapt and perform more efficiently, without the need for external market regulations. This behaviour speaks to the need to tighten EE mandates and develop suitable mechanisms for monitoring and enforcing compliance with EE mandates.

Considering the average age of the existing vessel fleet and the technical lifetime of large and very large vessels *i.e.* 25-30 years, there is an urgent need to enable an environment focused on fostering investment in carbon-zero vessels and renewable fuels, particularly green H_2. Renewable powerfuels appear to be the most promising renewable fuels, particularly e-ammonia. As the cost of renewable energy continues to fall and electrolysers and H_2 storage costs fall progressively, renewable ammonia is set to become the backbone for decarbonising international shipping in the medium and long term. The ammonia engine expected to be ready in 2023 will be a key milestone in unlocking the use of renewable ammonia in the years to come.

Overall, in the context of international shipping, limiting global warming by 1.5°C can be achieved by four CO_2 reduction measures. The i) indirect electrification by employing powerfuels and the ii) employment of advanced biofuels will contribute to reducing around 60% and 3% of CO_2 emissions, respectively, while iii) improvements in vessels' EE performance and iv) the reduced sectoral demand due to systemic changes in global trade dynamics will contribute to reducing CO_2 emissions by 20% and 17%, respectively.

Climate goals and decarbonisation ambition can be raised, but moving from nearly zero CO_2 to zero emissions requires a 100% renewable energy mix by 2050. For this purpose, adopting appropriate and timely co-ordinated international policy measures is needed. Stakeholders associated with the shipping sector must be fully mapped out and engaged, working to establish strategic partnerships with a common goal. Furthermore, taking early action is critical; applying realistic carbon levies will not only foster the deployment of renewable fuels but also prevent investment in fossil fuel infrastructure that risks becoming stranded. In parallel, it will be critical to invest in the production of powerfuels in geographical areas with high renewable energy potential and devote significant efforts to understanding the production costs of powerfuels in the short and long term.

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ANNEXES

ANNEX A

DECARBONISATION MEASURES AND OPPORTUNITIES AT PORTS

Cold ironing and grid connectivity

While ships are berthed and their auxiliary engines are turned on, they produce emissions such as SO_x (sulphur oxide), NO_x (nitrogen oxide), CO_2 (carbon dioxide), and particulates (Safety4Sea, 2019). Cold ironing (CI) can offset this inefficient fuel burn by allowing ships to turn off their engines while dockside and supplying onshore power to the ships. The decarbonisation aspects of this process are dependent on the source of the electricity, such as renewable sources invested in by the port, or sourcing from the national grid (Shell, 2020). For example, if the port country has a national grid predominantly supplied by clean energy such as renewable energy, upstream carbon emissions are negated and the process of CI allows for lower overall emissions. The opposite is also true: if the national grid is mainly supplied by fossil fuel sources, CI would eliminate SO_x, NO_x and particulate emissions from auxiliary engine use, but CO_2 emissions would still exist upstream in the process. In the United States, CI was adopted into the Clean Air Action Plan (CAAP) in 2011 (Port Technology, 2011).

Decarbonising port infrastructure relies mainly on changes in bunkering sources and introducing CI. However, other elements must be considered and integrated into the port decarbonisation process. The electrification of vehicles used for port functionality mitigates emissions from port infrastructure, and the use of electric-powered equipment reduces reliance on diesel and fossil fuel-based equipment (Wieschemann, 2014). These elements are realised through the replacement of standard diesel-based drive trains with fully electric drive trains and the use of fully electric or hydrogen-fuelled port infrastructure vessels, such as dredging ships and tugboats.

As mentioned, CI has proved to be an effective measure in mitigating emissions from port infrastructure, and currently various ports have integrated this technology into their infrastructure. Table A.1 presents a list of ports equipped with CI infrastructure around the globe.

The first large-scale CI berth was introduced in the Port of Los Angeles in 2004, which also introduced the world's first CI-compatible container ship (Safety4Sea, 2019). In 2014, California implemented a policy requiring that half of all container ships run on shore power while dockside (Safety4Sea, 2019). California is leading in terms of implementing berth regulations for CI in ports, with six ports equipped with CI infrastructure. These are the Port of Los Angeles, Long Beach, Oakland, San Francisco and Hueneme Port. In Europe, the first ports to introduce CI were in Goteborg, Sweden, where ferry terminals are equipped with CI infrastructure. In this instance, the shore power is supplied by local wind energy.

The port reported that an estimated 72.57 tonnes of NO_x, 54.43 tonnes of SO_x and 1.81 tonnes of particulate matter were mitigated annually using CI infrastructure (Zis, 2018).

Currently, Europe and North America have the majority of CI infrastructure globally, with a large concentration on the west coast of North America. Asia has the most shipping traffic annually but has limited investment in CI. Table A.1 only takes large ports into consideration. Smaller ports have installed CI – for example, the Port of Killini in Greece introduced the first CI infrastructure in the Eastern Mediterranean in 2018 (Safety4Sea, 2019).

Table A.1 **Planned and existing CI-equipped ports**

EUROPE		
Country	**City**	**Targeted vessels**
Belgium	Antwerp	Container, barges
	Zeebrugge	Ro-Ro
Finland	Helsinki	Ro-Ro
	Kemi	Ro-Ro
	Kotka	Ro-Ro
	Oulu	Ro-Ro
France	Le Havre	Not specified
	Marseille	Ferries
Germany	Lübeck	Ro-Ro
	Hamburg	Cruise
Netherlands	Amsterdam	River boats
	Rotterdam	Barges
Norway	Oslo	Ro-Pax
	Bergen	Supply vessels
Sweden	Goteborg	Ro-Ro
	Helsingborg	Ferry
	Piteå	Not specified
	Stockholm	Ro-Pax
UK	Milford Haven	Tugs

OCEANIA		
Country	**City**	**Targeted vessels**
New Zealand	Auckland	Cruise (planned)

NORTH AMERICA		
Country	**City**	**Targeted vessels**
Canada	Halifax	Cruise
	Montreal	Cruise
	Vancouver	Container and cruise
	Prince Rupert	Container
US	Los Angeles	Ocean going vessels/ OGV
	Long Beach	OGV
	Oakland	Container
	San Francisco	OGV
	San Diego	Reefer ships
	Seattle	Cruise
	Juneau	Cruise
	Pittsburgh	Bulk

ASIA		
Country	**City**	**Targeted vessels**
Azerbaijan	Baku	Container (planned)
China	Shanghai	Cruise
	Qingdao	Container
India	VO Chidambaranar	Bulk
Japan	Tokyo	Cargo ships and ferries
South Korea	Busan Incheon Ulsan Yeosu Gwangyang	Not specified
Taiwan	Taipei	Not specified

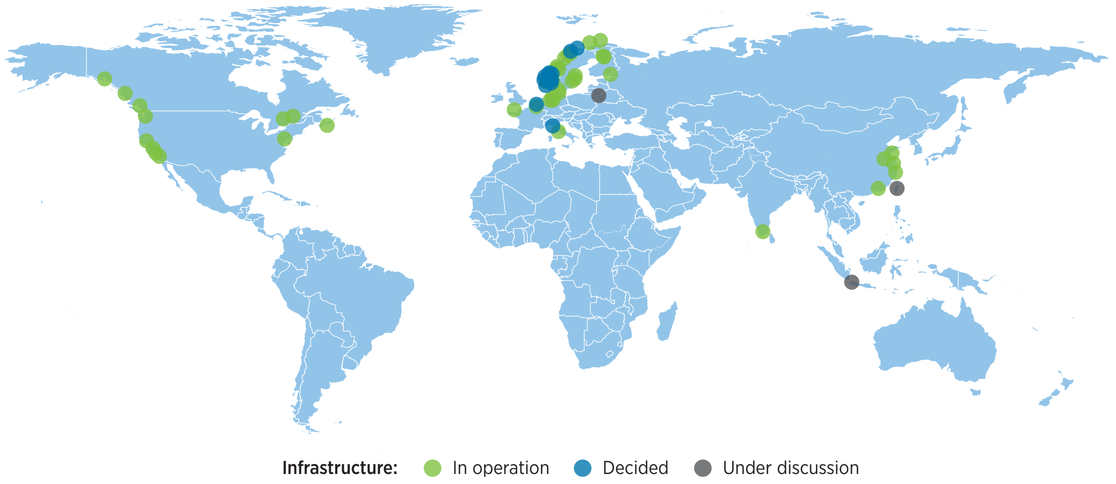
Note: Ro-Ro (Roll-on/roll-off) ships are vessels that are used to carry wheeled cargo.
Source: Zis (2018)

Clearly, CI is a prime example of how infrastructure can cut down on shipping emissions, but certain elements are needed for CI to function correctly. For instance, to integrate CI into a port, the necessary electrical infrastructure needs to be deployed. This infrastructure must be versatile, fit different ports and be suitable for a wide variety of vessels. Because of this need for versatility, a retrofit of the entire port terminal may be necessary. Installing CI differs in capital costs per port. For example, the infrastructure needed for one CI berth in Rotterdam was estimated to be USD 4.7 million (US dollars) compared with the Port of Gothenburg, which was estimated to be USD 955 000 in 2012 (Ssali, 2018).

Another aspect to consider is the integration of electrical infrastructure in ships in the form of retrofits or in the design of new ships. Transformers and inverters are required to be installed into ships before they can effectively use CI in ports. In the United States, the installation of electrical infrastructure was estimated at USD 400 000 per vessel in 2011 (Port Technology, 2011). This is an estimated cost for an average sized ship. Costs may vary depending on ship size.

The power source is the key CI element. Supply infrastructure is divided into four sections: supply from the national grid; fuel cell (FC) installation portside; port investment in power generation, particularly renewable energy; and power supply vessels (Coppola and Quaranta, 2014). Connection to the national grid is the most common form of power supply to ports because it has the lowest capital costs of all options. This requires basic infrastructure for transformers to connect to ships. Connection to the national grid is the predominant power source in ports that have high volumes of traffic annually, and thus high quantities of electricity are required. Installation of fixed FCs is another CI option for smaller vessels, such as dredging vessels, tugboats and fishing vessels. Depending on the demand of the port, FCs ranging from 200 kilowatts (kW) to 250 kW or from 1 500 kW to 2 000 kW can be installed dockside. Port investment into off-grid energy supply is one of the more expensive options in terms of capital costs, but it provides financial returns in the long term. Forms of off-grid supply include solar photovoltaic (PV) and wind energy in the vicinity of the port (Coppola and Quaranta, 2014). Furthermore, off-grid supply also requires investment in battery storage, which comes with its own high capital costs. Another form of CI is the use of a power supply barge, which provides versatile supply throughout a port. This method still requires port infrastructure to provide power supply to the barge, but it allows the barge to traverse the port to supply ships that do not have easy access to CI stations (Coppola and Quaranta, 2014). The Figure below presents the various types of shore power infrastructure installed globally.

Figure A.1 **Global shore power infrastructure**



Note: SP = shore power.
Source: DNV GL (2021b)

This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Auxiliary port infrastructure

The term "drive train" refers to the group of components in a vehicle's engine that supply power to the wheels and allow it to move. A variety of drive trains are used in portside equipment. The most common drive trains have components that use diesel engines and either hydraulic or electric motors. Alternatives to diesel drive trains are now feasible and are being implemented globally. These alternatives consist of combustion engines that use liquid natural gas (LNG) or compressed natural gas (CNG) to lower emissions from port equipment, hybrid drives that use a combustion engine and electric components, and fully electric drive trains. A port's choice of drive train for port equipment is motivated by the social and economic impacts on the port. LNG and CNG engines tend to be more expensive than their diesel counterpart in terms of maintenance and purchase costs (Wieschemann, 2014). In comparison to all the other options, fully electric drive trains seem to be ideal candidates for decarbonising port equipment because they have the highest overall energy efficiency and the lowest maintenance costs. The high efficiency of the fully electric drive train stems from the lower number of components that has compared with diesel drive trains. Because fully electric drive trains are equipped with lithium-ion batteries, refuelling and charging becomes a simple process. Furthermore, electric vehicles have low to zero emissions, except for the upstream emissions from the power source (Wieschemann, 2014).

Measures to decarbonise port vessels

Another step in decarbonising port infrastructure is using cleaner fuel sources for port vessels that maintain port functionality, such as dredging ships and tugboats. Through the use of hydrogen-fuelled and fully electric port vessels, emissions such as CO_2 can be greatly reduced (Bach *et al.,* 2020). Battery-electric (BE) ships are currently being introduced to the shipping sector, with one such example being in the Port of Gothenburg, Sweden, where two ferries are fully BE in their weekly usage. The electricity needed is supplied through CI infrastructure used in the Port of Gothenburg (Port Technology, 2011). More BE-powered ships are potentially going to be introduced into short-distance freight. The technology can be used in smaller vessels in ports, eliminating the fossil fuel demands of port vessels.

Hydrogen fuel, in the forms of ammonia and methanol, is a relatively new technology in comparison to BE for use in ships. However, hydrogen fuel has been the focus of increased interest due to its implications for long-distance freight. Producing vastly lower emissions than heavy fuel oil (HFO), this technology's integration into port infrastructure is key for decarbonising the sector (Bach *et al.,* 2020). Although both BE and hydrogen are ideal candidates for port vessels, BE tends to be a better candidate due to the maturity of the technology, the lower fuel costs and the moderate infrastructure adaptation needed for this technology.

Table A.2 **Comparison of hydrogen and battery fuel alternatives for short-range ships**

ASPECT	ELECTRIC (FULL)	ELECTRIC HYBRID	HYDROGEN
Reduction of greenhouse gas	Very high	Moderate-high	Very high
Reduction of NO_x	Very high	Moderate	Very high
Reduction of SO_x	Very high	Moderate	Very high
Investment cost (in vessels)	High	Moderate-high	High
Fuel cost	Low	Moderate	High
Availability (including infrastructure)	Moderate	Moderate	Low
Vessel adaptation	Very high	Low-Moderate	High
Infrastructure adaptation (including fuel production/ energy)	Moderate-high	Low-high	Very high
Market segment suitability	Vessels - Short routes	All - especially variable energy demand	All
Importance of regularity	High	High	Low

Source: Bach *et al.,* (2020)

ANNEX B
ENERGY EFFICIENCY SOLUTIONS

Energy efficiency (EE) operational measures

Voyage performance management

Just-in-time arrival and ship speed optimisation

Just-in-time (JIT) is a method whereby a ship optimises and maintains a particular speed to arrive at a port or piloting station in a timeframe that guarantees a berth, throughway or servicing (Hakirevic, 2020). The correct implementation of this process allows for port operation efficiency and decreases the time a vessel spends in anchorage outside of a port, which decreases fuel consumption and energy demand (Hakirevic, 2020).

Optimising speed during a ship's journey is another important EE fuel conservation measure. This process is applicable to new and existing vessels and is relatively easy to implement. In practical terms, a ship that reduces its speed by 10% could potentially save 20% of its fuel in a single voyage. Issues arise however with slower speeds due to economic conditions. Slower speeds decrease the amount of total cargo that can be transported annually, leading to economic shortfalls. Slow steaming – in which ships sail at slower speeds during sections of their voyage where time allows – can mitigate economic loss and allow for fuel savings for ships that have established design speeds. Cargo optimisation is an important factor in integrating slower ship speeds. Fully utilising a vessel's full cargo capacity is overall a beneficial strategy because it mitigates energy and fuel consumption over the long term (ABS, 2013).

Weather routing

Weather plays an important role in ship pathing. Planning a route based on the weather allows for a safe voyage and an accurate time of arrival. Fundamentally, weather routing has been based on the fastest and safest route. However, with the increasing importance of EE, particularly after 2013, ships have focused on weather routing optimised for a safe and energy-efficient route. As indicated by ABS (2013), current technology enables ships to have on-route navigational software that allows for up-to-date weather information. Installing and maintaining this software is estimated to cost USD 200 to USD 1000 per voyage, dependent on the type of software (ABS, 2013). Furthermore, this software can be used on all ship types. Energy and fuel savings from weather routing are highly dependent on the route length and the climate, but are more impactful during severe weather events (ABS, 2013).

Autopilot improvements

Inefficiencies in rudder control during voyages occur frequently. To mitigate energy consumption from this issue, autopilot software can be used to make calculated decisions about rudder movement and to optimise its utilisation (ABS, 2013). Introducing and updating autopilot software is estimated to save a maximum of 1% of fuel consumption in vessels. Although a relatively small fuel and energy conservation method, this software also benefits vessels' navigational aspects (Kabir, 2017).

Trim, draft, and ballast optimisation

The draft, ballast and trim of a vessel are instrumental in determining its fuel and energy consumption. The trim of the ship dictates the ability of the ship to maintain a maximum speed while keeping the shaft power at a constant, thus reducing energy and fuel usage (The Motor Ship, 2015). The optimal trim is dependent on the type of ship, and this is dependent on the difference between the aft draft and the bow draft. To optimise trim, even distribution of the cargo needs to be practiced with consideration of the locations of the ballasts (ABS, 2013). Overall savings of fuel and energy consumption from optimising trim are estimated to be up to 5% (Kabir, 2017).

Energy management systems

Reducing onboard power demand

To increase vessels' EE, the power demand of all onboard machinery and equipment needs to be decreased. Optimising the performance of onboard apparatuses requires fine-tuning in line with the manufacturer guidelines for each component. Another option would be the outright replacement of poorly performing equipment with high performing and more energy-efficient models (ABS, 2013). The process of streamlining a vessel's power demand requires a thorough analysis of the ship's baseline and maximum energy use. The next step involves identifying key pitfalls and losses of energy, and then developing a process of calibrating or replacing poorly performing equipment. The principal systems that require optimisation are the main and auxiliary engines and key smaller equipment, such as lighting; fans; cargo heating and cooling; onboard electronic systems; and heating, ventilating and air-conditioning (HVAC) units (ABS, 2013).

Fuel quality and consumption reporting

Fuel usage is the main contributor to greenhouse gas (GHG) emissions in the shipping industry. Fuel consumption is directly linked with energy demand on vessels. Therefore, all ships have a system of fuel consumption monitoring and reporting for bunkering logistics and fleet cost management. To maintain a correct system of EE management on a vessel, owners and fleet managers should use a fuel consumption measuring system that can target EE measures and bunker management with viable accuracy (ABS, 2013). A fuel consumption measurement system should report and monitor tank-level status, bunker and sludge discharge events, fuel-mass flow, power delivered to each component of the ship, and information regarding voyage and vessel operation. Fuel quality is a determining factor in energy and fuel consumption and is dependent on the water, fuel sulphur and fuel ash content (Kabir, 2017). It is estimated that if a vessel's fuel content has 1% water, fuel consumption in the vessel increases by 1% utilising standard HFO. To maintain decent fuel quality, third-party testing should be considered (ABS, 2013).

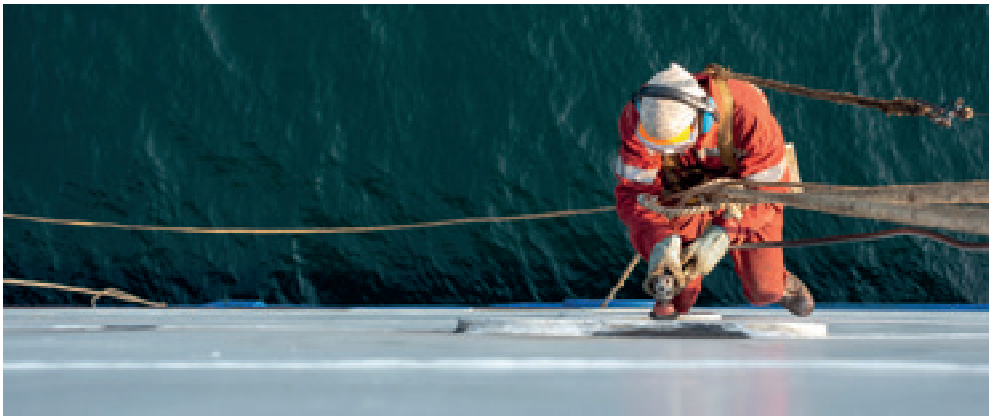
Vessel maintenance measures

Hull roughness management

Hull roughness determines the amount of friction between the ship and the water. If there is too much frictional force applied onto the ship, energy demand and fuel consumption are increased. To mitigate this impact, various methods can be applied to maintain optimum roughness of the hull. There are two aspects that need to be considered: physical and biological roughness. Physical roughness is defined as the surface profile of the hull determined by possible damage or decay to the hull structure. Most physical roughness factors occur during docking or dry-docking, when paint and coating can become scratched. If due caution is taken, physical factors can be avoided. Biological roughness is caused by animals such as barnacles and fouling of the hull from slime or algae (ABS, 2013). One method to prevent fouling of the hull is to use an anti-fouling coating. Currently there are three main types of coating. These are controlled depletion polymer coating, self-polishing copolymer and foul-release coating. It is estimated that with a high-quality coating, propulsion fuel consumption can be decreased by a total of 4%. Hull cleaning is another method used to mitigate biological roughness in hulls. Through the thorough cleaning of a hull, starting from the propeller and then moving forward along the ship, it is estimated that light slime clean-up can reduce fuel consumption by between 7% and 9%. Heavy slime cleaning provides a higher reduction in fuel consumption, up to 18%. Animals attached to ship hulls such as barnacles are considered macro fouling, and the removal of these can account for fuel savings of between 20% and 30% (ABS, 2013).

Propeller roughness management

Although propeller roughness may not impact fuel consumption vastly, relative to hull roughness, it is estimated that it could increase fuel consumption by 6% (ABS, 2013). The common factors that affect propeller roughness are corrosion and fouling from organisms similarly affecting hull roughness. Therefore, propeller maintenance is appealing to shipowners' usage measures such as propeller polishing and propeller coating. Propeller polishing should be completed regularly to maintain the performance of the propeller and to prevent build-up of slime, algae and other organisms. During this regular servicing of the propeller, damages in the forms of dent and scratches should also be attended to. Propeller coating functions the same way as hull coating, protecting the propeller from fouling and preventing corrosion (ABS, 2013). This is vital for energy and fuel saving on vessels.



EE design measures

Hull and superstructure

Ship sizing

Ships that have larger capacities tend to be more energy efficient due to their ability to transport more cargo at the same speed as smaller vessels while expending less power output. Comparing a container ship with a capacity of 4 500 TEU (twenty-foot equivalent unit) and one with 8 000 TEU, it is estimated that the ship with the larger capacity has a 25% overall fuel consumption reduction in comparison to the smaller ship. The EE and fuel consumption reduction diminishes the larger the ship gets. A comparison between the 8 000 TEU ship and a 12 500 TEU ship observed a 10% reduction of fuel consumption in the larger ship (ABS, 2013). Limitations occur with larger ships because ports may not be able to berth them. Furthermore, larger ships are only more efficient relative to smaller ships if their full cargo capacity is used (Lassesson and Andersson, 2009).

Principal dimensions

Hull length/beam dimensions play a key role in determining how efficiently a ship traverses the water. To decrease fuel consumption and energy demand, the design of new ships should optimise the length/beam ratio by increasing length and decreasing the beam of the vessel while maintaining draft (ABS, 2013). Optimising length/beam designs decreases fuel consumption by 3-5% in all ship types. Improving the hydrodynamic performance of a vessel's hulls is achievable through understanding key resistances affecting the hull and optimising the hull form (lines). Through optimising the hull, fuel savings are estimated between 5% and 8% (ABS, 2013).

Ship weight

The structural weight of a vessel has an impact on how a ship performs in terms of EE and fuel consumptions. The integration of high-tensile steel and other composite materials into ship structures allows for weight reduction. Optimising lower weights for large cargo ships allows for increased deadweight for the ship and increases its transport efficiency (ABS, 2013). The benefits of a lighter structural weight are proportional to the size of the ship, with larger ships achieving better efficiencies and fuel consumption reductions. Using high-tensile steel results in a potential fuel savings of 0.2-0.5% fuel consumption per tonne of cargo transported (ABS, 2013).

Aft-body and forebody optimisation

The fore and aft of a vessel are important aspects to consider when integrating energy-efficient design measures into ships. Design measures integrated to the forebody of the vessel include the design of the bulb, waterline entrance, the forward shoulder and the design of the bilge. A well-optimised bulbous bow allows for a reduction in wave-making resistance that works in tandem with bow wave from the hull to create a wave-cancelling effect that reduces the overall wave resistance on the ship's structure. In designing a bulbous bow, careful consideration of the placement of the forward shoulder and the bilge is vital. The importance of aft-body optimisation includes the mitigation of stern waves, improved flow towards the propeller and the avoidance of the eddy effect. Through the improvement of the stern flow, there is a potential for increased propulsion efficiency. Currently, designs in EE aft-body measures provide marginal results at high costs, and thus are not economically viable (ABS, 2013).

Propulsion systems

Propeller optimisation

Various forms of high-efficiency propellers exist to improve a vessel's propulsion. Each propeller installation is required to be designed specifically to suit a ship's operational profile and stern hydrodynamics. Currently, the optimal propellers for ships are those that have large diameters and fewer blades that function at lower revolutions per minute (RPM) than smaller, faster propellers. However, this is dependent on the size of the engine and vessel. It is important to consider hull hydrodynamics as well when installing a new propeller (ABS, 2013).

There a variety of propellers, each with specific benefits. The controllable pitch propeller has a low performance rate compared with a fixed-pitch propeller in situations that require a fixed RPM condition due to high RPM and small pitch values. However, it is possible to programme the propeller controller to match the controllable pitch propeller optimal pitch settings, which maximises and optimises efficiency performance better than a fixed-pitch propeller (ABS, 2013). Ducted propellers function in a cylindrical duct, which uses a process of either accelerating or decelerating the flow in front, over and behind the propeller to provide propulsion. Further examples of propellers are Kappel propellers, propellers with end-plates to reduce tip vortex, contra-rotating and overlapping propellers, and podded and azimuthing propulsion. It is estimated that fuel and energy savings from optimising propellers range from 3-10% (ABS, 2013).

Enhancement of propulsion devices

Many devices can improve EE in vessels from the development stage. Wake-equalising and flow separation-alleviating devices improve the flow around the hull of a ship by mitigating issues arising from propeller and hull resistances. These devices include Grothues spoilers, which are small, curved triangular plates fitted at the side of the hull in front of the propeller; wake equalising ducts, which function similar to the Grothues spoiler; and stern tunnels, which deflect water towards the propellers (ABS, 2013). The installation of wake equalising and flow separation alleviating devices is estimated to save 0-5% in fuel consumption.

Pre-swirl and post-swirl devices can be incorporated into vessel design to mitigate energy and fuel consumption. Pre-swirl devices can be retrofitted onto existing ships as well as onto newly designed ships. Installing pre-swirl appendages can mitigate between 2% and 6% of fuel consumption. Post-swirl devices have performed similarly to pre-swirl devices in terms of EE. Both of these devices are used to condition the flow towards the propeller (ABS, 2013).

Air lubrication systems

Air lubrication systems can prove instrumental in mitigating resistances on a vessel, and thus improving propulsion. Two forms of air lubrication exist, air cavity systems and micro-bubble systems (ABS, 2013). In air cavity systems, a thin layer of air is applied onto the bottom of the hull, which reduces skin friction due to lower wet surface area on the ship. Micro-bubbles, although not as effective as air cavity systems, are easier and less expensive to maintain, leading to lower energy demand. Introducing air lubrication systems to a vessel can lower fuel consumption by a maximum of 10% (ABS, 2013).

Power systems

Main engines

With internal combustion engines (ICEs) still the predominant engine used in ships, efforts need to be made to improve EE in ICEs to reduce fuel consumption and further decrease GHG emissions.

A key EE measure to implement in ships is main engine efficiency measurement instrumentation to track fuel consumption and energy demand. A shaft power meter is the most accurate way to measure engine power output in real time. This meter is installed directly onto the propulsion shaft. Two versions of the meter exist: the strain gauge and the optical gauge. To track the current fuel consumption of each primary consumer, a fuel flow meter can be installed. The most commonly used fuel flow meters are the positive displacement and the Coriolis gauges (ABS, 2013).

Main engine performance measurement and control is another aspect vital to maintaining EE on vessels. Diesel analysers are one such tool. These monitor engine balance, ignition timing, cylinder overload prevention and cylinder wear and are useful for planning maintenance. These analysers come in two forms: portable, which is the most commonly used form, and fixed. Furthermore, introducing automated combustion control systems such as computer-controlled surveillance and intelligent combustion control, as well as delta tuning (for low load operation) systems, can optimise engine control, thereby reducing energy and fuel consumption (ABS, 2013).

Auxiliary equipment and engines

Improvements to a ship's auxiliary systems in the design stage can boost the vessel's EE. Shaft generators are prime examples of an energy supplier to the rest of the ship. These use constant RPM from the main engine to produce electricity for all the auxiliary equipment and base energy demand for a vessel. Furthermore, hybrid auxiliary power generation that uses fuel cells (FCs), diesel/gas generators and batteries can improve ship energy performance (Lassesson and Andersson, 2009). The number of service generators is highly dependent on the sizing of the ship (ABS, 2013).

HVAC systems have a smaller impact on energy demand than other aspects of a vessel. However, prioritising the incorporation of highly efficient HVAC systems can mitigate energy consumption that can be used in other areas to greater effect. Further auxiliary aspects can be improved on in the development stage of a ship, such the optimisation of fans, pumps and compressors throughout the ship. Waste heat recovery can be used to provide electrical gain using steam exhaust gas heat recovery (ABS, 2013).

Inclusion of wind and solar energy

Integrating renewable energy sources into the design of ships is a relatively new innovation. Wind energy is considered viable for optional energy generation for vessels because wind resources are abundant. Various measures can be integrated into a ship's design, and one of the more common and commercially available measures are towing kites (ABS, 2013). These are relatively straightforward devices that deploy a kite tethered to the vessel that provide extra propulsion power, thus leading to fuel consumption savings. Another device currently in the concept stage is the turbosail. However, there are no practical applications available for large cargo vessels (ABS, 2013). Introducing solar power to vessels is also currently in development. However, due to the low output from solar photovoltaic (PV) panels, they are better used to power auxiliary systems and supplement the energy demand in a vessel. These technologies are undergoing constant innovation, and therefore future developments may prove to be more impactful for EE ship design.

ANNEX C
OVERVIEW OF ENGINE TECHNOLOGY

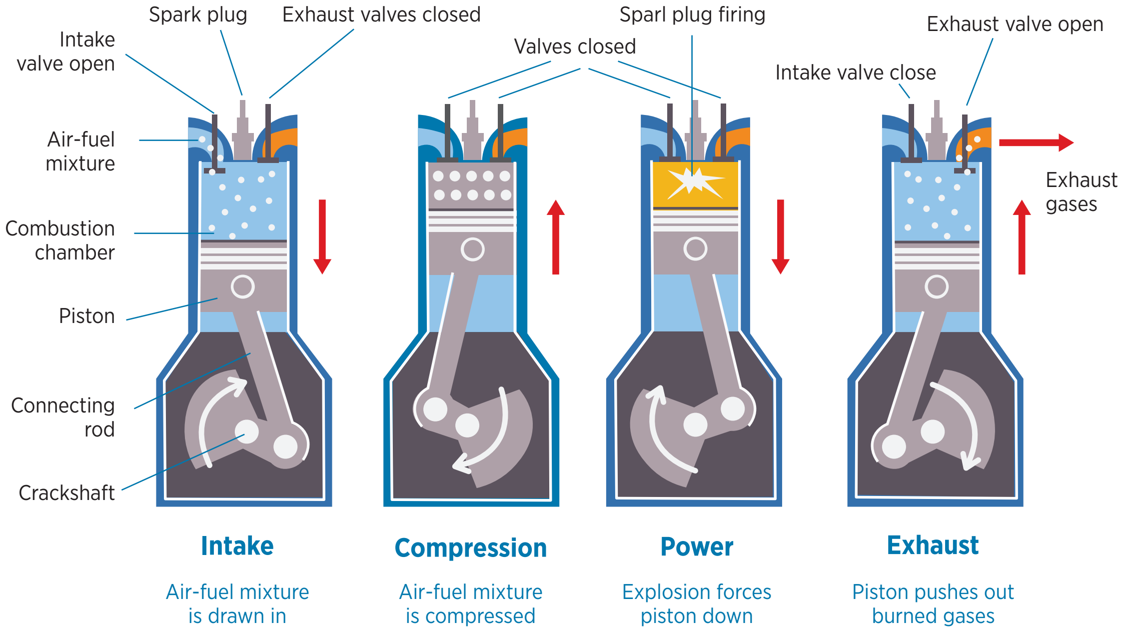
Otto cycle ICE

The Otto cycle type ICE refers to engines that use spark ignition. Currently there are two different kinds of Otto cycle engines, those that use two strokes and those that use four strokes. Globally, Otto cycle engines are highly used in the automobile industry but are also used in maritime shipping. Dual-fuel two-stroke Otto cycle engines have seen an increase in attention due to the effort to decarbonise the shipping sector, as alternative fuels are beginning to be employed (Riviera, 2020). MAN Energy Solutions, for example, has announced plans to introduce a more energy-efficient, low-pressure, two-stroke dual-fuel engine called the MAN B&W ME-GA that runs mainly on liquid natural gas (LNG) but can use methanol and other fuel oils to reduce emissions without impacting performance or efficiency (MAN ES, 2020). Currently, two-stroke engines are the preferred choice for large merchant vessels operating with Otto cycle engines (Wankhede, 2021).

Operating principles

The Otto cycle works on a basic principle whereby a set of processes are used in spark ignition internal combustion in four steps. These steps consist of a mixture that is compressed into a cylinder by a piston. Firstly, the intake stroke occurs, in which gas and air are drawn into the engine cylinders. The pistons then begin to compress the mixture. Before the piston reaches the top of the cylinder, spark ignition occurs whereby the mixture is ignited and pressure is created within the cylinder, which pushes the piston in the other direction (Kondratiev, 2020). When the piston reaches its lower limit, the valve exhaust occurs whereby the valve opens, and the burned mixture is released. This process is outlined in Figure C.1 for a four-stroke Otto cycle ICE.

Figure C.1 **Otto cycle in a four-stroke engine**



Source: Fallah (2014)

As described in Figure C.1, a four-stroke Otto cycle ICE consists of four different stages: the intake phase, compression phase, power phase and exhaust phase. Therefore, in a four-stroke engine, the piston completes two strokes every cycle, and ignition occurs once per cycle. This type of ICE requires no premixing of fuel and oil as these engines have a separate compartment for oil (Fallah, 2014). On the other hand, two-stroke engines simplify the process by completing the combustion process in one piston stroke. During this process, the spark plugs fire twice, produce power once every two strokes, but require oil to be premixed with fuel before its usage (Kondratiev, 2020).

Fuels employed

Two-stroke and four-stroke Otto cycle ICEs both use conventional fuel, with the exception that two-stroke engines require premixed oil with fuel, whereas four-stroke engines do not. This is due to the four-stroke having separate compartments for oil (Fallah, 2014). Currently, most maritime applications of Otto cycle engines use LNG and heavy fuel oil (HFO). However, with current technical progression on these engines, it is possible to use fuel blends mixed with biofuel and methanol and possibly to use these alternative fuels as drop-in fuels to mitigate emissions (MAN ES, 2020).

Advantages and disadvantages

There are various pros and cons to consider when comparing two-stroke and four-stroke Otto cycle engines. The main areas of comparison are the efficiencies of the different engines, the emissions, and the capital and operating costs of each. Otto cycle engines, particularly low-pressure engines, have an emission reduction of 85% in nitrogen oxide (NO_x) emissions (DNV GL, 2020b-c). Furthermore, they mitigate particulate emissions by 95% (DNV GL, 2020b-c). This is compared with utilising LNG instead of HFO. However, if alternative fuels are used in these engines, such as biofuels, reductions in these emissions are even higher (Brito Cruz, Souza and Cortez, 2014).

The advantages of utilising two-stroke engines can be seen in the efficiency of the engine. Currently, two-stroke engines have higher thermal and engine efficiency than four-stroke engines in ships. Furthermore, the weight reduction in the ship allows the vessel to store more cargo (Wankhede, 2021). The disadvantage of a two-stroke engine is reflected in its maintenance. Because two-stroke engines are simpler than four-stroke engines, they are simpler to repair. However, due to the fact that two-stroke engines perform at higher RPMs, they degrade quicker and therefore have increased operational costs (Wankhede, 2021).

Diesel ICEs

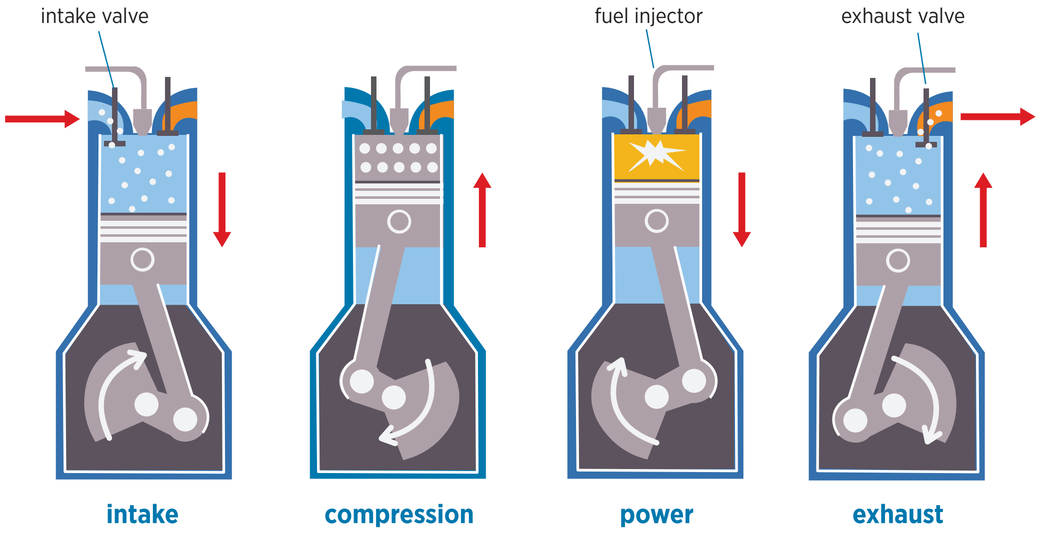
Diesel ICEs or compression engines are some of the most commercially available ICEs globally, with high usage in the motor vehicle industry. These engines are also used as the main engines for maritime shipping. The invention of the diesel engine was one of the key catalysts for the growth of the industry and the transportation sector globally and will play an influential role in future years in decarbonising the shipping sector (Hellenic Shipping, 2020a). With the need for cleaner fuels in the shipping sector to achieve IMO's emission reduction goals, companies such as MAN Diesel & Turbo, Wärtsilä and Mitsubishi have been developing new diesel ICEs that are more fuel efficient and allow for the introduction of alternative fuels (Kantharia, 2019). Furthermore, dual-fuel diesel engines have become popular choices for vessel engines because they mitigate emissions from ships through the use of biofuels and methanol (Congbiao *et al.,* 2020).

Operating principles

The basic operating principle of a diesel ICE uses multiple steps referred to as strokes. The overall process occurs over four differing strokes. There are two types of diesel ICE used in the shipping industry: the four-stroke and the two-stroke engine. An entire diesel engine consists of multiple cylinders that are driven by the combustion of air and fuel (Hermann and Raatz, 2014). Pistons enable the process of combustion to occur. The four steps required in a diesel ICE are the induction stroke, compression stroke, ignition stroke and exhaust stroke.

The first stage of the process is the induction stroke. This involves the piston within the cylinders moving downward toward the bottom of the cylinder. As this occurs, an inlet is opened that allows air to fill the cylinder until the piston reaches the bottom (Hermann and Raatz, 2014). The next stage, the compression stroke, requires all the valves in the system to be closed. The piston begins to move upwards, compressing the air trapped within the cylinder (Hermann and Raatz, 2014). During this process, the air within begins to heat up to high temperatures, up to 900 degrees Celsius (°C) (Hermann and Raatz, 2014). Once the compression stroke is almost finished, fuel is injected into the cylinder at a high pressure. The ignition stroke then begins after ignition lag, and then combustion occurs when the diesel fuel ignites due to the heat of the compressed air in the chamber (Proctor, 2020). The amount of energy released by combustion is directly proportional to the mass of the fuel injected (Hermann and Raatz, 2014). When ignition occurs, it drives the piston downwards, converting chemical energy into kinetic energy (Hermann and Raatz, 2014). The final stage is the exhaust stroke, when the exhaust valve opens just before the piston reaches its lowest point. Once the piston pushes upwards again, the exhaust gases are released from the chamber.

Figure C.2 **A diesel four-stroke process**



Source: Proctor (2020)

Shown in Figure C.2 is the four-stroke process need for a diesel ICE. The difference between a four-stroke and a two-stroke engine is that a two-stroke completes its combustion process in one stroke and then uses an exhaust stroke, thus simplifying the process. As with the Otto cycle ICEs, two-stroke engines produce power once every two strokes, whereas a four-stroke produces power once every four strokes (Kantharia, 2019). Although the diesel engine and the Otto engine use the same principle, the key difference is that a diesel engine uses compression to ignite the fuel, whereas an Otto cycle ICE requires a spark ignition (DNV GL, 2020c). Furthermore, LNG has a high ignition temperature, and therefore a pilot fuel is required to be blended into the fuel used by a diesel engine to trigger combustion (DNV GL, 2020c). Pilot fuels would be required for fuels such as methanol and biofuels.

Fuels employed

As with the Otto cycle engines, diesel ICEs use petroleum fuels composed of heavy hydrocarbons (Kondratiev, 2020). These fuels include HFO, marine gas oil (MGO), LNG and liquefied petroleum gas (LPG). However, the use of alternative fuels in diesel hybrid engines has attracted some interest as a way to offset emissions from vessels (IJERA, 2018). Fuels that consist of sediment and water have the potential to cause harm to the engine, and clean fuel is necessary to maintain fuel injection efficiency (Kondratiev, 2020). A cetane number is considered for these fuels and refers to the quality of the fuel. In the United States, the American Society of Testing and Materials (ASTM) uses the ASTM D975 "Standard Specification for Diesel Fuel Oils" to assess the cetane number (Kondratiev, 2020).

Advantages and disadvantages

When deciding whether to install a diesel ICE in a vessel, there are multiple pros and cons to consider. The key concerns regarding engines are their emissions, their overall efficiency, and their capital and operational costs. Diesel engines, while utilising LNG, have the highest reduction in CO_2 emissions compared with other engines utilising LNG, with a 26% reduction compared with HFO (DNV GL, 2020c). Furthermore, high- pressure diesel engines can mitigate up to 40% NO_X emissions and nullify particulate emissions up to 95% (DNV GL, 2020c). However, these emissions can be decreased to a greater extent if alternative fuels are used to replace or are blended with LNG.

As with the Otto cycle, two-stroke diesel engines tend to produce more power, because the power-to-weight ratio is higher than that of a four-stroke engine (Wankhede, 2021). This is due to four-stroke engines being larger than two-stroke engines since the combustion process is simplified (Wankhede, 2021). Despite the simplification of the process, the mechanisms required by a two-stroke engine are complex and therefore tend to have higher capital costs. Furthermore, since two-stroke engines function at a higher RPM than four-stroke engines, more frequent maintenance is required (Wankhede, 2021). These costs tend to be balanced when considering fuel costs, however, because two-stroke engines can run on low-grade fuels, thus reducing operating expenditures (Wankhede, 2021).

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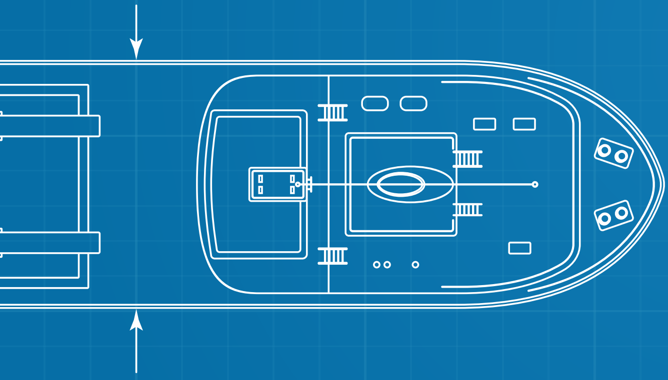

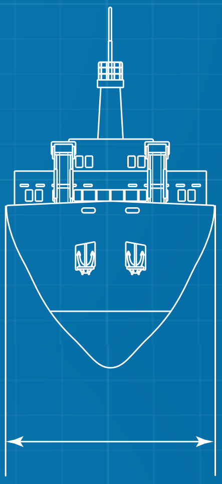

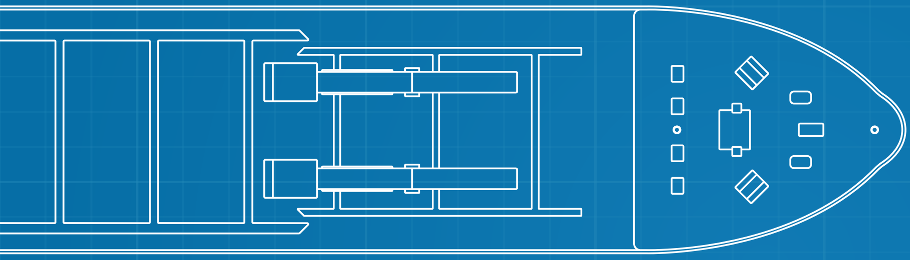

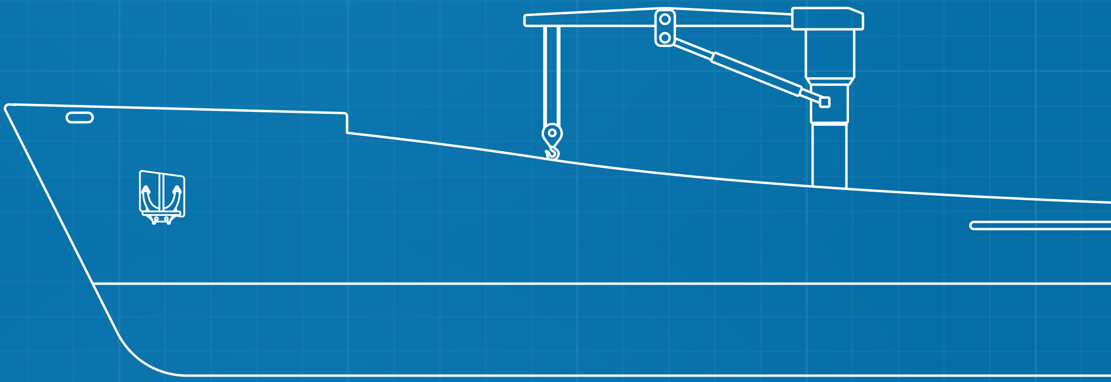

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