In Association with:

STUDY ON THE READINESS AND AVAILABILITY OF LOW- AND ZERO-CARBON SHIP TECHNOLOGY AND MARINE FUELS

Full Report

Report for: International Maritime Organization (IMO)

Future Fuels and Technology Project

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Ricardo Energy & Environment, Gemini Building, Fermi Avenue, Harwell, Oxfordshire, OX11 0QR, UK | +44(0)1235 75 3000 | ee.ricardo.com
Registered company no. 08229264 | VAT no. GB 212 8365 24

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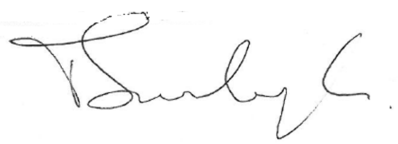
Contact:
Tim Scarbrough, Gemini Building, Fermi Avenue, Harwell, Didcot, OX11 0QR, UK

T: +44 (0) 1235 753 159
E: tim.scarbrough@ricardo.com

Author:
Michael Campbell, Ed Eyton, Graeme MacLean, Aleix Pons, Tim Scarbrough, Nikos Vasileiadis, Justin Wan (Ricardo)
Øyvind Endresen, Henrik Helgesen, Tore Longva, Ingeranne Strøm Nakstad, Øyvind Sekkesæter, Ola Gundersen Skåre, Dorthe Alida Arntzen Slotvik (DNV)

Approved by:
Tim Scarbrough

Signed



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FOREWORD

The decarbonization of international shipping is a priority for IMO and by mid-2023, the organization aims to have in place a revised and strengthened 2023 IMO GHG Strategy.

With this in mind, IMO launched the ***"Future Fuels and Technology for Low- and Zero-Carbon Shipping Project (FFT Project)"*** in September 2022 to provide an assessment of the state of availability and readiness of low- and zero-carbon ship technology and marine fuels, in order to help inform Member States as they work on developing IMO instruments to reduce GHG emissions from international shipping.

In June 2022, the 78th session of the IMO Marine Environment Protection Committee (MEPC 78) noted the need for more information to support the revision process of the Initial GHG Strategy.

To that end, the FFT Project procured this study to provide an assessment of the state of readiness and availability of low- and zero-carbon ship technology and marine fuels.

This study assesses the availability and readiness of low- and zero-carbon ship technology and marine fuels that can decarbonise international shipping, and the feasibility of achieving different decarbonisation scenarios.

The findings of this study can inform the ongoing discussions on the revision of the Initial IMO GHG Strategy to be finalised at MEPC 80.

About the Future Fuels and Technology Project (FFT Project)

The Future Fuels and Technology for Low- and Zero-Carbon Shipping Project (FFT Project) is a partnership project being implemented by IMO with funding from the Republic of Korea. Expected to run until 2025, it consists of three main phases:

- A study of current and projected global uptake and dissemination of low- and zero-carbon marine technology and fuels.
- Identification of and support for incentives and regulatory mechanisms, including safety and training issues, to promote the uptake of alternative fuels and technology including mid- and long-term reduction measures.
- Promotion of technological cooperation – for example, through pilot projects – and organization of outreach activities to reinforce mutual understanding and cooperation between developed and developing countries and the global shipping industry.

This study was conducted by Ricardo and DNV for the IMO FFT Project, funded through the Voyage Together Trust Fund and complemented by the IMO GHG TC-Trust Fund, in particular through a contribution by Japan, funded by the Nippon Foundation.

For further information or to provide feedback: jseo@imo.org and Michael.Campbell@ricardo.com

The full report is available on the FFT Project Web Page of http://futurefuels.imo.org

FUTURE FUELS & TECHNOLOGY PROJECT FOR LOW/ZERO CARBON SHIPPING

EXECUTIVE SUMMARY

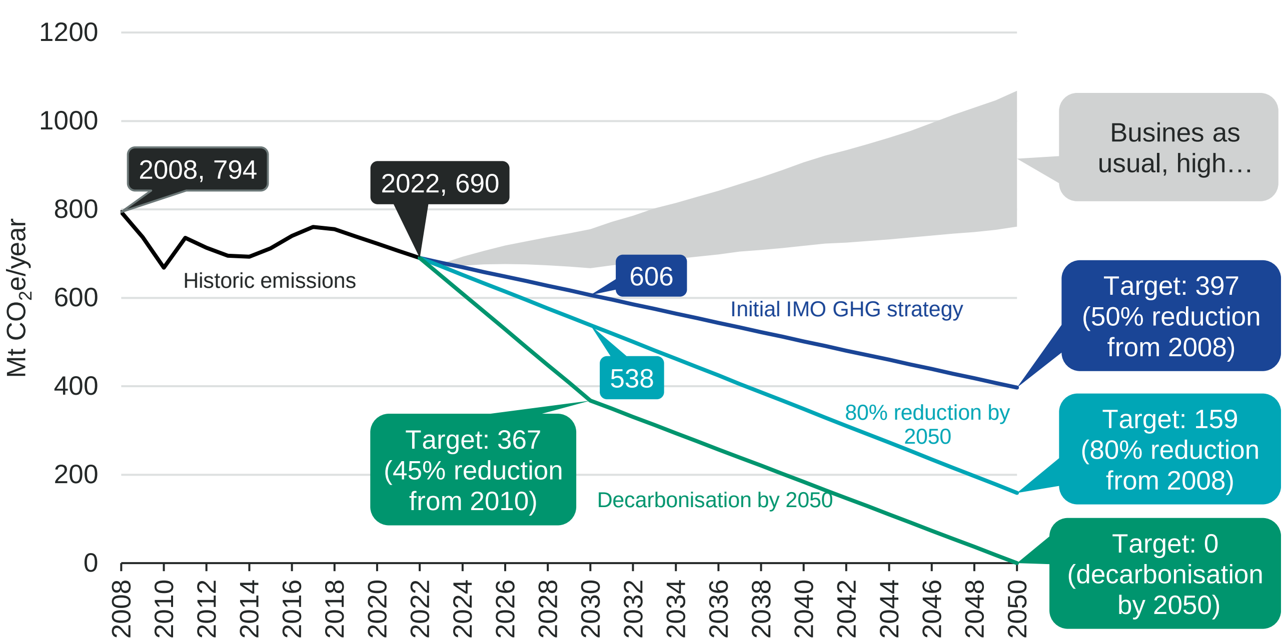
This study assesses the availability and readiness of low- and zero-carbon ship technology and marine fuels that can decarbonise international shipping, and the feasibility of achieving different decarbonisation scenarios. This document is the full report, a condensed 30-page summary report is also available.

What are the pathways to decarbonise?

Three conceivable decarbonisation scenarios are considered (Figure E1):

- The **Initial IMO GHG Strategy** reducing total annual Greenhouse Gas (GHG) emissions by 50% by 2050 compared to 2008.
- **80% reduction by 2050** approximately aligned to IEA's 'Net Zero Emissions by 2050' scenario and IRENA's '1.5°C pathway scenario', In this scenario other sectors reduce GHG emissions more than the maritime sector or even achieve negative emissions to enable global net-zero emissions in 2050.
- A **decarbonisation by 2050** scenario which represents international shipping reaching zero GHG emissions in 2050. This would be in-line with other sectors' reduction goals according to IPCC enabling no or limited overshoot of the 1.5°C target.

Figure E1: Three decarbonisation scenarios with targets compared to business as usual GHG emissions



The business as usual demand for energy for international shipping is evaluated for low and high growth scenarios: in both cases demand is forecast to grow between now and 2050 which without policy intervention would lead to an increase in GHG emissions. The use of energy efficiency measures beyond the business as usual scenario could lead to reductions of up to 27% in the energy demand by 2050.

How could we meet these pathways?

Decarbonisation will require the use of low-carbon and zero-carbon fuels ('candidate fuels') and technologies that are identified as reducing GHG emissions compared to fossil fuels. The candidate fuels considered in this study included advanced biofuels, e-fuels made from renewable energy, 'blue' fuels with carbon captured and stored (CCS) during their production and the use of on-board carbon capture with a blend of fossil and biofuels.

The potential availability of the candidate fuels to 2030 is assessed from existing and planned projects, and looking further ahead, based on reviews of multiple global energy system forecasting studies. **The assessment indicates the potential for significant availability of candidate fuels, but that depends on demand.** This assessment of availability does not represent a maximum supply but indicates a possible outturn if incentives and policies for scaling up production and a firm demand are agreed.

Regarding bunkering, some candidate fuels can use existing infrastructure, while others will need new infrastructure to be built. Methanol already has ship-to-ship bunkering proven, and ammonia can build on its existing global network of storage terminals. Assuming availability for such fuels, **bunkering infrastructure, distribution, and storage capabilities will be sufficiently developed to avoid constraining roll-out**.

It is similarly positive for **shipyards: there is capacity in the industry to scale up** the production and installation of energy converters, energy efficiency technologies and onboard carbon capture plants over short time periods once demand is clear.

An assessment of the technical and commercial readiness of the technologies needed to reduce the energy demand of the vessels, produce the candidate fuels, and use them on-board, found that **technology development is not expected to be a barrier to their roll-out**.

While candidate fuels are and will be more expensive than currently used fuels, this is not a barrier to deployment if the demand signal is clear. Short term cost changes – such as the costs of switching to candidate fuels and investing in new vessels – are barriers to decarbonise in the current framework of policy measures and ambition level. But with a clear signal of demand over defined timescales, increased costs can be planned for. This assessment does not evaluate any potential impacts on States.

Is it feasible to meet these decarbonisation scenarios?

None of the three decarbonisation scenarios assessed in this study will be achieved under business as usual; action is needed. **All three decarbonisation scenarios are expected to be feasible if policies to transition the sector to a more ambitious decarbonisation pathway are agreed and implemented very soon.** The only significant gap was found for the *Decarbonisation by 2050* scenario by 2030, considering the need to increase the uptake of candidate fuels well beyond currently announced projects to meet this target by 2030. This gap does not, however, preclude achieving the targets for the pathway in 2040 and 2050.

Decarbonisation scenario	2030	2040	2050
Initial IMO GHG strategy	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition
80% reduction by 2050	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition
Decarbonisation by 2050	✗ Major gaps	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition

The feasibility analysis does not point to significant gaps in terms of technology and commercial development for the achievement of decarbonisation pathways, particularly in the short term. The availability of candidate fuels for the shipping sector is only expected to be sufficient to meet demand if there is firm demand from the sector and capacity to transition early on. To reach the decarbonisation trajectories in 2050 an average annual growth rate in fuel production of 6-12% from 2030 is required, which is well below the historical sustained growth rates for solar and wind power generation.

The feasibility of these decarbonisation scenarios, and particularly the most ambitious pathways, requires an early clarification of further policy targets and measures to help unlock investment in candidate fuel production and their associated infrastructure. From a potential basket of measures, both technical and economic measures are likely to be needed to ensure the feasibility of this transition, complementing each other. Technical measures can provide long-term clarity for the industry on expected level and scope of mitigation efforts. Economic measures with revenue raising and disbursement mechanisms could be deployed early in the transition to help smooth the cost increase, particularly for first movers and help develop economies of scale around the production, distribution and use of candidate fuels for the benefit of the rest of the market.

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List of abbreviations

Abbreviation	Definition
ALK	Alkaline electrolysis
ATR	Autothermal reforming
BAU	Business as usual
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CII	Carbon intensity indicator
CH_4	Methane
CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalents
CRL	Commercial readiness level
DAC	Direct air capture
DME	Dimethyl ester
DWT	Deadweight tonnage
EEDI	Energy efficiency design index
EEXI	Energy efficiency existing ship index
EGCS	Exhaust gas cleaning systems
EJ	Exajoule
FAME	Fatty acid methyl ester
FT	Fischer-Tropsch (process)
GHG	Greenhouse gas
GJ	Gigajoule
GT	Gross tonnage
GW	Gigawatt
GWP	Global warming potential
HEFA	Hydroprocessed esters and fatty acids
HFO	Heavy fuel oil
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
IMO	International Maritime Organisation
KW	Kilowatt
LCA	Life cycle analysis
LFO	Light fuel oil
LOHC	Liquid organic hydrogen carrier
LPG	Liquefied petroleum gas
LNG	Liquefied natural gas

Abbreviation	Definition
MGO	Marine gas oil
MJ	Megajoule
Mt	Megatonnes
MW	Megawatt
N_2O	Nitrous oxide
NOx	Oxides of Nitrogen (Nitrogen Oxide, Nitrogen Dioxide)
NH_3	Ammonia
OPEX	Operating expenditures
PEM	Proton-exchange membrane
RFNBO	Renewable fuels of non-biological origin
SEEMP	Ship energy efficiency management plan
SMR	Steam methane reforming
SOFC	Solid oxide fuel cell
TRL	Technology readiness level
TtW	Tank-to-wake
VLSFO	Very low sulphur fuel oil
WtT	Well-to-tank
WtW	Well-to-wake

1 INTRODUCTION

1.1 BACKGROUND AND CONTEXT

In 2018, the International Maritime Organization (IMO) adopted the *Initial IMO Strategy on reduction of GHG emissions from ships* (Initial IMO GHG Strategy) (Resolution MEPC.304(72)) (IMO, 2018), setting out a vision which confirms IMO's commitment to reducing greenhouse gas (GHG) emissions from international shipping and to phasing them out as soon as possible.

Marine Environment Protection Committee (MEPC) 77 initiated the Revision of the Strategy and MEPC 78 and 79, following consideration of varying views on the levels of ambition required and their achievability requested the Secretariat to consider carrying out additional studies and organising information session(s) and/or symposia, as appropriate, supporting the revision process of the Initial IMO GHG Strategy. And in June 2022, MEPC 78 noted the need for more information to support the revision process of the Initial IMO GHG Strategy.

As part of that support provided by the IMO Secretariat, the IMO recently launched the *Future Fuels and Technology* project (FFT Project), funded through the Voyage Together Trust Fund of the Republic of Korea and implemented by the IMO Secretariat. The FFT Project consists of three main phases:

1. A study of current and projected global uptake and dissemination of low- and zero-carbon marine technology and fuels (the present study)
2. Identification of and support for incentives and regulatory mechanisms, including safety and training issues, to promote the uptake of alternative fuels and technology including mid- and long-term reduction measures; and
3. Promotion of technological cooperation – for example, through pilot projects – and organisation of outreach activities to reinforce mutual understanding and cooperation between developed and developing countries and the global shipping industry.

1.2 AIMS AND BASIS

Contributing to the first phase of the FFT Project, the present study aims to provide an assessment of the state of availability and readiness of low- and zero-carbon ship technology and marine fuels to support GHG emissions reduction from international shipping. This provision of technical analysis to the Organization is to support policy discussions held in the Committee, and to help inform Member States as they work towards the revision of the Initial IMO GHG Strategy by providing a feasibility analysis on the strengthened level of ambitions.

This study was carried out between January and March 2023 using available sources at that time, and by necessity followed a rapid timescale with limited opportunity for additional analysis and consultation. Ricardo and DNV would like to thank the external experts who were consulted through the preparation of the report for their assistance, as well as the IMO's Marine Environment Division for their support, steer and review during preparation of this paper. An extensive range of sources has been used during this study and in support of the report. A full bibliography is included at the end of the report, and the appendices provide detail of methodologies applied and references for data sources used. The publication of this study and the evidence it presents provides an opportunity to spark discussion and debate to inform the discussions around the Revised IMO GHG Strategy.

The assumptions, modelling and results are in this study are the sole responsibility of the authors and do not pre-judge the conclusions of negotiations of the Revised IMO GHG strategy, including any scope discussions associated with it. Any considerations of policy options are not intended to infer recommendation.

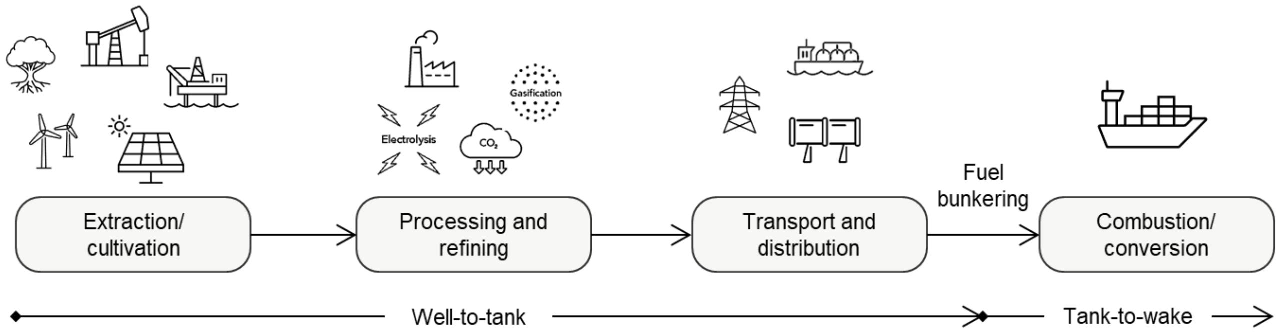
1.3 SCOPE AND ASSUMPTIONS

1.3.1 Scope of the study

The Initial IMO GHG Strategy set ambitions for the reduction of GHG emissions from international shipping using 2008 as a reference year. It is expected that the Revised IMO GHG Strategy will set enhanced ambitions for international shipping. Without prejudging the conclusions of negotiations of the Revised IMO GHG Strategy, the scope adopted by this study is set out below.

1. **This study uses the voyage-based allocation of international shipping** from the Fourth IMO GHG Study 2020 (IMO, 2020), which according to the authors of the Fourth IMO GHG Study 2020 is consistent with IPCC's guidelines and definitions. The Fourth IMO GHG Study 2020 estimated the 2008 GHG emissions from international shipping as 794 MtCO_2e using the voyage-based allocation method.
2. The 2008 estimate covers tank-to-wake (TtW) GHG emissions, and the Initial IMO GHG Strategy does not make any explicit reference to TtW or well-to-wake (WtW) emissions. Figure 1-1 illustrates the scope of well-to-tank (WtT) and TtW emissions. WtW is the sum of WtT and TtW.

Figure 1-1: Illustration of the scope of well-to-tank (WtT) and tank-to-wake (TtW) emissions



Various terms have been introduced in the proposals for ambitions in the revised IMO GHG Strategy, such as 'lifecycle emissions', 'net-zero CO_2 emissions', 'climate-neutral' and 'zero or near-zero emissions'.[1] This study does not prejudge the discussions around these terms, their interpretation, nor whether the revised GHG Strategy should cover WtW or TtW GHG emissions. Rather, we aim to show possible decarbonisation pathways to evaluate the feasibility of strengthened GHG emission reduction targets and the implications on WtT and TtW GHG emissions.

However, when evaluating the GHG emission reduction potential towards the targets defined in Section 2, one approach needs to be selected. Accordingly, **this study calculates GHG emissions according to a TtW scope where CO_2 emissions from combustion of biogenic carbon or carbon from Direct Air Capture (DAC) are considered zero.** This approach is consistent with the TtW value 2 of the life cycle analysis (LCA) guidelines under development according to the reporting of the Correspondence Group to MEPC 80[2].

3. **This study does not consider acquiring carbon credits or offsets from other sectors** as a means to achieve the GHG emission targets.
4. **This study includes carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (N_2O) emissions**, which currently are the main GHGs from shipping contributing to climate change, according to the Fourth IMO GHG Study 2020. Black Carbon emissions were also identified by the Fourth IMO GHG Study 2020 to have a significant climate impact, but are not included in this study as this is not explicitly covered by the exiting Initial IMO GHG Strategy, and are also not included in the scope of the IMO's upcoming LCA guidelines as agreed by the 9th intersessional working group on GHG emissions (ISWG-GHG 9).[3] The IMO has a separate work item addressing the impact of Black Carbon from international shipping on the Arctic (output 3.3 in the 2022-2023 biennial plan). The potential global warming impact of hydrogen (UK BEIS, 2022)[4] is not included.

1.3.2 Assumptions

The GHG emissions in this study are calculated as CO_2-equivalents (CO_2e) using the Global Warming Potential (GWP) over a 100-year horizon (GWP100), as given in the IPCC Sixth Assessment Report (IPCC, 2021). The GWP values are unitless values indicating the equivalent global warming potential of a unit of GHG

[1] MEPC 79/WP.10 - Report of the Working Group on Reduction of GHG emissions from ships
[2] Draft guidelines on lifecycle GHG intensity of marine fuels (LCA Guidelines), provided 13 March 2023 for Round 6 of the Correspondence Group on Marine Fuel Lifecycle GHG Analysis.
[3] MEPC 77/WP.6
[4] Hydrogen has recently been shown to be a GHG if released into the atmosphere

relative to a unit of CO_2 over the given time horizon. The GWP values used in this study are 29.8 for fossil CH_4, 27.0 for non-fossil CH_4 and 273 for N_2O.

Assumptions have been made on the carbon intensity of fuels, and the GHG reduction from fossil fuels. These are set out in section 2.2.

1.3.3 Definitions

The following definitions are used throughout this study:

Term	Definition
Advanced biofuels	Second/third generation biofuels made from advanced biomass feedstocks (e.g. waste, algae) that do not compete with food/feed for land use.
Additional energy efficiency measures	A selection of all available future energy efficiency technologies and measures in addition to the BAU energy efficiency measures, such as wind-assisted propulsion and 30% speed reduction, that can contribute to reducing GHG emission and energy demand.
Additional projects	A candidate fuel high availability scenario for 2030, which extrapolates, based on historical growth rates of similar technologies, from all existing announced fuel production projects, assuming additional projects are announced until 2024 which could be commissioned and in operation by 2030
Alternative fuels	All non-conventional fuels, such as LNG, LPG, ammonia, methanol, hydrogen, biofuels, e-fuels
Announced projects	A candidate fuel mid availability scenario for 2030, which assumes all announced fuel production projects go ahead, regardless of whether final investment decisions have been made
BAU trajectories	A candidate fuel low availability scenario for 2040 and 2050 based on the median of availabilities in various business as usual forecasts
Biofuels	Fuels made from biomass. Includes conventional biofuels and advanced biofuels.
Blue fuels	Fuels based on hydrogen made from fossil energy sources with carbon capture and storage (>90% capture rate). Blue hydrogen and blue ammonia.
Business as usual (BAU) energy efficiency measures	A selection of technologies or measures taken up by the fleet in the BAU scenario based on cost effectiveness and compliance with currently adopted policies such as EEDI, EEXI, CII and SEEMP.
Candidate fuels	A selection of fuel paths that have close to zero tank-to-wake GHG emissions and can contribute to achieving the GHG reduction ambitions, while also having significantly reduced well-to-wake GHG emissions. Explicitly the fuels we are considering as among the candidate fuels include advanced biofuels, e-fuels, blue fuels, electricity and fossil fuels blended with bio- or e-fuels with onboard carbon capture and storage.
CO_2 equivalent emissions (CO_2e) and Global Warming Potential (GWP)	CO_2 equivalent emissions is the amount of CO_2 emission that would cause the same integrated radiative forcing or temperature change, over a given time horizon, as an emitted amount of a GHG or a mixture of GHGs. Most typically, the CO_2-equivalent emission is obtained by multiplying the emission of a GHG by its global warming potential (GWP) for a 100-year time horizon. This report uses a 100-year time horizon (GWP100).
Confirmed projects	A candidate fuel low availability scenario for 2030, which assumes fuel production projects with final investment decisions made go ahead
Conventional biofuels	First generation biofuels made from conventional biomass feedstocks (e.g. food and feed crops). The use of this feedstock for fuels may compete with food/feed for land use.

Term	Definition
Conventional fuels	Liquid fossil fuel oils (HFO, LFO) and gas oils (MGO)
Decarbonisation trajectories	Candidate fuel mid and high availability scenarios for 2040 and 2050 based on the median and high end of availabilities in various decarbonisation forecasts
E-fuels	E-fuels or electrofuels are based on hydrogen produced by electrolysis primarily using renewable and nuclear electricity. These are sometimes referred to as renewable fuels of non-biological origin (RFNBO), green, or synthetic fuels.
Exajoule (EJ)	Measurement of energy, 1 EJ equals about 24 million tonnes of oil equivalents or 278 TWh.
Fossil fuels	Fuels from fossil sources including conventional fuels, LPG and LNG
Greenhouse gases (GHG)	Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself and by clouds. This property causes the greenhouse effect (Masson-Delmotte, et al., 2018). There are a number of GHG, and this study includes carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (N_2O).
International shipping	Based on the voyage-based allocation method of international shipping in the Fourth IMO GHG Study, which includes shipping activities which occurs on voyages between two ports in different countries, including the preceding port call.

2 DECARBONISATION SCENARIOS AND GHG REDUCTION TARGETS

Overview

- This section defines three decarbonisation scenarios, each with GHG emission targets for 2030, 2040 and 2050 for international shipping in order to provide a range of possible decarbonisation targets to 2050 compared to a business as usual scenario following currently adopted policies.
- The candidate fuels which can contribute to reaching the GHG emission targets of three decarbonisation scenarios for international shipping are defined. These are fuel paths (including fossil fuels used in conjunction with onboard carbon capture and storage) that have close to zero TtW GHG emissions and can contribute to achieving the GHG reduction ambitions, while also having significantly reduced WtW GHG emissions.
- The section summarises a literature review of WtW and TtW GHG emissions of candidate fuels.

Key findings

- The identified candidate fuels, which have the potential to reduce TtW GHG emissions to zero or close to zero and the scope for large WtW GHG emissions savings, include:
    - Advanced biofuels
    - E-fuels (with and without captured carbon from direct air capture or biogenic sources)
    - Blue fuels using carbon-capture and storage (CCS)
    - Blend of fossil fuels with advanced biofuels/e-fuels and on-board carbon capture
    - Electricity delivered as shore power
- Conventional biofuels have been excluded due to their potentially large WtT GHG emissions and sustainability concerns.

2.1 DECARBONISATION SCENARIOS

In addition to a business as usual (BAU) scenario, three decarbonisation scenarios for international shipping are selected for this study to provide a range of possible decarbonisation targets to 2050, as follows:

- The ***Business as usual*** scenario does not have any absolute emission targets and follows a trajectory based on uptake of energy efficiency and emission-reduction solutions based on cost effectiveness and compliance with currently adopted policies. The adopted policies are the EEDI, EEXI, CII and SEEMP, assuming that the CII reduction factors increase by 2 percentage points per year from 2027 to 2030.[5]
- The ***Initial IMO GHG Strategy*** scenario follows a trajectory matching the (minimum) ambition of the Initial IMO GHG strategy, i.e. reducing total annual GHG emissions by 50% by 2050 compared to 2008.
- The ***80% reduction by 2050*** scenario follows a trajectory where shipping reduces GHG emissions by 80% by 2050 compared with 2008, approximately aligned with the shipping trajectories in IEA's Net Zero Emissions by 2050 scenario (IEA, 2022c) and IRENA's 1.5°C pathway scenario (IRENA, 2021). In this scenario other sectors reduce GHG emissions more than the maritime sector or even achieve negative emissions to enable global net-zero emissions in 2050, according to IEA and IRENA.
- The ***Decarbonisation by 2050*** scenario follows a trajectory where shipping reduces GHG emissions with the same share as other sectors according to IPCC's model pathways with no or limited overshoot of the 1.5°C target, with 45% reduction in 2030 compared to 2010 and reaching zero GHG emissions in 2050 (IPCC, 2018).

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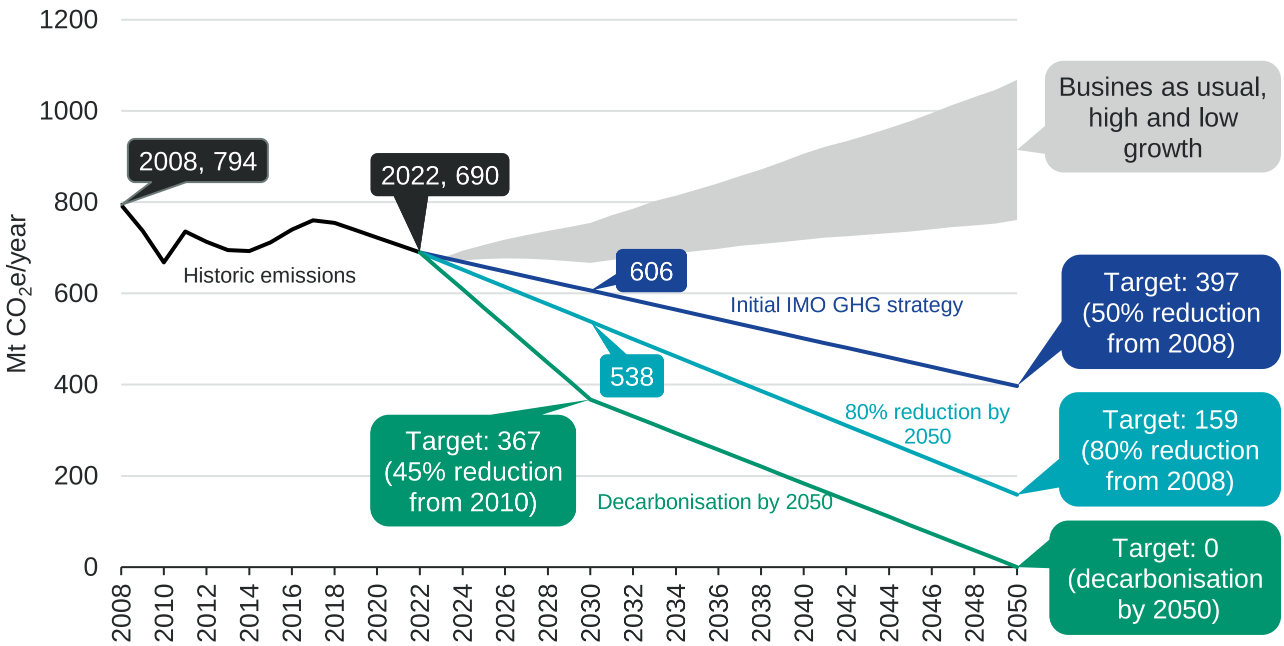
[5] According to the 2021 Guidelines on the operational carbon intensity reduction factors relative to reference lines (CII reduction factors guidelines, G3) (MEPC.338(76)), the reduction factors for 2027 to 2030 will be 'further strengthened and developed taking into account the review of the short-term measure'. This study assumes that the reduction factors are strengthened, similarly as for the years 2023 to 2026, by 2 pp per year.

There is no specific proposal for the revision of the IMO GHG Strategy for a trajectory achieving 80% reduction in 2050. However, this scenario is included to demonstrate possible achievability of the enhanced level of ambition by providing a more fine-grained evaluation of what is feasible. The targets and trajectories for the BAU and three decarbonisation scenarios are shown in Table 2-1 and Figure 2-1. The BAU scenario emissions are taken from Section 5.3.

Table 2-1: Characteristics of decarbonisation scenarios and 2030, 2040 and 2050 targets for TtW GHG emissions

Scenario	Characteristics	2030 target	2040 target	2050 target
Business as usual (BAU)	Shipping reduces emissions according to the currently adopted IMO regulations (EEDI, EEXI, CII and SEEMP)	No target	No target	No target
Initial IMO GHG Strategy	Shipping achieves the (minimum) ambitions of the Initial IMO GHG Strategy	606 $MtCO_2e$ (interpolated)	502 $MtCO_2e$ (interpolated)	397 $MtCO_2e$ (50% reduction relative to 2008)
80% reduction by 2050	Shipping reduces GHG emissions by 80% by 2050	538 $MtCO_2e$ (interpolated)	349 $MtCO_2e$ (interpolated)	159 $MtCO_2e$ (80% reduction relative to 2008)
Decarbonisation by 2050	Shipping reaches zero GHG emissions in 2050	367 $MtCO_2e$ (45% reduction relative to 2010)	184 $MtCO_2e$ (interpolated)	0 $MtCO_2e$

Figure 2-1: TtW GHG emission trajectories for the BAU and three decarbonisation scenarios for international shipping from 2022 to 2050.



Notes: Historical emissions for 2008 and 2012-2018 are based on the Fourth IMO GHG Study 2020 using the voyage-based allocation method, while the emissions for 2009 to 2011 are based on the annual changes from 2008 calculated by the Third IMO GHG Study 2014 using the vessel-based allocation method. Emissions from 2019 to 2021 are interpolated. The BAU emissions from 2022 to 2050 are projected by this study (see Section 5.3). 2040 targets for these scenarios are linearly interpolated between the 2030 and 2050 targets.

2.2 DEFINING CANDIDATE FUELS

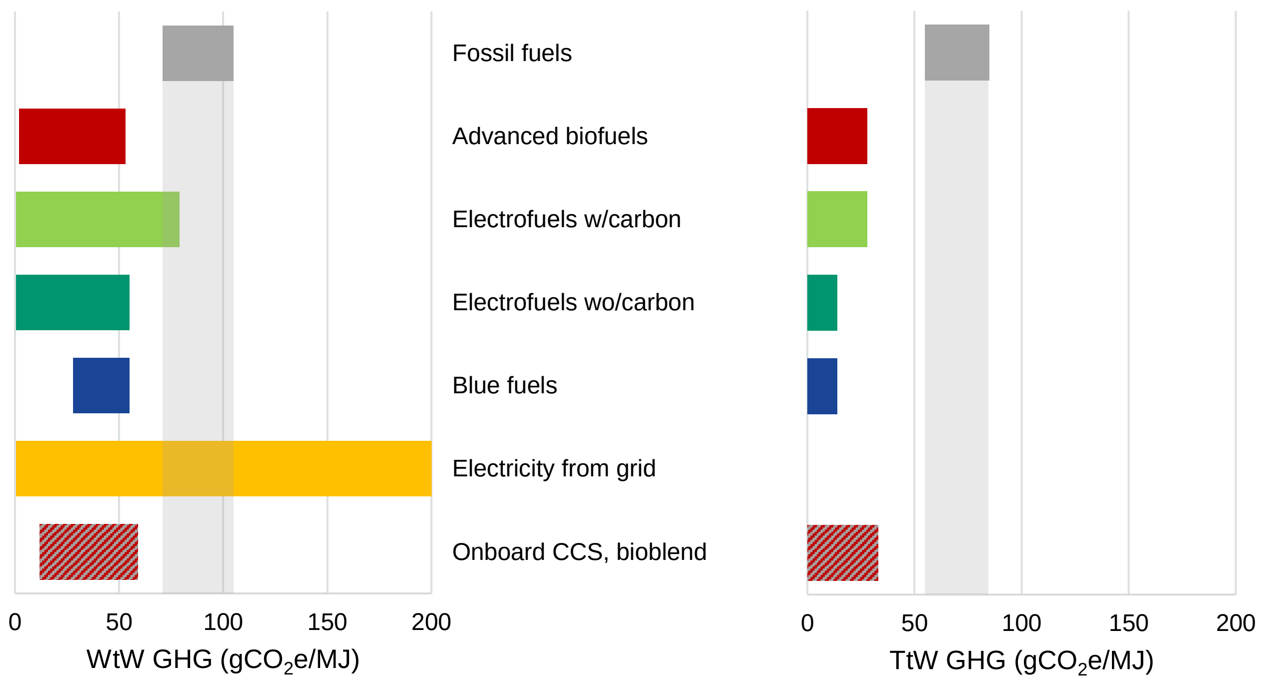
Achieving the decarbonisation scenarios defined in Section 2.1 requires a transition to low-carbon and zero carbon fuels and an uptake of additional energy efficiency measures. In this section, we only focus on the low- and zero-carbon fuels. There are, however, no clear definitions in the Initial IMO GHG Strategy of what low-carbon or zero-carbon fuels are.

To avoid any connotations from other terms and definitions, **this study uses the term 'candidate fuels' to denote fuel paths (including fossil fuels used in conjunction with onboard carbon capture and storage) that have close to zero TtW GHG emissions and can contribute to achieving the GHG reduction ambitions, while also having significantly reduced WtW GHG emissions**. The candidate fuels also include fuels with biogenic carbon or carbon from direct air capture (DAC).

Note that this does not include any energy efficiency measures, including wind-assisted propulsion. These solutions are covered separately in the energy demand calculations (see Section 5.4) as they contribute to reduce the total energy demand, and we here focus on the emissions from onboard energy use.

This study has made a high-level assessment based on available literature of the WtW and TtW emissions of potential candidate fuels. Table 2-2 provides a list of the candidate fuels considered in this study with a short explanation and example of fuel types / energy carriers, and ranges of potential GHG emission reduction based on a literature review. Appendix 1 has more details on the WtW and TtW assessment and considerations. Figure 2-2 shows the ranges of WtW and TtW GHG emission per candidate fuel from Table 2-2.

Figure 2-2: Well-to-wake (left) and tank-to-wake (right) GHG emissions ranges per candidate fuel.



All the candidate fuels identified in Table 2-2 can reduce TtW GHG emissions to zero or close to zero. For onboard carbon capture[6], a blend of biofuels/e-fuels and fossil fuels needs to be applied to achieve zero-or close to zero TtW GHG emissions.[7] The WtW and TtW GHG emission with a bio-blend is shown here. The WtW GHG emissions can also potentially be significantly reduced compared to the reference fossil fuels. However, the candidate fuels, depending on the primary energy source, production pathway and energy converter, also have the potential for both large WtT and TtW GHG emissions. For this reason, conventional biofuels are excluded. Electricity from the grid also has potentially high WtW GHG emissions, though this is included as it also has the potential to reach zero WtW GHG emissions. For the purpose of this study, candidate fuels are assumed to have zero TtW GHG emissions.

[6] The CO_2 captured onboard is assumed to be temporarily stored onboard before removal to landside infrastructure for permanent storage.
[7] Conventional biofuels have not been considered as candidate fuels due to concerns of wider environmental impacts such as land use.

Table 2-2: Candidate fuels with production paths and potential tank-to-wake (TtW) and well-to-wake (WtW) GHG emission reduction compared to fossil fuels. See Appendix 1 for the assessment.

Fuel	Description	Possible fuel types / energy carriers	GHG reduction (% from fossil fuel reference)	
			TtW	WtW
Fossil fuels (reference)	*Fossil fuels*	*HFO, LNG, LSFO, MGO*	*55–85* gCO_2e/MJ	*71–105* gCO_2e/MJ
Biofuels	Fuels made from advanced biomass feedstocks (e.g. waste, algae)	biomethanol biomethane biodiesel	67–100%	50–98%
E-fuels	Fuels based on hydrogen produced by electrolysis using primarily renewable or nuclear electricity, with no carbon content	e-hydrogen e-ammonia	84–100%	48–100%
E-fuels	Fuels based on hydrogen produced by electrolysis using primarily renewable or nuclear electricity, combined with carbon from biogenic sources or direct air capture	e-methanol e-methane e-diesel	67–100%	25–100%
Blue fuels	Fuels based on hydrogen made from fossil energy sources with carbon capture (>90% capture rate) and permanent storage	blue hydrogen blue ammonia	84–100%	48–73%
Electricity	Grid electricity produced from a mix of fossil and renewable sources	Electricity provided as shore power	100%	90% increase to 100% reduction
Fossil fuels and onboard carbon capture and storage	Fossil fuels blended with 30% advanced biofuels or e-fuels with onboard carbon capture (>70% capture rate) and permanent storage.	HFO, LNG, LSFO, MGO – blended with biodiesel, biomethane, e-diesel or e-methane	61–100%	44–89%

The reduction values are relative to the higher fossil fuel reference values. TtW' includes CO_2 emissions from combustion of biogenic carbon or carbon from DAC. See Appendix 1 for details.

3 TECHNICAL AND COMMERCIAL READINESS

Overview

This section:

- Identifies and assesses the technical and commercial readiness of energy efficiency technologies and candidate fuels and their pathways out to 2050, which are required to achieve three decarbonisation scenarios and its GHG reduction targets identified in Section 2.
- Establishes an understanding of what the technology readiness level (TRL) and commercial readiness level (CRL) is of each of the technologies and fuel pathways now, and how they are forecast to develop to 2050.
- Considers onboard technologies such as propulsion devices and energy efficiency measures, as well as candidate fuels, their production pathways and the supply to the vessels and onboard use.
- Draws on literature from published sources, existing work, and expertise from DNV and Ricardo, and consultations with experts.

Key findings

- Several energy efficiency technologies are already mature with potential for greater roll-out. Other energy saving technologies are already operating commercially or transitioning to commercial development by 2030, providing event further potential for greater uptake.
- On fuel production pathways:
    - Biofuel production pathways are in commercial development and forecast to be fully mature before 2030.
    - E-fuel production pathways are transitioning to commercial operation today, forecast to reach full maturity in the 2030s.
    - Blue hydrogen and ammonia production pathways are forecast to reach full maturity before 2030 and mid-2030s respectively.
- Fuel combustion engine technologies with new candidate fuels are forecast to reach commercial operation by 2030 whereas fuel cell technologies may take until the late-2030s to fully mature.
- There is uncertainty around the development of onboard CCS beyond first commercial operation forecast to be in the early 2030s based on currently available information.
- More positively, **these forecasts could be considered as maximum durations to commercialise, because if demand was higher – through a more ambitious Revised IMO GHG Strategy and supporting policies – technology development would accelerate**.[8] This is because the forecasts are based on existing literature and expertise, which have an inherent unconscious bias because they are grounded in the context of a demand set by the Initial IMO GHG Strategy and without an agreed set of policies to achieve the ambition of the Initial Strategy.
- Therefore, it is concluded that **the technologies and fuels needed to meet the demand of a more ambitious decarbonisation scenario will be technically and commercially ready in time**. Or in other words, the roll out of technologies and fuels needed to meet demand is not expected to be hindered by their technical and commercial readiness. This finding was a key theme from the experts engaged to validate the findings of the literature review.

3.1 METHODOLOGY

The readiness of fuel production and energy efficiency technologies and the fuels for commercial use in shipping is evaluated using technology readiness level (TRL) and commercial readiness level (CRL) scales. TRLs have been a widely used concept for several decades, originating from NASA (NASA, 2012) using a numerical scale of 1 to 9. CRL scales have been developed to assess the commercialisation of a technology or product, which may be limited by cost competitiveness and other barriers to market. In this study the analysis

[8] Similar arguments have been made or implied in previous submissions (e.g. ISWG-GHG 13/3/3): that projections of future commercialisation based on current technology development often underestimate what is possible if increased demand is specified.

on TRL and CRL has been completed following IEA's methodology (IEA, 2020a), where the following combined readiness level sequence has been considered (Figure 3-1):

Figure 3-1: Extended sequence of TRL and CRL as used to evaluate technical and commercial readiness

Maturity	Rating	Description of readiness level
Basic research	TRL1	Basic principles of scientific research observed and reported
	TRL2	Invention and research of practical application
	TRL3	Proof of concept with analytical and experimental studies to validate the critical principles of individual elements of the technology
Development	TRL4	Development and validation of component in a laboratory
	TRL5	Pilot scale testing of components in a simulated environment to demonstrate specific aspects of the design
	TRL6	Prototype system built and tested in a simulated environment
Demonstration	TRL7	Prototype system built and validated in a marine operational environment (including small-scale/auxiliary use/demonstration deployments)
	TRL8	Active commissioning where the actual system is proven to work in its final form under expected marine operating conditions (pilot/trial deployments)
Deployment: early adoption	TRL/CRL9	Operational application of system on a commercial basis – technically ready but a limited number of vessels/first-of-a-kind facilities
	CRL10	Integration needed at scale: solution available commercially but needs further integration efforts to achieve full potential – may be 100's or a few 1000 vessels or small number of at-scale facilities, small share of market
Mature	CRL11	Proof of stability reached, with predictable growth

Colour indicates readiness level shown on figures through this section

The definitions for each level were used to evaluate evidence to rate the maturity of technologies. Little consistent evidence could be found through reviewing literature to support the assessment of commercialisation of technologies through their expected costs and competitiveness, although some cost information was gathered (e.g.: around the costs of vessels using the candidate fuels) and is discussed in Section 7. A more consistent assessment of commercialisation was found to be the expectation of market uptake, whether that is number of vessels, fuel production facilities, or penetration of the market, and so the evaluation of commercial maturity in this section is based on such forecasts of volumes achieved and market uptake. Therefore, a CRL of 9 or even 10 may not imply a technology is competitive from a cost perspective, as there may be non-cost drivers for development and early adoption.

It must also be recognised that the assessments reflect the current forecasts of the development and commercialisation paths of the technologies, which themselves are influenced by both expected costs and the current or expected policy landscape. Commercial development of all technologies and fuels that are not yet mature will depend on non-technical factors creating a demand for the technology or fuel. These include the costs of candidate fuels compared to conventional fuels (considered in Section 7), and the costs of technologies and the efficiencies they enable. Regulatory factors also have a significant influence, such as which fuels will be favoured (or restricted), how their sustainability will be assessed (such as different feedstocks for biofuels the use of captured carbon in e-fuels), and how onboard CCS will be treated.

The process used to evaluate the TRL and CRL of the technologies and fuels covered several stages as set out in Figure 3-2. This brings together internal and external literature with an internal review and consultation with industry experts.

Figure 3-2: Process for evaluating technology and fuel TRL/CRL

A tabular system of formalising the assessments was established which enabled the information for TRL and CRL level projected over time (from the present until 2050) to be collated, maintaining reference to the sources used to inform the assessments, and allow expert review. The literature review considered well over 100 published sources including reports and studies, technical papers, press releases, and manufacturer and supplier websites, as well as internal documents from Ricardo and DNV.

The external consultation was carried out over a period of 3 weeks. Experts consulted included representatives of shipowners, shipyards, technology suppliers (covering engine and fuel cells), and fuel producers, and was used to verify the evaluations from literature, addressing any discrepancies and gaps, and gain deeper insight. While this represents a consultation with a limited number of experts it is hoped that the publication of this study gives an opportunity for a larger number of experts to provide feedback.

The scope of the evaluations was set out as detailed in Table 3-1.

Table 3-1: Scope of technology and fuel readiness evaluation

Area	Included in scope	Excluded
Energy efficiency technologies and measures	Energy saving vessel design characteristics	Operational measures not dependent on technology maturity (e.g., hull cleaning)
	Propulsion efficiencies	
	Other vessel operation efficiencies (including slow-steaming)	
	Energy reduction/assistance technologies	
Wind assistance	Wind propulsion assistance technologies	Non-commercial vessel use
Shore power	Use of shore power (cold ironing)	Grid electricity generation
Candidate fuel production	Candidate fuel and energy carrier production pathways	Unabated fossil fuels
	Key candidate fuel and energy carrier production process individual stages	Resource extraction or electricity generation
Candidate fuel powertrain technologies	Electricity	Nuclear and gas turbine (see section 3.6.4
	Internal Combustion Engine	
	Fuel Cell	
On-board CCS	Carbon capture (on-board)	Land-based storage

The sections below present the findings from this evaluation process. A full list of the technologies assessed is provided in APPENDIX 6 along with the evaluated TRL/CRL projections and the key literature sources used. The graphics indicate the approximate timescales for the achievement of key TRL/CRL levels as defined in Figure 3-1, and should be considered as indicative and based on existing literature and expertise.

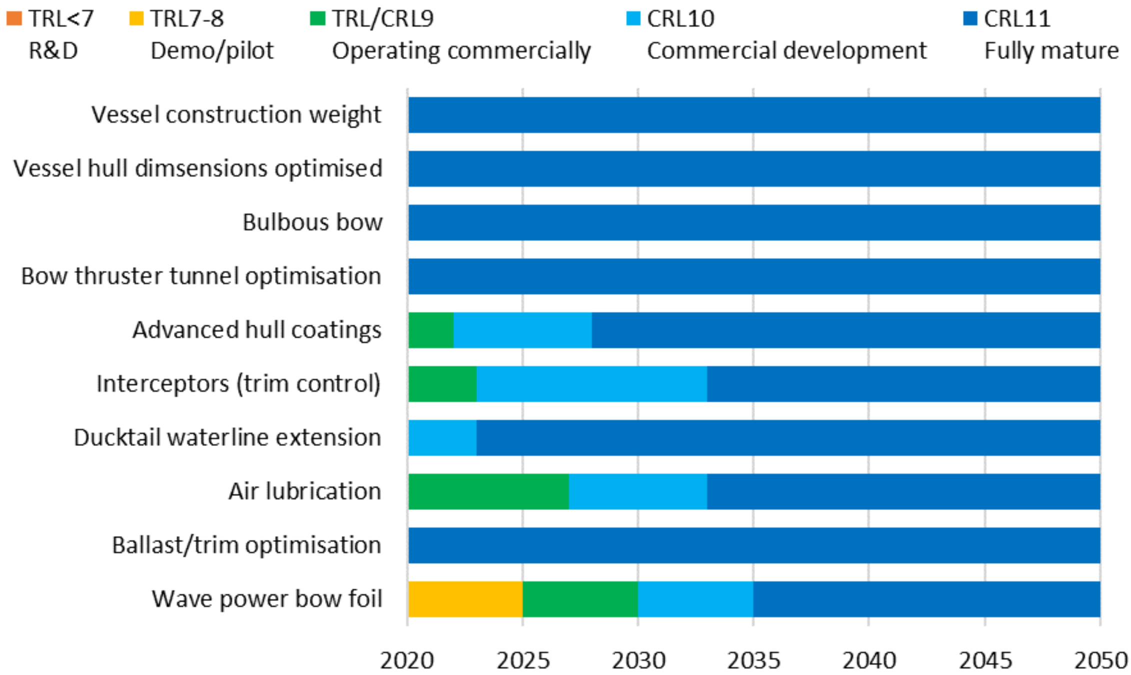
3.2 ENERGY EFFICIENCY TECHNOLOGIES AND MEASURES

In 2021 the IMO adopted a set of short-term measures to reduce the carbon intensity of all ships by 40% by 2030 compared to 2008 levels (IMO, 2021). These short-term measures included the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII), which added to the already adopted Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). Ships are required to calculate their yearly operating CII and EEXI, and depending on their levels of carbon intensity, they are awarded with a rating from A to E of their energy efficiency. To achieve a positive rating, a mix of operational and technical solutions are required. These solutions can include improving the ship's design through various methods, reducing power demands onboard, and using wind energy to assist in the vessel's propulsion, as evaluated in this section. The technologies cover a range of different maturity stages, and many are continuously evolving, although a significant number have already reached commercial readiness to some degree and have been deployed on commercial vessels. Nonetheless, there exists scope for further deployment of technologies that are ready for commercial use but have not yet adopted in large scale.

3.2.1 Vessel design

A range of processes and methods which can be applied to improve and optimise a vessel's efficiency through its design and construction have been evaluated for their technical and commercial readiness as shown in Figure 3-3. Some industry-wide established solutions have been identified as fully mature as they have been implemented, tuned, and improved by naval architects and engineers for many years.

Figure 3-3: Forecast of readiness and availability of vessel design technologies



The hull's shape and design lines play a very significant role in the vessel's sailing performance, speed and resistance which directly translates to fuel consumption. There exist various software and digital solutions to optimise different virtual hull models to develop the **optimal hull and structural arrangement of the vessel**, which lead to **construction weight savings**, thus reducing the hull's resistance and fuel consumption. In that context and in terms of hull design, the bow of the vessel has always been a matter of optimisation as it contributes significantly to the vessel's water resistance. One of the most efficient solutions is that of the **bulbous bow**, which is a protruding bulb-shaped structure located at the bow and it has been fitted to ships from the last century. Studies suggest that it can help reduce the vessel's resistance improving fuel consumption by 15% (Ye, 2015), while also reducing wave-making resistance since the effective waterline length is increased leading to smaller ship displacement. The **optimisation of the bow thruster tunnel** opening, located port and starboard of the bulbous bow, has been researched by the industry and academia to assess its fuel savings contribution and the levels it impacts the vessel's resistance, and it has been widely used in commercial applications. These are evaluated as mature technologies (CRL11)

Advanced hull coatings that are applied to the exterior of the hull to mitigate corrosion and damage, typically applied in 5-year intervals. Coatings that lower the vessel's resistance offer fuel efficiencies, and can consist of epoxy, polyurethane, and silicon amongst others. This technology is applicable to all types of vessels, and higher friction reduction potential can be observed to vessels with higher block coefficients (that is, more full-bodied ships) (GloMEEP, n.d.). Friction-reducing hull coating is considered technically developed and ready (TRL9), already applied in commercial operations, and is expected to become more competitive moving forward, reaching full maturity (CRL11) before 2030.

Interceptors are metal plates vertically placed below the transom of the ship. Due to the high-pressure area behind the propellers, this plate bends the flow over the back of the ship downward, producing a lift effect similar to that of a traditional trim wedge (Wärtsilä, 2008). These are technically mature (TRL9) being widely applied in faster boats and recreational craft, and although fitted to some cruise ships and Ro-Ros there is some potential for commercial growth, although they may not be suited to many commercial vessels.

Extending the ducktail area of a ship elongates the waterline which reduces resistance. This is seen in smaller vessels and some commercial vessels such as cruise ships, but although a commercialised method of reducing fuel consumption (CRL10-11), it may not be widely applicable to all vessel types.

Air lubrication systems have been placed by the IMO (MEPC.1/Circ.815) in the "Innovative Energy Efficiency Technology" category, and thus it is a technology that is expected to offer further fuel savings in the future. Efficiencies are achieved by pumping air underneath the area of the hull directly in touch with the liquid flow, or, in the case of discrete bubbles, by altering momentum conveyance and average density in the boundary layer (American Bureau of Shipping, 2019). Since the 1980s there have been a few manufacturers and developers testing and applying in small scale this technology, but to date it hasn't reached the deployment levels that were expected and globally there are less than 100 ships utilising air lubrication systems (American Bureau of Shipping, 2019) (TRL9). Experts were interested in this technology, but it was reported that the operational profile of the vessel and wave and weather conditions significantly affect this "air mattress", limiting its effectiveness. Nonetheless, further development is expected to improve its effectiveness and competitiveness by late 2020s, reaching maturity (CRL11) by 2035.

Optimising ballast and trim during voyage is a method that has been in use for more than 30 years (CRL11) to optimise the vessel's deadweight and the dynamic positioning of the hull while sailing.

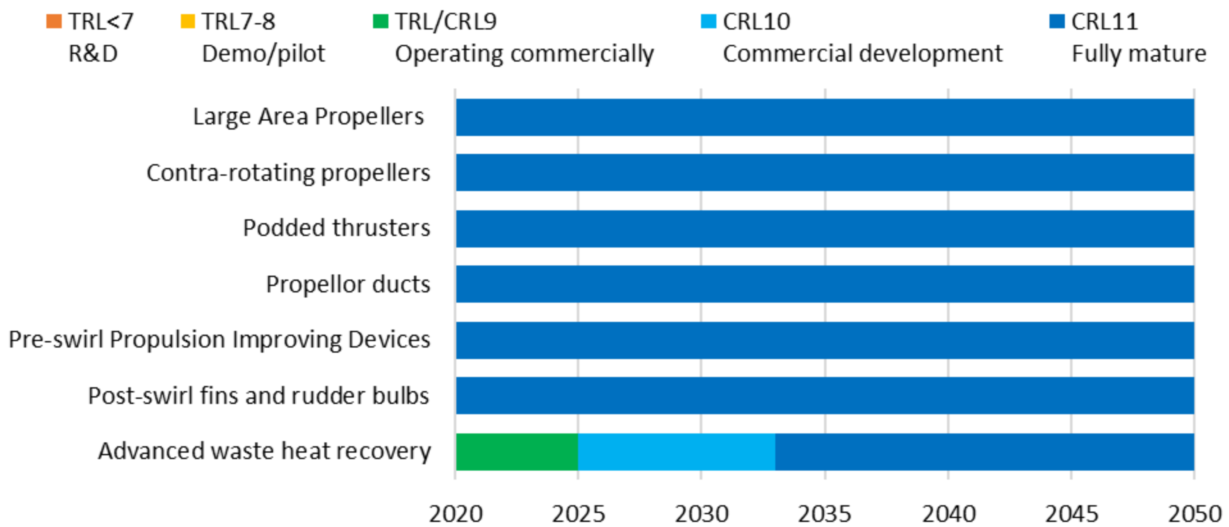
A more recent innovation is the development of **wave power bow foils** which utilise wave motion and power to assist the propulsion of the vessel, rather than act against it. This relatively simple technology is said to offer 5% to 15% fuel savings depending on vessel and sea state (J.A. Bowker, 2022) (Wavefoil, 2023), is being demonstrated on several vessels (TRL8), and is entering commercial use (TRL9). If the expected fuel savings are established at relatively low cost the technology has the potential to commercialise rapidly being retrofittable.

Although some of the more recent technologies mentioned offer some percentages of fuel savings, consulted experts highlighted that their application may not be suited to all vessel types, and fuel savings offered by these solutions may not achieve the scale that the industry needs to reach its future goals.

3.2.2 Propulsion assistance and efficiency technologies

The efficiency of the propulsion system is key to the vessel efficiency, and a range of technologies exist from the powertrain through to the propellor. Many of these are established and mature although continued development and improvement can increase benefits or applicability. A selection of such technologies is evaluated for current and future readiness in Figure 3-4.

Figure 3-4: Forecast of readiness and availability of propulsion efficiency technologies



Propeller Technologies. Large area propeller (LAP) is a widely commercialised (CRL11) technology which is implemented through moving the propeller aft behind the hull and thus increasing its diameter together with its efficiency (Knutsson & Larsson, 2011). Plenty of research has been conducted in this design of larger-diameter propellers and was proved that besides better propulsive efficiency, improved hull efficiency, suction on the hull and wake profile were achieved (Duplex, 2015). Another propeller-related technology that assists in lowering ship emissions are **contra-rotating propellers** (CRP). This concept is realised through placing a pod behind the main propeller which rotates in the opposite direction of the main propeller, and thus recuperates some of the lost energy from the rotating flow behind the propeller at the front (Ricardo, 2022). CRPs are being researched widely in academia, and subsequently manufacturers have been developing this technology and deploying it to several vessels in recent years (Jukola & Ronkainen, 2006) (CRL11).

Thruster technologies. Podded thrusters are one of the most efficient alternatives to the classic propeller design, with several manufacturing companies producing and deploying such hardware. They have been commonly used and commercialised for many years (Carlton, 2012; Eyres & Bruce, 2012) (CRL11) and offer several advantages. **Podded thrusters** combine propulsion and manoeuvrability in one system by attaching a fixed propeller to a rotating body, allowing the vessel to steer and sail more efficiently. With this solution, propeller shafting can be removed from the vessel, providing more valuable space which can be exploited to carry increased quantities of cargo or provision and thus save emissions per ton of cargo, and so this technology has been commercialised (CRL11). Another mature (CRL11) technology offering improved energy efficiency to the vessel are **propellor ducts**, or more commonly known as Kort nozzles. These are ring-shaped ducts, with hydrofoil cross-section, that surround the propeller (Wärtsilä, 2023). They have been well developed by the maritime industry in the last years and their application can be found in various sea-going vessels.

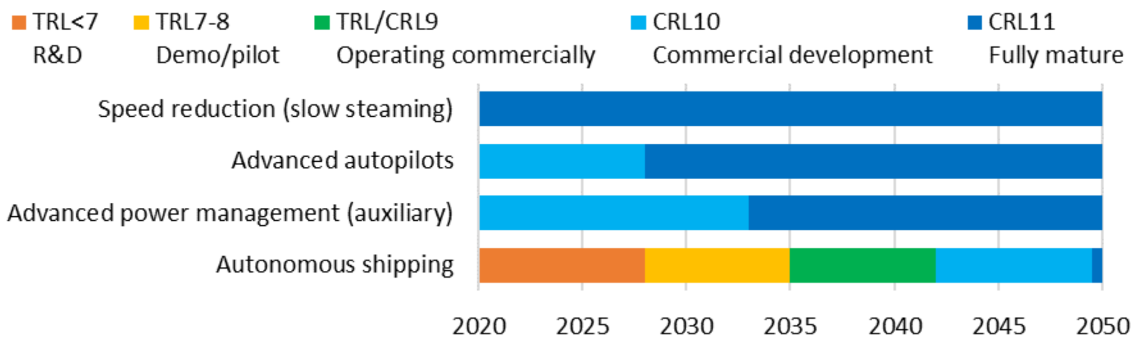
Swirl-based hardware. Propulsion Improving Devices (PID) have been used by the industry to improve the vessel's energy efficiency. One of these technologies is a **pre-swirl** PID, which is mounted immediately before the propeller and essentially pre-corrects the flow that the propeller faces, while at the same time reduces power losses (Hollenbach & Reinholz, 2011). This device is fitted in most vessel types but usually to faster vessels, such as containerships and Ro-Ro vessels, while energy savings from this technology can range from 3% to 9% (GloMEEP, 2016). On the other hand, post-swirl PIDs, another element identified as an energy efficiency solution, are responsible for conditioning the flow at the aft end of the propeller. This entails converting the rotating components of the propeller-generated flow into usable axial flow. Others only need to reduce undesirable flow features (such as the vortex at the propeller hub) or to reroute issues caused by the uneven loading of the port and starboard blades (ABS, 2011). These devices have been used in various shipping applications and have been widely commercialised and available in recent years (CRL11).

Advanced waste heat recovery. While there are well established methods to recover some waste heat, advanced technologies can be used to recover more low-grade waste heat energy from the engine exhaust or cooling systems to provide useful electricity or shaft power, thus reducing the fuel consumed to power the vessel as well as the overall emissions produced. These include the use of exhaust turbine and thermo-electric generators, organic Rankine and Kalina cycle systems, and other novel thermodynamic cycles, which have seen development for marine applications in recent years. The IMO Global maritime energy efficiency partnership has estimated that savings of 3% to 8% are possible although there may be practical lower limits on engine size and retrofitting might be difficult (IMO-GLOMEEP, 2023), while other sources support its viability for smaller ships with variable operating profiles (Wee, 2022). Although there are relatively few such systems in use in vessels currently, these technologies are now available and operating commercially (TRL9) (The Maritime Executive, 2021) and increasing pressure to improve fuel efficiency are expected to see them mature with widespread adoption (to CRL11) over the next 10-15 years. Advanced waste heat recovery systems can also be applied to high-temperature fuel cells.

3.2.3 Voyage / operational measures

Energy efficiencies can be made in the management of vessels during voyages. The readiness of technologies and measures in this area is summarised in Figure 3-5.

Figure 3-5: Forecast of readiness and availability of voyage / operational efficiency technologies



Reducing the speed of a ship during a voyage is known to save fuel and energy, a tactic that has become widely used in recent years to mitigate the carbon footprint of the ship. “Slow steaming”, as it is known in the industry, has become established as a sector-wide trend (CRL11) since mid-2008, and the IMO has recommended that researchers look into the advantages of a speed reduction while considering safety concerns, the distance travelled, market or trade distortion, and keeping in mind that such a measure has no impact on shipping’s ability to reach remote geographic areas (Degiuli, Martic, Farkas, & Gospic, 2021). However, a concern for this measure is that this approach can increase the time of a round trip by 10%-20%, which directly translates to a requirement for an increased number of actively sailing ships if the same service level is maintained, which will reduce the positive impact that the lower speeds offer (Degiuli, Martic, Farkas, & Gospic, 2021). As the benefits of slow steaming vary depending on the types, sizes and routes of the ships, these benefits can be further increased by applying additional technical solutions (Dere & Deniz, 2019).

Another measure to reduce energy on board and optimise the ship’s fuel and energy consumption is **advanced power management** of auxiliary power use. This is a technique that has been implemented in vessels in recent years through optimising operational profiles and using low-energy equipment. Components of advanced power management systems are the Energy Management System (EMS), which monitors and controls the power distribution and energy consumption, the Battery Energy Storage System (BESS) which is storing excess energy and releases it in times of need, as well as accommodation and hotel lighting management systems which reassure that the hardware used is the highest available in terms of efficiency. As part of the readiness assessment, this technology has been characterised as approaching maturity (CRL10 today, forecast to transition to CRL11 in around 10 years).

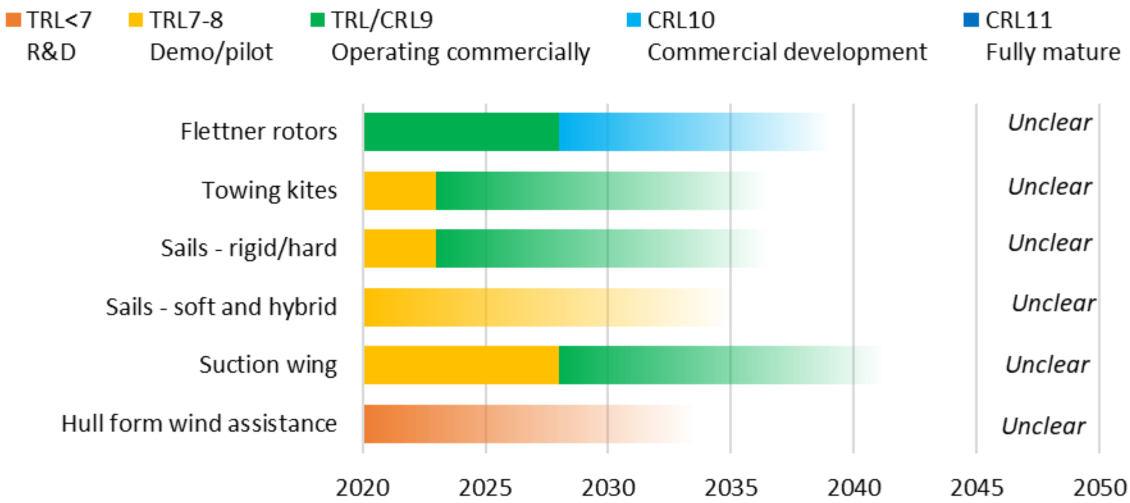
Advanced autopilots also assist in voyage optimisation, as they have been broadly used to offer the ship a level of navigation autonomy. Autopilots control the vessel’s speed and course by adjusting the steering in response to changes in sailing conditions and they also provide dynamic position keeping. The technology behind them has been very mature and used in a lot of applications (Korchanov & Veremey, 2000). More recent solutions determine the optimal fuel-efficient course for the vessel to travel using real-time data on weather, ocean currents and overall ship performance, and required schedules and just-in-time arrival, reducing energy use for the voyage. Moreover, some autopilots offer energy monitoring capabilities, which help monitoring the on-board energy consumption and adjust operations accordingly. These recent developments are still being commercially developed (CRL10) and forecast to mature in the next few years.

Autonomous shipping is a novel concept which is said to benefit efficiency through not requiring crew living quarters and stores, allowing more space for cargo. According to literature (Makkonen, Nordberg-Davies, Saarni, & Huikkola, 2022) autonomous solutions go beyond conventional (remote) services since they have the technological capacity to decide and learn from experience to optimise operations outside of the confines of specific boundaries using artificial intelligence models. Currently at a research and development stage (TRL6), it is currently an immature technology for which adequate regulations are still needed and must be proven in all operational and weather conditions. Although the autonomous shipping industry has been forecasted by some to expand by 20 times (vs 2019 levels) by 2030 (Koscielecki, 2019), it is expected to take at least 10 years to be ready for commercial operation (TRL9) and full maturity (CRL11) may not be reached until 2050. Concerns over its significance (limited benefit) for GHG emissions and extent of future uptake are raised by the consulted experts, who highlighted that this technology is a long way from being ready for commercial use and that lack of approvals and robust legislative frameworks are not the only burdens to overcome.

3.3 WIND ASSISTANCE TECHNOLOGIES

Wind propulsion assistance technologies have been considered in this paper as energy saving technologies to reduce the demand on using fuel for propulsion. The use of renewable wind energy for ship propulsion is – using sails – an ancient technology, but its application to modern commercial vessels is novel. Wind assistance technologies offer potential fuel savings (IMO, 2022a), but are mostly at prototype and demonstration stage, as seen in the Figure 3-6. Since their effectiveness and practicality is not yet widely demonstrated, their potential for commercialisation across shipping remains unclear. Estimates for their potential fuel saving impact vary significantly and will depend on the vessel type and the route considered. Nonetheless, some sources (E4tech, UMAS, Frontier Economics, 2019) and experts suggest that wind power could play an important role in the future of decarbonising the industry, and the technologies could commercialise rapidly if shown to be effective and incentivised by rising fuel costs.

Figure 3-6: Forecast of readiness and availability of wind assistance technology



Flettner rotors are a form of auxiliary ship propulsion, powered by the wind, and they are effectively a cylinder installed vertically on the deck of a vessel with a disc, called endplate, located on top. These have achieved sufficient readiness levels for commercial use (TRL9) with a few tens of vessels already sailing or soon to be deployed using them, although estimates of their potential fuel savings vary between 1% and 50% (Chou T. , Kosmas, Acciaro, & Renken, 2021), or 5% and 23% (CE Delft, 2016). Their commercial development is expected to accelerate (CRL10) from the late 2020's, but their use will not be suited to all vessels[9] and market penetration will depend on fuel/cost savings achieved, and so their potential for future commercialisation is unclear.

Towing kites have achieved pilot demonstrations (TRL8) and are approaching the required readiness level for commercial operation (TRL9), which is expected before 2025. Estimates for their fuel saving potential varies between 1 % and 50% (Chou T. , Kosmas, Acciaro, & Renken, 2021) or 3% to 5% (CE Delft, 2016). According to different experts they might be an effective solution for auxiliary propulsion, but as with Flettner Rotors they will not be suited to all vessels, and so until their practicality and effectiveness has been more widely demonstrated their commercialisation path (CRL10-11) is unclear.

Rigid and soft sail technologies have also been evaluated but show lower levels of maturity for commercial shipping with only prototypes planned at this stage. Rigid sails show a higher level of maturity (TRL8) as than soft sails (TRL7) there are a few vessels piloting this technology with more planned (Chou T. , Kosmas, Acciaro, & Renken, 2021) suggesting readiness for commercial operation (TRL9) is to be achieved soon. The same source provides estimates of potential fuel savings between 5% and 60%.

Suction wings are non-rotating wing sails with vents and internal fan, such as the e-SAIL and the Turbosail. This technology is also at the pilot demonstration stage (TRL8) and expected to start operating commercially before 2030 (Finland, et al., 2022) (TRL9).

There has been no indication of commercial application of **hull form wind assistance**, besides some theoretical concepts introduced in recent years (TRL3). This concept's hull functions as a very large aerofoil, using wind energy to lift and move the ship while onboard software can potentially track weather forecasts to determine the optimal route (LadeAS, 2013). Wider commercialisation of these technologies is again unclear until they have been effectively demonstrated.

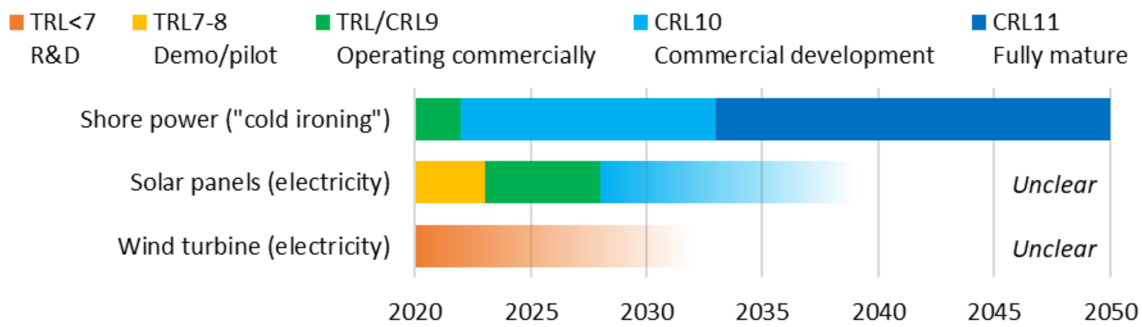
Wind assistance can be considered as a propulsion technology, and essentially utilises an alternative renewable energy source. However, the outcome of using wind assistance for commercial vessels is a reduction in the use of a primary fuel, which can offset costs and limited bunkering capacity of the candidate fuels as well as reducing any GHG emissions (TtW or WtW) due to the primary fuel use. The approach used in this study considers wind assistance amongst the measures that reduce fuel energy demand, in effect as an efficiency measure.

[9] Literature indicates the highest potential for bulk carriers and limited potential or suitability for container or passenger vessels for example.

3.4 SHORE POWER AND ELECTRICAL ASSISTANCE

Powering a vessel's electrical needs from a shore connection when in port removes the need to run on-board engines, addressing local air quality, and, as the local electricity grids decarbonise, reducing GHG emissions. This is known as shore power, or cold ironing. The readiness of shore power, along with other technologies for electrical assistance using on-board renewable energy sources, is evaluated in Figure 3-7.

Figure 3-7: Forecast of readiness and availability of shore power and electrical assistance



The use of **shore power** has been common for smaller vessels (and naval vessels) for many years, but the electrical demand of larger vessels (which can reach 10 MW, or even 20 MW for cruise ships) has been a barrier to wider adoption. Increased concern for air pollution around ports and ambition for decarbonisation has led to interest for larger vessels to plug-in when in port, helped by common international standards. As of 2020, around 4500 vessels (>5000GT) were thought to be equipped with shore power capability, and although this is a small proportion of the total fleet, around 15% of container vessels had shore power capability (British Ports Association, 2020). Worldwide, around 150 berths were identified as being equipped for shore power, many of which were provided with the help of government funding. Wider provision of shore power is being mandated in the EU, California, and China (U.S. Environmental Protection Agency, 2022).

This suggests commercial development of shore power has started (TRL10) and could progress rapidly, but there are barriers. Installing shore power has a high cost, requiring high-capacity electricity network upgrades and equipment to match electricity voltage and frequency to the vessel. Lack of consistent demand from vessels means commercial returns are uncertain, especially where electricity costs (and taxation) compared to fuel prices may not incentivise its use. From the vessel perspective, while a shore power connection can be retrofitted, the incentive to do so depends on cost of installing and using it compared to the fuel use saved, which in turn depends on how widely available it is. There is evidence of significant growth in the use of shore power, and while it is expected to need to be supported by favourable measures, not least to overcome the "chicken-and-egg" situation, maturity with widespread use could be achieved within a decade.

Renewable electricity generation technologies could supplement a ship's electrical load, saving energy demand from the engines. **Solar panels** are fully mature on land, have been used on large cargo vessels in pilot demonstrations (TRL8), and are starting to enter the market commercially (TRL9). In theory solar panel technology is ready and relatively easy to deploy, but their use is limited by practical constraints on the area of the vessel that can be covered and by the contribution they bring to meeting auxiliary power demand being limited. This means the extent of possible commercialisation is unclear. **Wind turbine** power generation is also possible, but marine applications appear to be limited to theoretical concept studies (TRL3). The practical constraints and the limited benefits, especially compared to wind assistance for propulsion (Section 3.3), suggest on-board wind turbines are unlikely to be deployed in the foreseeable future.

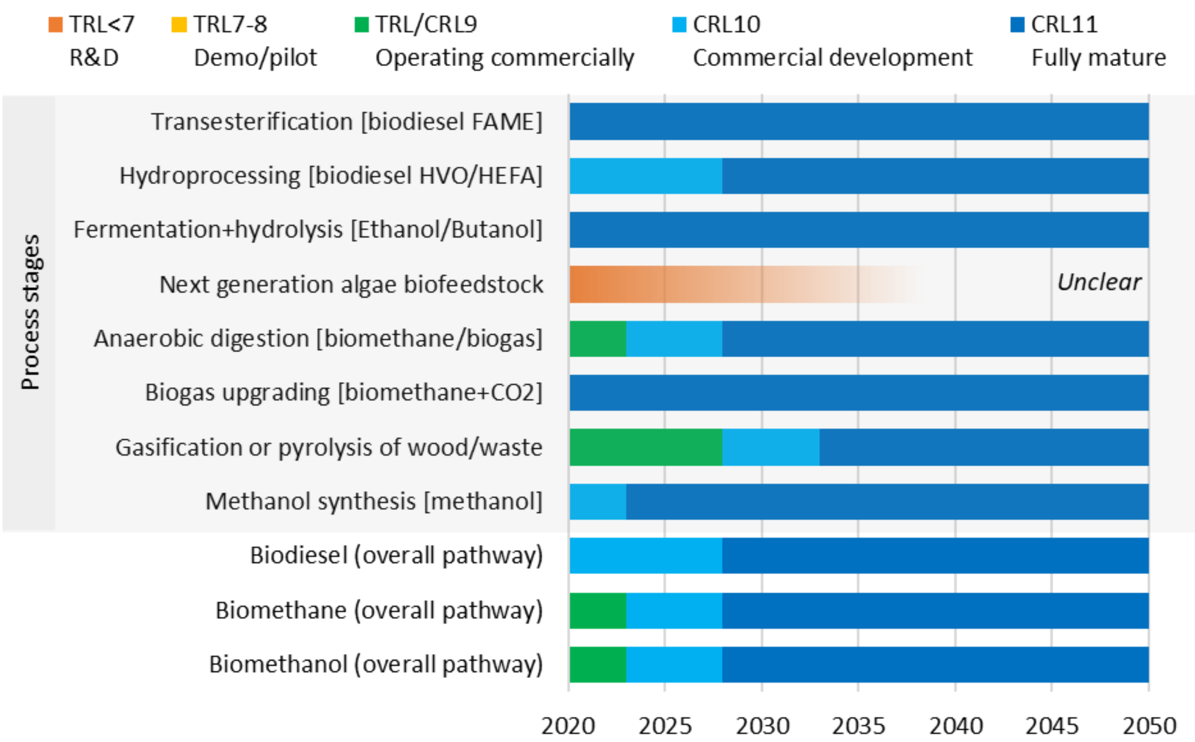
3.5 CANDIDATE FUEL PRODUCTION

A range of alternative (non-conventional) fuels with potential to reduce GHG emissions on a TtW or WtW basis were identified in Section 2.2, but many of these candidate fuels are not widely available today, and their production requires technology that in some cases is still in development.

3.5.1 Biofuels

Advanced biofuels using waste biogenic feedstocks are increasingly being favoured by policymakers[10] due to the sustainability concerns around crop feedstocks, and their lower WtW emissions. In this study a range of biofuel production pathways are evaluated that can use waste feedstocks, although in most cases the key production stages are similar regardless of the source of the feedstock. Production stages may be used for different types of biofuels, while a type of biofuel may be produced by different methods. The permutations of fuel types, process stages, and compatible feedstocks can therefore be quite complex. In this evaluation we have identified key technologies in the production of biofuels and considered the typical or most likely overall pathway for the biofuel types that are most relevant to maritime. The readiness of these process stages and fuel pathways is shown in Figure 3-8.

Figure 3-8: Forecast of readiness and availability of biofuel production stages and overall pathways



Biodiesel use is well established in road vehicles and is already used in shipping, albeit blended with fossil fuel oil, and so is currently at CRL10. Current biodiesel production uses transesterification to produce Fatty Acid Methyl Ester (FAME), and hydroprocessing to produce Hydrotreated Vegetable Oil (HVO) and hydroprocessed esters and fatty acids (HEFA). HVO and HEFA are seeing increasing interest for transport use, both in road vehicles where HVO is a better substitute for diesel than FAME at high blends, and in aviation where HEFA can be used as a sustainable aviation fuel. Although there will be some technological development, wider commercialisation (CRL11) will involve scale-up of plants and sourcing of waste feedstocks, largely driven by these non-maritime demands. As with any biofuel, commercialisation is likely to ultimately be limited by feedstock availability (Norwegian Ministry of Climate and Environment, 2022).

Biomethane and biomethanol are also already used in shipping in small quantities (TRL9), and with an expected increase in the number of methane/LNG and methanol fuelled vessels which can use them, these biofuels are expected to commercialise more widely in the shipping sector over the next 5-10 years.

Biomethane can be produced from anaerobic digestion of biogenic waste – such as manure, crop or wood residues, or municipal waste – or (less commonly) by gasification of wood or other waste. Both technologies

[10] For example, Annex IX of the EC Renewable Energy Directive II contains a list of feedstocks which, if used in the production of biofuel, allow the fuel to be considered twice its energy content in achievement of energy objectives. There is also a dedicated target for advanced biofuels produced from feedstocks listed in Part A of Annex IX.

are technically mature and being commercialised (CRL9-10), although the distributed nature of the feedstocks tends to lead to decentralised production.

Biomethanol is also produced through gasification of wastes to produce a syngas which is synthesised to methanol over a catalyst. The syngas also includes a high proportion of CO_2 which can be captured and re-used, such as in carbon-containing e-fuels (see below). These production stages are technically ready and in commercial operation (CRL9-10), but given the planned facilities, commercialisation is expected to develop rapidly (to TRL11) over the course of this decade (IRENA, Methanol Institute, 2021).

Research is ongoing to develop the use of algae as a feedstock for biofuels, but we identified no evidence to show when this research will get beyond laboratory scale (TRL5-6) to a demonstration, let alone reach commercialisation (Laursen, et al., 2022).

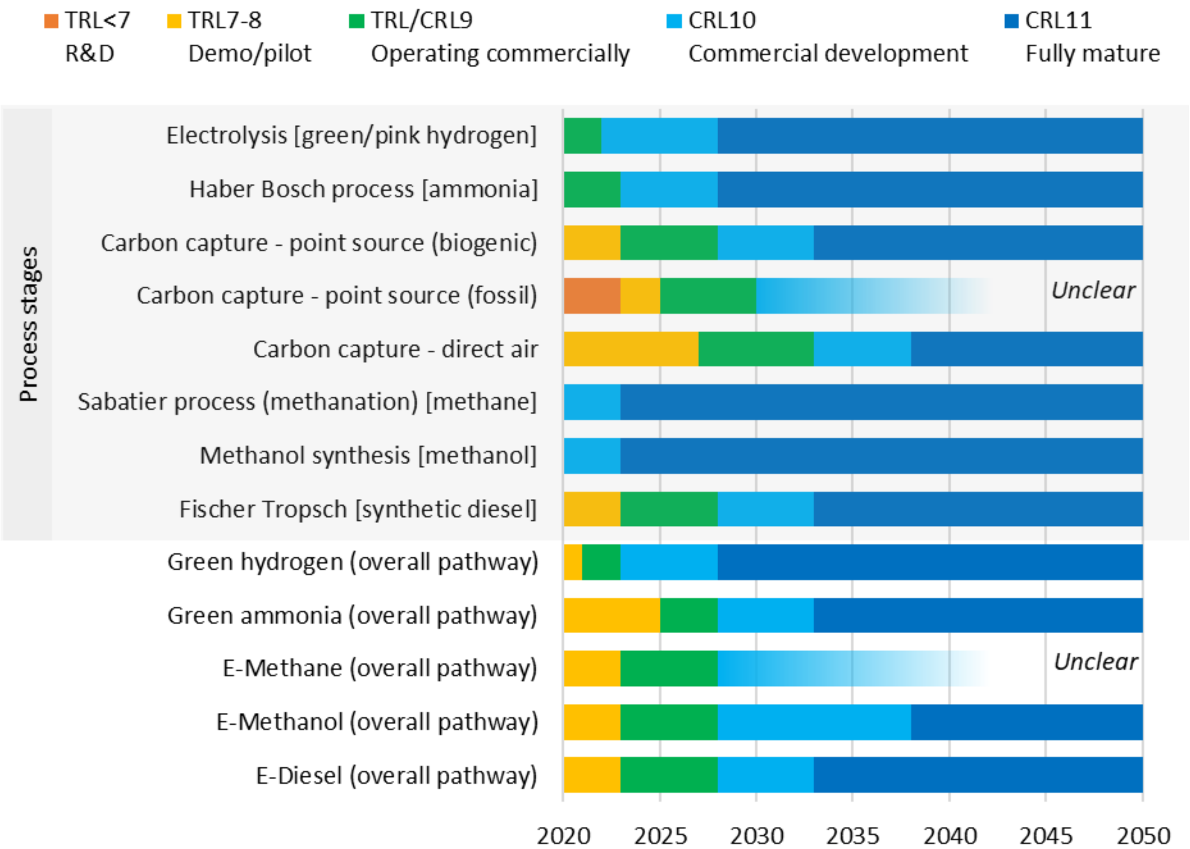
3.5.2 E-fuels

E-fuels are produced via the use of renewable or nuclear electricity to make “green” (renewable power) or “pink” (nuclear power) hydrogen[11]. The hydrogen produced can then be synthesised into other fuels via a variety of production processes, some of which require the addition of carbon which can come from direct air capture (DAC), biogenic processes (by-products of biofuel production), or from fossil sources such as unavoidable wastes and industry combustion or process waste gases. To be a truly renewable fuel, carbon should come from DAC or biogenic sources. While the production of electricity has been omitted from the scope of this study since its provision is not specifically for maritime use, renewable hydrogen and e-fuels require renewable energy that is *additional* to (and does not divert from) local grid supply. E-fuel supply is therefore limited only by the available renewable energy (and carbon capture), and so theoretically doesn’t have the feedstock constraints that biofuels can but will demand large-scale provision of this additional renewable electricity capacity and electrolyser capacity. This itself provides a limitation; especially as renewable energy projects take time to deliver.

As with biofuels, the end fuels can be produced via different processes although some stages of the production may be shared by different fuel types. As such, we have identified key technologies in the production of the fuels and considered the typical overall pathway for each fuel type. The forecasts of readiness of these process stages and fuel pathways are shown in Figure 3-9 below.

[11] The colours of hydrogen explained: https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum

Figure 3-9: Forecast of readiness and availability of e-fuel production stages and overall pathways



While most hydrogen today is made from steam-reformed fossil methane gas, a mature but carbon and energy intensive process, **green hydrogen** (or e-hydrogen) is produced by electrolysis of water using renewable energy. There are two dominant technologies used for water electrolysis: proton exchange membrane (PEM) and alkaline electrolysis (ALK). Both are technologically ready and operating commercially (TRL/CRL9) but are currently considered too expensive and inefficient to generate hydrogen at a cost competitive with conventional processes. For large scale production to be viable, challenges regarding increasing the power density of stacks and reducing both the size of the system and its complexity need to be addressed, along with ensuring continuous steady-state operation can be achieved so the process is at its most efficient. There is therefore some uncertainty about whether electrolysers will reach sufficient scale to reduce costs before blue fuels (i.e. produced from fossil sources using carbon capture and storage, see Section 3.5.3) become available at competitive cost. In addition, the rate of development of renewable energy production can be a limiting factor in the short term, since such projects take time to deploy. Nonetheless, production capacity was found to be increasing rapidly this decade, demonstrating commercial development (TRL10).

Green ammonia (e-ammonia) is produced using green hydrogen combined with nitrogen via the Haber Bosch process. Other pathways exist to convert hydrogen and nitrogen to ammonia, but these are still at research and development phase (EMSA/ABS, CE-DELFT, & ARCSILEA, 2022). Green ammonia relies on the green hydrogen technology (and cost challenges) discussed above. Despite the apparent maturity of the individual nitrogen separation and Haber Bosch processes currently used to produce ammonia from fossil gas, integration as part of a green ammonia plant will only be piloted by 2025 and demonstrated at scale in the mid-late 2020's (TRL10), and some development is still ongoing. However, the consultation with experts identified significant production capacity for green ammonia in the pipeline, as evaluated in Section 6.

Manufacture of synthetic **e-methanol, e-methane, and diesel e-fuels** requires a source of CO_2, which can come from point sources such as waste streams, gases from industrial or biogenic processes, or direct air capture (DAC)[12]. Since this CO_2 is released when the fuel is used it can only be considered a renewable fuel

[12] There is no benefit in taking carbon removed from blue fuel production and adding into another fuel. The EU Renewable Energy Directive states that recycled carbon fuels must use waste streams that cannot be avoided and are unsuitable for material recovery or recycling.

if that CO_2 was previously extracted from the atmosphere – using DAC, or via biogenic feedstocks. Recycled carbon fuels (RCF) using waste (via gasification) or industrial waste gases may enable GHG emissions reductions compared to fossil fuel use[13] but are not considered renewable fuels, waste gases also need impurities removing reducing efficiency. Currently, capturing carbon from biogenic processes at point sources (such as anaerobic digestion or combustion) is the most viable pathway to producing renewable e-fuels, although as plants scale the availability of carbon from these sources may become a limitation. DAC is operational in a few small-scale plants (TRL7-8), with larger plants in development and capacity expected to increase rapidly through the late 2020s (CRL9+), so commercial maturity (CRL11) is possible during the 2030s (IEA, 2022a). The availability of sustainable CO_2 is evaluated in Section 6.6.3. A visual summary and comparison of carbon use in fuels is in Figure 2-1.

Methanol is commonly produced via the methanol synthesis of syngas, which can be taken from a variety of fossil and renewable sources. **Green e-methanol** uses syngas produced using green hydrogen and carbon captured from DAC or biogenic sources. Currently, e-methanol plants are mostly at demonstration scale (TRL8), highlighting that carbon capture is still too expensive and inefficient to operate at any scale relevant for international shipping, but IRENA reported four plants at greater commercial scale (TRL9) were touted to begin operation in the mid-2020s, as well as 7 announced without a set start-up year (IRENA, Methanol Institute, 2021). Wider commercialisation will depend on demand as well as technical maturity and efficiencies, and the availability of captured carbon, but is expected during the 2030s (CRL10-11).

Like e-Methanol, **e-Methane** is produced from green hydrogen-derived syngas and captured CO_2, but methanated via the Sabatier process. Sabatier is already used at large scale to manufacture methane with syngas originating from coal gasification (Topsoe, 2015), and the process of manufacturing e-methane has been demonstrated at very small scale[14] but would need integration to develop a commercial plant (Norwegian Ministry of Climate and Environment, 2022), with similar challenges to methanol. One producer has announced that they are developing at least 4 projects larger than 300 MW in Germany, Austria and Bulgaria, which indicates a shift to early adoption (CRL9-10) within the next few years (Kiwi AG, 2023), but the path to technical maturity remains unclear. The low-cost availability of fossil gas and increasing biomethane production means there is likely to be little interest in investing in e-methane plants in the near future, but barriers are commercial rather than technical.

Synthetic e-diesel is created from a syngas of green hydrogen and captured carbon via the reverse water-gas shift reaction (RWGS), and then the Fischer-Tropsch (FT) catalytic process to produce a liquid hydrocarbon fuel.[15] FT can produce a range of “drop in” fuels compatible with conventional fossil fuels including diesel, and paraffinic fuel which is of interest to the aviation industry. Both the FT and RWGS processes are established (TRL9) in other contexts, but their integration needs to be proven at scale; few plants are currently producing synthetic liquid fuels, and at a small demonstration scale (Concawe, Aramco, 2022) (TRL8). Nonetheless, there is a lot of interest in such fuels driven by the aviation and automotive sectors, so commercial plants (TRL9) are expected within a few years and wider commercialisation (CRL10-11) is likely within a decade, although the high demand for renewable energy needed for liquid e-fuels means they are likely to have high costs which could limit their use in shipping.

3.5.3 Blue (Captured Carbon) Fuels

Hydrogen and ammonia contain no carbon atoms and so no CO_2 is released when they are used. Currently the majority of hydrogen and ammonia is produced by steam methane reforming (SMR) using natural (fossil) gas, a process that releases CO_2 into the atmosphere, such that there is no benefit in using hydrogen or ammonia produced in this way to replace fossil fuels. However, if the CO_2 released during production could be captured and stored so it is not released into the atmosphere the fossil gas could be turned into a low-carbon fuel. This process is known as carbon capture and storage (CCS), and fuels which have had carbon emissions removed during production using CCS are known as ‘blue’ fuels.

The forecasts of readiness of the process to produce blue fuels and the blue hydrogen and ammonia fuel pathways are shown in Figure 3-10.

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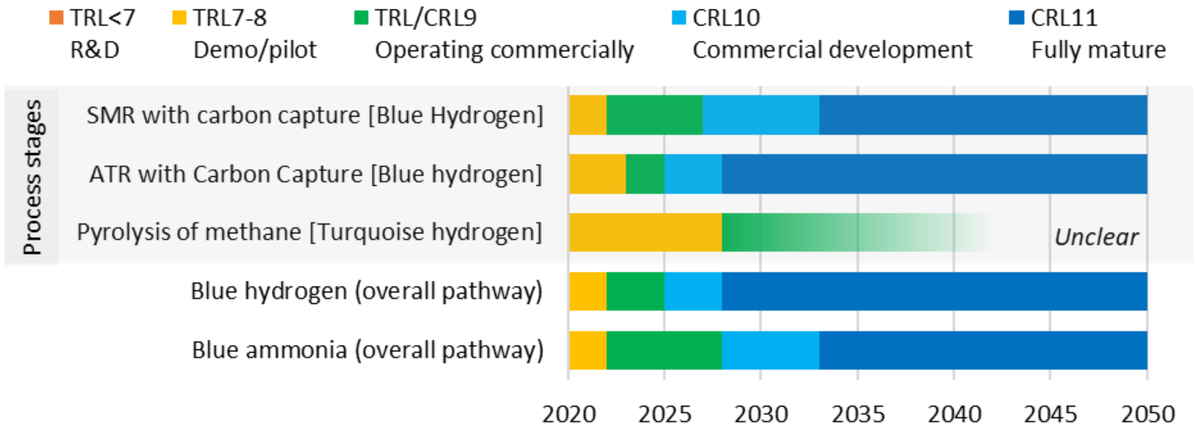
[13] The EU Renewable Energy Directive sets a target of 70% GHG reduction for RCFs compared to a fossil comparator

[14] A green SNG plant has been in commercial operation in Germany since 2013, using green hydrogen (6MW) and CO_2 captured from organic waste

[15] For the purposes of this study, we consider the reverse water-gas shift reaction (RWGS) as part of the Fischer-Tropsch (FT) process in the creation of synthetic e-diesel, and as such is not evaluated separately in Figure 3-9.

Figure 3-10: Forecast of readiness and availability of blue fuel production stages and overall pathways



CCS technologies have proven challenging for large scale hydrogen production and are costly for (**SMR**) plants which are responsible for most of the hydrogen production today. However, CCS has been found to be more cost-effective at higher carbon capture rates using the **autothermal reforming (ATR)** process, and several facilities are expected to be operational from the middle of this decade (IEA, 2022b) (TRL9). Therefore, although ATR is not currently as mature as SMR, it is expected to mature more quickly for use with CCS and rapidly reach maturity (CRL11) within around 10 years. The expert feedback indicated ATR may become the preferred technology for blue hydrogen production. Wider commercialisation depends on the economics rather than technology, although if retrofit of CCS to existing SMR plants is challenging and costly, market penetration may be slow.

Current **ammonia** plants already capture around two thirds of the total CO_2 already from the process gas (a fully mature technology), which is used in the fertiliser and food industries. Higher capture rates are expected to be needed for the ammonia to be considered as 'clean ammonia', such that capture of CO_2 from the flue gas stream will be needed. Our assumption is that blue fuels will need capture rates of at least 90% (see Section 2.2). Blue ammonia in this guise (i.e. with higher CO_2 capture rates) is expected to reach readiness in line with and commercialise following the path of blue hydrogen. Blue ammonia therefore is likely to mature (CRL10-11) around the same time as, or even ahead of green ammonia, in around 7-10 years' time.

CCS relies on a route to permanent **storage of the captured CO_2**, and availability of carbon storage infrastructure may be a limitation to the commercialisation of blue fuels which varies regionally. Blue fuel production facilities are likely to be developed in conjunction with carbon storage facilities, and being fixed infrastructure, do not face the same challenges as dealing with carbon captured on-board vessels which is discussed in Section 6.6.

An alternative hydrogen production method is pyrolysis or thermal decomposition, which produces a solid carbon by-product rather than CO_2 gas, with obvious advantages when it comes to carbon storage. This process known as **'turquoise' hydrogen** production is currently at demonstration scale (TRL7). While it could reach commercial use (TRL9) by 2030, it is unclear if or when it could scale up cost-effectively to compete with other blue production pathways.

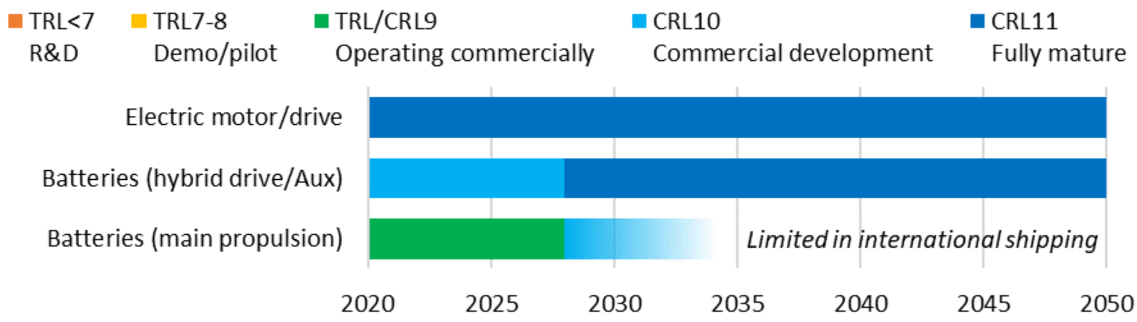
3.6 CANDIDATE FUEL VESSEL PROPULSION TECHNOLOGIES

As well as a range of potential future fuels for maritime use, there are a range of powertrain technologies for propulsion that can use these candidate fuels.

3.6.1 Electric propulsion

Electricity is used on all ships for auxiliary and hotel loads and can also be used for propulsion. Figure 3-11 shows the development of electric propulsion technologies.

Figure 3-11: Forecast of readiness and availability of electric propulsion technologies



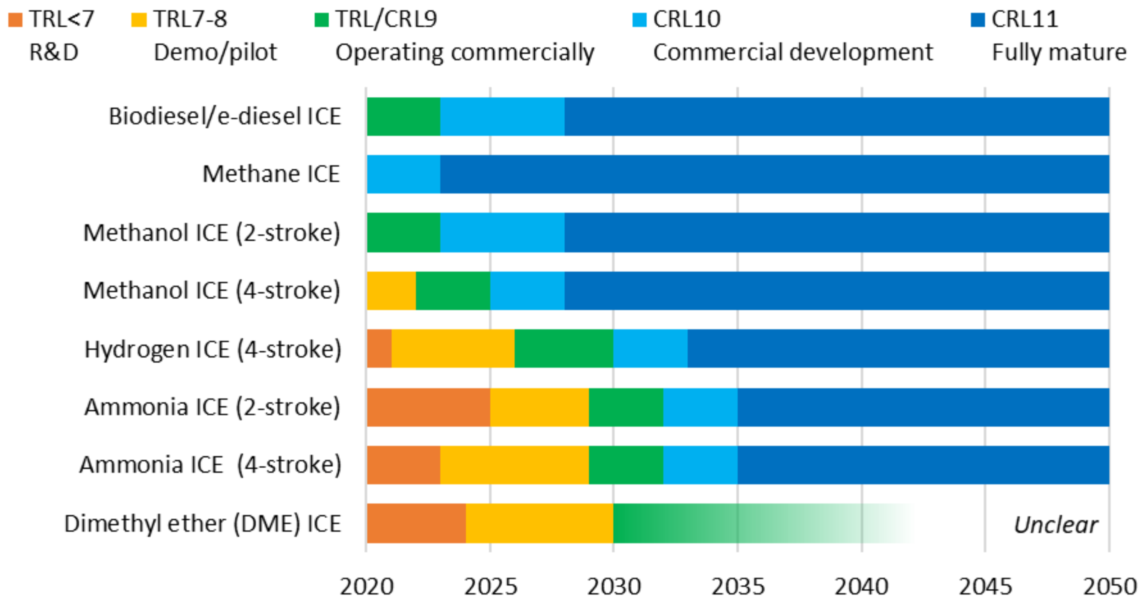
The use of electricity for propulsion is not new, with integrated electric propulsion well established in the form of diesel-electric drive for a variety of vessels (CRL11). Batteries have also found widespread use in managing auxiliary power demands. In recent years the use of hybrid drive systems utilising batteries to store energy have also become established, suitable battery technology having been taken from that developed for road vehicles and stationary power storage. As with hybrid cars these offer efficiencies where loads vary and have found use in ferries for example. Indeed, it is also possible for the batteries to provide the entire propulsion energy for the vessel, producing a battery-electric ship with no emissions (tank-to-wake). DNV research in 2022 found 396 battery and hybrid vessels in operation and a further 417 on order (DNV, 2022b) (CRL9-10).

Of course, the use of battery-electric vessels will be limited to where it is practical to store sufficient energy for the voyage in a battery, such as ferries and workboats, and while battery technology may improve it is not expected to be a solution for the majority of international shipping. Nonetheless, the readiness of electric propulsion and hybrid electric powertrains using batteries is an enabler for the use of other candidate fuels. Also, while it is unlikely that an existing vessel is retrofitted with a hybrid or battery electric powertrain during its life, equipping new vessels with electric propulsion as part of its powertrain could facilitate a change of fuel and power unit later in its life. The expert consultation revealed that some new vessel builds were being specified with electric propulsion to “de-risk” the use of an ICE powertrain, future-proofing the vessel for alternative ICE or fuel cell power units.

3.6.2 Internal combustion engines (ICE)

The internal combustion engine (ICE) has been the mainstay of vessel powertrains for over a century, and despite its drawbacks of air pollution, noise and vibration, it has become widespread. It is robust and reliable, versatile in size and fuel type, has a good power density, and is relatively low-cost and easy to maintain. It is therefore logical that solutions to using the ICE while reducing or eliminating its GHG emissions are being pursued. In fact, ICE technologies are in development for all the candidate fuels discussed in this study as shown in Figure 3-12. The use of ICE does result in some emissions, including GHG emissions other than CO_2, and these should be considered as part of the TTW emissions assessment of fuels. Emissions and their control are discussed at the end of this section.

Figure 3-12: Forecast of readiness and availability of ICE with candidate fuels



GHG emissions of ICE can be reduced through substitution of fossil fuels for **biofuels** if the carbon emitted from biofuel combustion is assumed to be countered by the CO_2 absorption during plant growth. Various forms of biodiesel are already available (including HEFA and HVO) and are used in maritime, albeit in limited quantities and generally as a blend with fossil fuel at present. With minimal adaption of the engine needed there are no significant technical barriers to its wider use in existing vessels (TRL9), although there can be some practical implications compared to conventional fuels, and its higher cost than fossil fuel oils and supply constraints will limit its uptake. **Synthetic liquid fuels** such as e-diesel are similarly backward-compatible with existing engines. Longer term regardless of whether they are taken up widely for maritime use, biodiesel or e-diesel fuels are likely to play a role in decarbonising *existing* smaller vessels using gas or diesel oil where replacement or retrofit of existing powertrains may not be economic, and as a pilot fuel for some ICE types using other fuels as noted below.

Liquified Natural Gas (LNG) or methane gas has become an established marine fuel in recent years, but while this is argued to offer a small tank-to-wake GHG savings against heavier fuel oils[16] it is still a fossil fuel. However, biomethane is chemically similar to natural gas, and so the engine technology is ready (CRL10) in both 2-stroke and 4-stroke engines. While it is therefore straightforward for an LNG-fuelled vessel to use biomethane, retrofit of a fuel-oil vessel to use biomethane would be complex and unlikely.

Methanol has also been used in vessels for a few years and is seeing an increase in interest, with several new methanol vessels on order and expected to achieve rapid commercial development within the next few years. The 2-stroke engine is currently used more widely due to its use in methanol tankers (CRL9-10), although a few 4-stroke engines are also already in use (TRL9). Retro-fit of existing vessels to use methanol is feasible and has also been demonstrated, and although increasing bunker tank capacity may be required since methanol has a lower energy density than fuel oil, it is more practical than installing a gaseous fuel system and tanks for hydrogen or ammonia.

Hydrogen 4-stroke engines are now reaching prototype demonstration stage (TRL7-8) and are soon expected to be available commercially (TRL9). Early engines will be dual-fuel and use a mixture of hydrogen and diesel. The rate of commercialisation after that will depend on demand for and availability of supply of hydrogen, and overcoming practical challenges, including safe storage and handling. The development of regulations for on-board use of hydrogen may be a limiting factor in the near-term (DNV, 2022b). The low volumetric energy density of hydrogen is a particular practical challenge which is touched on in the next section of fuel cells, and experts were in agreement that hydrogen was unlikely to play a role in long-distance shipping for larger vessels, so there is unlikely to be demand to drive the development of 2-stroke hydrogen engines. Retrofit of a vessel

[16] Methane "slip" or release of unburned methane (which has a high GWP) can offset the benefit of the lower carbon intensity of LNG (Nikita Pavlenko, 2020)

to use hydrogen is technically possible, indeed it may be possible to convert existing engines (particularly to a dual-fuel arrangement), although the storage and handling of hydrogen adds complexity. It may be more practical for vessels that are already gas-fuelled (LNG).

Development of **ammonia-fuelled engines** is a little behind hydrogen engines being still at the laboratory stage (TRL5), although it is receiving a lot of interest and is progressing rapidly, expecting to reach demonstrations by 2025 (TRL8). 4-stroke engines are currently slightly ahead of 2-stroke (TRL7) although they may reach commercial readiness (TRL9) around the same time in the late 2020's. In fact, a 2-stroke ammonia-fuelled tanker is expected to launch in 2024 (Wärtsilä, 2020b), and ammonia engines are reported to be expected on the market (for ordering) from 2024 (DNV, 2022d). Commercialisation could follow rapidly if there is the demand since the technology change from existing engines is small. As with hydrogen there are practical challenges outside of the engine including regulation, although this is expected to mature more quickly than hydrogen and is not seen as a barrier to the adoption of ammonia. Retrofit is expected to be most feasible for LNG-fuelled vessels (although increased storage may be needed since ammonia has approximately half the volumetric energy density as LNG) but may be much more challenging for oil-fuelled vessels.

Dimethyl Ether is a gaseous fuel that combusts with diesel-like properties, and like methanol it can be produced from renewable sources. It has previously been demonstrated (TRL6) but there is little evidence it is being seriously considered for maritime use at present, and this was confirmed by the expert consultation. Technically, there are few barriers to its use in diesel-cycle engines and it could become commercially available for new or retrofitted engines relatively quickly, but methanol may be preferred due to its comparative ease of bunkering. However, an on-board alcohol-to-ether process could be used to produce DME from methanol, enabling the use of diesel-cycle engines (without a pilot fuel) and offering another technology option for using methanol as a fuel.

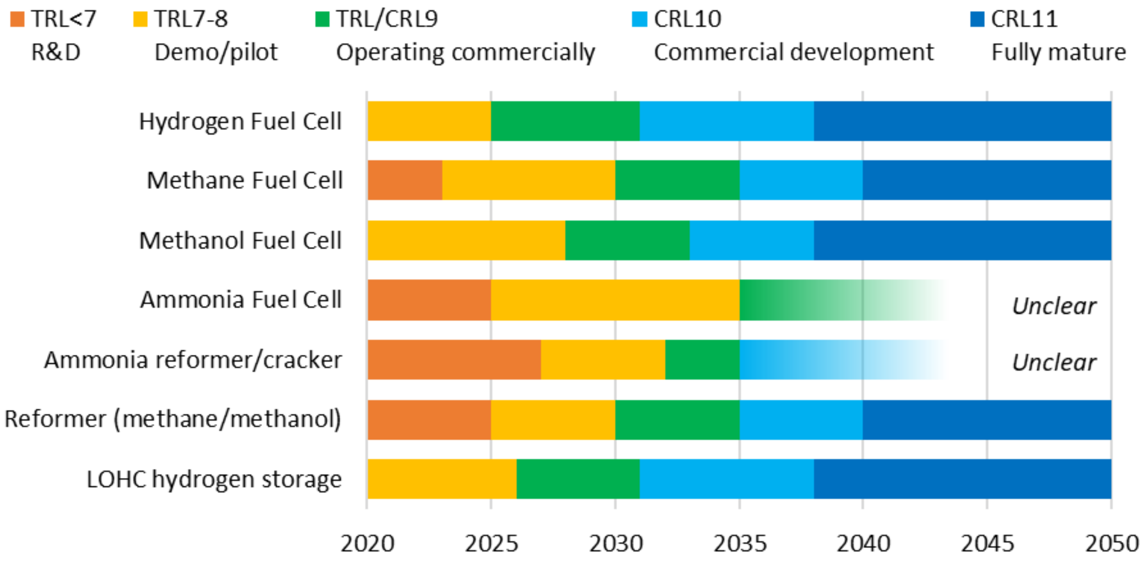
Some of these candidate fuels will need a "pilot" fuel, a small quantity (around 5%) of fuel used to ignite the main fuel in a diesel cycle. This is likely to be a diesel-type fuel which could be biodiesel or e-diesel, although alternative options are being developed such as reforming a small portion of the main fuel to hydrogen to use as a pilot.

The use of biodiesel, biomethane, methanol and DME will result in the emission of CO_2, although if these fuels are renewable (i.e., the carbon has been extracted biogenically or directly from the atmosphere) this is offset by its production. The potential for carbon capture is discussed in Section 3.7 below. ICEs also can emit a range of other GHGs and pollutants depending on their fuel(s). Other than CO_2 the principal GHGs of concern are methane, which has a very high global warming potential and is likely to be emitted from methane/LNG engines; and N_2O, particularly from ammonia engines. Hydrogen is also considered a GHG, and development of hydrogen engines must consider the prevention of hydrogen emissions (UK BEIS, 2022). Other pollutants include NOx (all engines); CO, hydrocarbons, and particulate matter (carbon-containing fuels); and ammonia (especially but not exclusively from ammonia engines). The fuels considered here should not emit any significant quantity of SO_2 or black carbon, although use of a fossil pilot fuel might. The readiness levels assume the engines are developed with adequate emissions control systems and meet existing standards for pollutants, for which proven technologies exist, but GHG emissions will also need to be controlled, monitored, and/ or accounted for.

3.6.3 Fuel cells

Fuel cell technology has been around a long time but only recently has become commercialised in the transport sector for road vehicles, and for stationary power generation. In a fuel cell electricity is produced by the oxidation of hydrogen, with the emission of water vapour. Fuel cells are capable of higher efficiencies (up to around 60%) than ICE. There are a range of fuel cell technologies with different characteristics and levels of development. Proton-exchange membrane (PEM) hydrogen fuel cells are perhaps the most widely developed at present with good suitability for road vehicles, but the solid oxide fuel cell (SOFC) offers fuel flexibility and currently higher power ratings. Other fuel cell types that are being considered for shipping include high-temperature PEM (HTPEM) and Molten-carbonate (MCFC). SOFC and MCFC operate at high temperatures, and the addition of waste heat recovery can increase efficiency as high as 85% (DNV GL, 2017). Figure 3-13 shows the technology readiness of fuel cell powertrains with a range of fuel types without detailing the fuel cell type, or the fuel used by the fuel cell, but rather considering whichever technology (or technologies) reaches commercialisation first. Fuel cells are likely to see use for auxiliary power generation alongside ICE for propulsion, and thus commercialisation of auxiliary power fuel cells may occur more quickly than shown in Figure 3-13.

Figure 3-13: Forecast of readiness and availability of fuel cell powertrains



Hydrogen fuel cells are already entering demonstrations (TRL8) helped by developments for other sectors, and commercial applications (TRL9) are expected in the late 2020's, at least for smaller vessels. They offer zero tank-to-wake emissions with quiet vibration-free operation and few moving parts. The key challenges are scaling up the power output, ensuring reliable for sustained operation, and the fuel storage/handling and regulatory barriers as discussed for ICE. The uptake of hydrogen – or any type of – fuel cells will ultimately depend on their benefits (such as improved efficiency) outweighing any disadvantages (such as cost) compared to ICE.

As with its use in ICE, hydrogen applications are limited by storage capacity/space. Ammonia, discussed below, acts as a medium for higher density hydrogen storage, and other solutions may become available in the future, but one technology that is expected to be ready and suitable for maritime in the short-term is liquid organic hydrogen carrier (**LOHC**). This stores the hydrogen in a liquid organic compound which can be handled in a similar way to diesel, the LOCH fluid is passed through a heated catalyst to release the hydrogen for use on-board while the LOHC fluid is recycled (H2 Industries, 2022). This process does add to the on-board energy demand reducing overall efficiency and requires processes to offload spent fluid for reprocessing as well as bunkering fresh H_2-enriched LOHC, adding to transport requirements. LOHC is entering demonstrations (TRL7-8) and is expected to be commercially available within a few years (TRL9), which means it will be able to support the use of hydrogen fuel cell or ICE propulsion systems and so commercialisation is likely to be in line with them.

Methane and methanol can be used directly in some types of fuel cell, including SOFC which are at a high readiness level and high-power outputs in stationary power applications. Small-scale demonstrations have taken place and development to marine application scale (as auxiliary power, TRL7) is expected in the next couple of years (Ceres, 2023) with readiness for main propulsion towards the end of the decade. Alternatively, methane and methanol can be reformed on-board to produce hydrogen, which enables a wider range of fuel cell technologies (including PEM), albeit with additional complexity, space, and energy demands on-board. Development of on-board reformers for methane and methanol is at a similar stage and rate to SOFC, and so either technology is expected to be available for methanol fuel cell vessels to be operating commercially (TRL19) from around 2030. However, SOFC are attractive for auxiliary power use on board vessels using methane or methanol fuel which could create confidence and experience that accelerates their commercialisation for propulsion use.

As with methane and methanol, **ammonia** can be used directly in some types of fuel cell or reformed through a cracker to produce hydrogen. SOFC is the most likely technology for direct ammonia use in the near term, although its high temperatures can lead to NOx emissions, and the first vessels to pilot ammonia fuel cells (TRL7-8) are expected in the late 2020s although commercialisation (CRL9-10) may take another decade. Cracking ammonia into hydrogen enables a wider choice of fuel cell types to be used, although the cracking and purification of the hydrogen (to avoid poisoning the fuel cell) adds complexity, and use of this technology on-board may take around 10 years to reach maturity (TRL9). Ammonia cracking technology could enable earlier and wider take-up of fuel cells with ammonia and accelerate their commercialisation. As with methane and methanol, demand for auxiliary power fuel cells could also help commercialisation. However, the wider commercialisation (CRL10-11) of ammonia fuel cell technologies for propulsion is unclear, depending on how its efficiency, cost, and robustness compares with ICE, which as seen above will be well established by the time ammonia fuel cells are expected to become available commercially.

Whether used directly in a fuel cell or reformed into hydrogen first, the use of methane or methanol releases CO_2. The potential for capturing and storing this is considered in Section 3.7. Fuel cells can be responsible for other emissions too: hydrogen, methane or ammonia slip from the exhaust, and NOx and even N_2O can be formed in high-temperature fuel cells (SOFC), and so as with engines, to reach maturity any potential emissions must be controlled. Methane, hydrogen, and N_2O are greenhouse gases and should be considered when evaluating the TTW emissions of a fuel cell vessel. However, emissions may be controlled with catalysts and other technologies, and emissions control is not seen as a significant technical barrier.

Retrofitting a vessel with a fuel cell powertrain is more complex than the conversion of an ICE to an alternative fuel, on top of the need to change fuel storage and supply systems. However as noted in 3.6.1, building new vessels with possible future conversion in mind – such as using an electric propulsion system – could make exchanging an ICE for a fuel cell a more practical proposition.

3.6.4 Other powertrain technologies

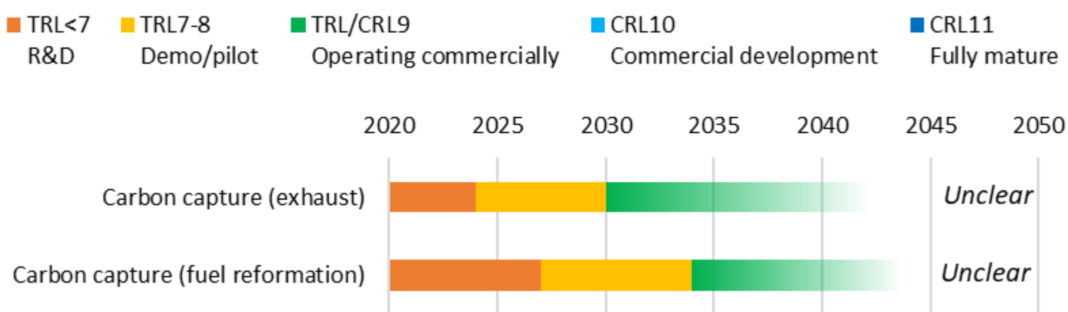
Gas turbines are not widely used in commercial shipping and are considered unlikely to be adopted with new low-carbon fuels, since they are less efficient in marine use than ICE. However, they are flexible to different types of fuel, so although they have not been assessed here there are unlikely to be significant technical barriers to their adaption to use the fuels considered in this study.

Nuclear power emits no emissions at the point of use and has been proven in use in naval ships over many years, so arguably presents an ideal solution to decarbonise shipping, although the risks (safety, environmental, security, and political) are also well established. Generation IV nuclear reactor designs are said to reduce safety risks (with passive safety measures) and waste issues, and by not using weapons-grade fuel eliminate the security risks. However, readiness for deployment in land-based reactors is not expected before the mid-2040's (GEN-4 International Forum, 2013) and so are unlikely to play any significant role in the maritime sector in the timeframe of this study. While nuclear powered merchant vessels may become feasible, the key barriers will be safety, security, cost, and political considerations rather than technical, and so we have not considered their contribution to decarbonising shipping in this study.

3.7 ON-BOARD CARBON CAPTURE

Whether a vessel uses a fossil fuel or a low-carbon fuel, if the fuel contains carbon, then CO_2 will be released. Carbon capture technology offers the potential to reduce those exhaust carbon emissions if the captured carbon is then stored. On-board carbon capture and storage (CCS) can be broadly classified as being applied to the exhaust gas of an engine, or to the reformation of fuel into hydrogen for a fuel cell (including where that happens inside the fuel cell), and the technology readiness of both is evaluated in Figure 3-14.

Figure 3-14: Technology readiness of on-board carbon capture



There are several technologies to enable CCS to be applied to an exhaust gas stream, but while they may be considered mature for fixed land-based applications they are not yet developed for on-board use, although projects are said to be nearing demonstration (TRL7-8). There are some important considerations for CCS; one is the proportion of carbon removed from the exhaust (the capture rate). Some early systems are entering the market with a low capture rate[17], but technical readiness here (TRL9) assumes achieving a relatively high capture rate (capable of at least 70% as per Section 2.2). A need for effective certification of carbon capture rate was identified in the expert consultation. Another consideration is the ability to compress and store the captured CO_2 on-board the vessel, this offers space challenges that may be similar to the use of hydrogen. Also, carbon capture systems (including liquifying and storing the CO_2) are energy intensive, increasing energy (and so fuel) use by between 15% and 40%. Finally, a handling and storage ecosystem is required at ports to receive and guarantee the permanent storage of the CO_2, along with storage capacity, as evaluated in Section 6.6.

In theory capturing CO_2 from a fuel reformer poses fewer challenges than extracting CO_2 from engine exhaust (and the technology is like that for producing “blue” hydrogen), although development of on-board carbon capture technology from reformation is not yet as mature (TRL6). It is expected to be ready for first commercial deployment (TRL9) by the mid-2030s, or possibly sooner, prior to subsequent full commercial maturity. The same challenges of compressing and storing the captured CO_2 and the energy used by the process, and the need for disposal infrastructure, apply.

These considerations on top of the engineering and practical challenges of installing reliable carbon capture plant and storage capacity onto a vessel mean it is not clear how quickly and widely the technology could be commercialised once it is ready, since the barriers are no longer the technical readiness. If it is proven to be effective (and cost-effective) and is practical to retrofit it could see rapid commercialisation from the late 2030s, but if the use of alternative low-carbon fuels as outlined above is found to be more practical and effective the market for exhaust carbon capture could be limited. In other words, if it is economically and practically more attractive to apply carbon capture to the fuel production plant and use a carbon-free fuel (such as hydrogen or ammonia), there could be little incentive to commercialise on-board carbon capture. Similarly, if the fuel being used is renewable (i.e., the carbon has been extracted biogenically or directly from the atmosphere), the additional benefit from the complexity of on-board carbon capture could be difficult to justify. The greatest potential for on-board carbon capture is likely to be as a retrofit to existing fossil-fuel vessels where the costs and challenges are less than conversion to an alternative fuel.

[17] The Filtree system by Value Maritime is reported to capture up to 40% of exhaust CO_2 at present: https://shipandbunker.com/news/world/688997-value-maritime-completes-carbon-capture-retrofit-on-eps-tanker

4 READINESS OF MARITIME INFRASTRUCTURE TO PROVIDE CANDIDATE FUELS AND VESSEL TECHNOLOGIES

Overview

- Vessels will not be able to adopt the new candidate fuels without bunkering facilities. This section assesses the readiness of ports to provide candidate fuels to ships, and lists current port and bunkering infrastructure projects.
- The capacity of manufacturers and shipyards to build and retrofit ships is essential to estimate how fast a technology could be scaled up in the shipping sector, and so the capability of shipyards to transition to building ships running on candidate fuels is also assessed.

4.1 PORT AND BUNKERING INFRASTRUCTURE

Key findings

- The existing orderbook for methanol and hydrogen vessels will drive demand for bunker facilities.
- There are several port and bunkering investment projects planned, including green shipping corridors.
- Bio- and e-diesel, and bio- and e-methane will be able to use existing bunkering infrastructure.
- Ammonia, hydrogen and methanol will need new bunkering infrastructure to be built: methanol already has some refuelling infrastructure developed with ship-to-ship bunkering proven, and ammonia will need to build on its existing global network of storage terminals.
- Assuming availability for such fuels, the bunkering infrastructure, distribution, and storage capabilities will be sufficiently developed to avoid any potential constraint on roll-out.

4.1.1 Data and method

A high-level mapping of current bunkering infrastructure for the world fleet is reviewed for both conventional and alternative fuels, and an outlook of the development of infrastructure for bunkering of the candidate fuels identified in Section 2 is considered. This section covers neither shore-side electricity nor reception and storage facilities for captured CO_2 on ships.

Data and information used in this section were collected through a comprehensive literature review. DCS data (IMO, 2022b) and data from IEA (2021a) have been used to map the current bunkering volumes and infrastructure, globally and in the major bunkering hubs. DNV's Alternative Fuels Insight database (AFI, 2023) has been used to identify where it is possible to bunker alternative fuels today, supplemented with data from port authorities and the industry. Further input from industry papers, the World Ports Climate Action Program (WPCAP, 2023), the Nordic Roadmap project (Frithiof, 2022), and announcements from port and bunkering networks are used to identify the different plans and projects, developments and trends related to bunkering of alternative fuels.

The findings are presented in three main parts:

- Current bunkering volumes globally and in the major ports, with a specific focus on bunkering infrastructure in Singapore and Rotterdam.
- Current fuel consumption and bunkering infrastructure for alternative fuels.
- Development and trends for bunkering availability and infrastructure, and a discussion on how to leverage existing infrastructure to speed up bunkering availability for the candidate fuels.

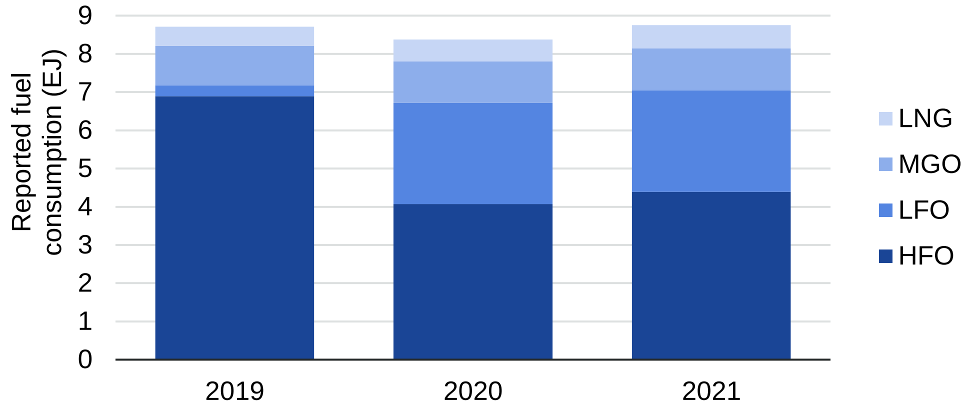
A list of planned port and bunkering projects for the candidate fuels is included in Appendix 5.

4.1.2 Current bunkering volumes

The global port and bunkering infrastructure supports both international and domestic shipping. The world's merchant fleet of 2021 consisted of almost 119,000 ships above 100 GT, of which cargo-carrying ships account for roughly half (Equasis, 2022). The remaining half is work vessels employed in activities such as offshore service and supply, passenger transport, fishing and general services such as towage or surveying. The work vessels are, on average, far smaller than cargo carrying ships. The larger cargo ships in international trade have the largest share of total installed power in the world's merchant fleet, and account for most of the maritime fuel consumption and emissions.

There is a well-established global bunker market with a fully developed infrastructure for conventional fuels today, with an increasing share of LNG. For 2021, the reported fuel oil consumption for ships of 5,000 GT or above in international trade was 212 million tonnes. Almost all (99.9%) of the fuel oil that was reported was either HFO, LFO, LNG or MGO (Figure 4-1). The remaining fuels outside of these four fuel types amounted to 0.11% (reported under 'Other' fuels in Figure 4-3). Almost 6% of the fuel consumed in 2021 was LNG, which has been an increasingly popular fuel with consumed volumes rising, in energy terms, from about 0.5 EJ in 2019 to about 0.6 EJ in 2021. However, a majority of the LNG is consumed by LNG carriers where the fuel is taken from the cargo. About 75% of the total reported fuel usage of all types reported to the IMO was consumed by three ship types: tankers, bulk carriers, and containerships. From Figure 4-1 we also observe a significant increase in the use of LFO in 2020, due to introduction of the 2020 IMO sulphur requirements (IMO, 2022b).

Figure 4-1: Annual consumption of LNG, MGO, LFO, HFO for all ships of 5,000 GT and above in international trade (IMO, 2022b). Consumption of other fuel types is not shown.



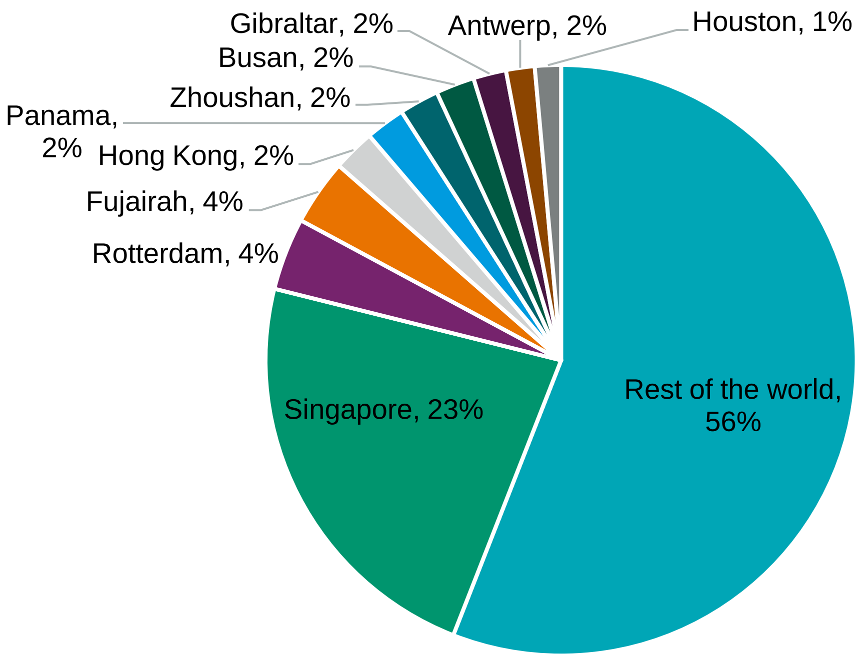
Beyond the fuel consumption reported by IMO (2022) for ships above 5,000 GT there is an additional amount consumed by ships smaller than 5,000 GT. The total bunker volume sold to ships in international trade was 217 Mt in 2019, including LNG, according to sales figures from IEA, while the energy demand analysis in this report estimates the fuel consumption in 2022 as 211 Mt (see Section 5.3). Furthermore, in addition to ships in international trade, there is also fuel consumption by the domestic and fishing fleet, reported by IEA as a further 57 Mt in 2019 (IEA, 2021a).

4.1.3 **Major bunkering ports and infrastructure**

Most refuelling operations for deep-sea shipping take place at the major refuelling hubs, which are located strategically along the major international trade lanes. There are usually price differences between the different bunker locations, often allowing shipowners to take an opportunistic approach to bunkering. Tank capacities on board the vessels usually allow for bunker quantities that are sufficient for several voyages. In locations with comparatively low bunker prices, an owner will tend to bunker the vessel to maximum. In cases where the vessel runs low on fuel, but the closest bunkering port has high prices, the owner will tend to bunker just enough to reach the next bunker port with lower prices. Ships in regular trades such as container lines can plan for an optimal bunkering location, while ships in irregular trades such as bulk and tank tramp shipping needs to ensure that the ship has sufficient bunker capacity to reach bunkering locations.

Figure 4-2 shows that close to half of all fuel volumes are bunkered at the major bunkering hubs, where the Port of Singapore is by far the largest bunkering hub, accounting for about 23% of total bunker volumes.

Figure 4-2: Fuel sold in the 10 major bunkering ports in 2020 (IPEC, 2021) compared with the total bunkers sold in 2019 (IEA, 2021a)



4.1.4 Current bunkering infrastructure in Singapore and Rotterdam

Ship bunkering operations can be categorised into three typical modes:

- **Truck-to-ship**: Small volumes of fuel can be transferred directly from a tank truck to a vessel. This is a highly flexible solution with comparatively low investment costs and risk. However, this type of bunkering is only suitable for smaller quantities and is superseded by other solutions once infrastructure scales up and larger fuel volumes are demanded by larger ships.
- **Shore-to-ship:** Stable and long-term bunkering demand allow for use of shore-to-ship transfer, where a tank facility is connected to a bunker quay via a pipeline. High bunkering rates and consequently short bunkering time can be achieved with this system. However, shore-to-ship bunkering has the disadvantage of being inflexible.
- **Ship-to-ship:** For sea-going vessels in international trade, ship-to-ship transfer by bunker barges or sea-going bunker vessels is often used in bunkering operations. This type of bunkering allows for transfer of large fuel quantities. Sea-going bunker vessels provide good flexibility regarding the location for bunkering, as their operational range is not limited to harbour areas.

Ship-to-ship bunkering using dedicated bunkering vessels is a significant part of all bunkering operation in the major ports. However, the lack of data and transparency in the industry makes it hard to find aggregated statistics on the status of conventional bunkering vessels and barges today. In the following, we describe bunker barge operations focusing on Singapore and Rotterdam.

The **Port of Singapore** is the largest and most important bunkering port in the world. It is located on the southern end of the Malay Peninsula in Asia, making it a natural connection point between East and West trade. Singapore is linked to 600 ports in 123 countries (Ship Technology , 2020). It is one of the world's busiest ports in terms of total shipping tonnage, total cargo tonnage handled and as a transhipment port, with over 130,000 calls every year. As the largest bunkering port in the world, Singapore has announced its aim to provide a range of alternative fuels in the future (Maritime and Port Authority of Singapore, 2023).

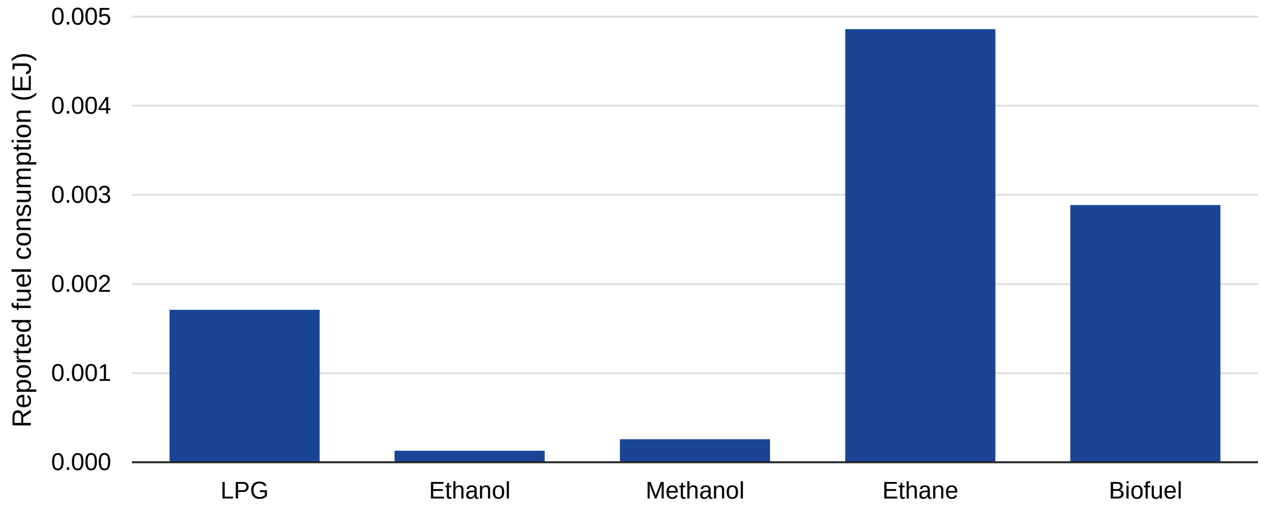
Using AIS data, Aarsnes (2018) found that some 19,900 bunker operations were performed in the Port of Singapore during one year across a wide range of ship types. The Port of Singapore had 210 bunker barges registered as of March 2021 (Lim, Sahu, & Nair, 2021).

The **Port of Rotterdam** is the largest bunkering port in Europe and one of the top bunkering ports in the world. It is a global trade centre for seagoing vessels and inland waterway vessels. The total length of Rotterdam's quays is about 80 km, and data from 2021 showed about 28,000 seagoing vessels and almost 100,000 inland waterway vessels visiting the port (Port of Rotterdam, 2023a). Port of Rotterdam stated that it uses 180 different bunker vessels for supplying visiting vessels (Port of Rotterdam, 2023b).

4.1.5 Current bunkering infrastructure for alternative fuels

The uptake of alternative fuels today is very limited beyond LNG. According to the reported 2021 fuel oil consumption data submitted to the IMO for ships of 5,000 GT and above in international trade, just 0.11% of the total consumption of 8.8 EJ were alternative fuels excluding LNG, and 7% if including LNG. Figure 4-3 shows the amount reported for the various alternative fuels, except for LNG which was reported at 0.6 EJ (IMO, 2022b).

Figure 4-3: Consumption of LPG, ethanol, methanol, ethane and biofuel for 2021 reported by all ships of 5,000 GT and above in international trade (IMO, 2022b)



This study does not have information about how these fuels are produced, but it is expected that most are fossil-based today, except the biofuel. It should also be mentioned that ethanol, methanol, and ethane can be produced from non-fossil sources, but we assume this is not the case for the reported numbers in Figure 4-3. Another uncertainty is the fuel bunkered by vessels smaller than 5,000 GT, which are not included in the reporting.

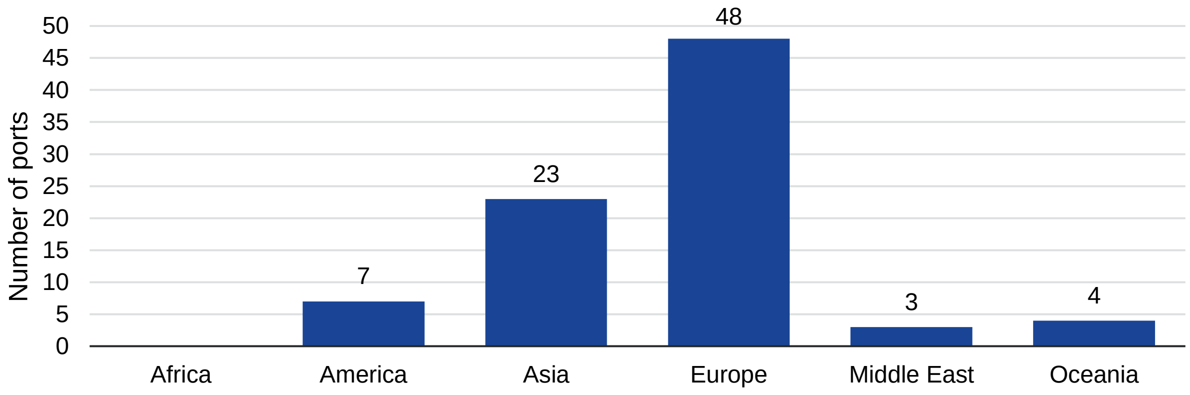
Furthermore, while it is clear that there is limited availability for bunkering of alternative fuels beyond LNG at any ports today, there is little information on the nature of the bunkering of these fuels. It can be assumed that the bunkering operation is mainly done from small-scale terminals with truck-to-ship transfer, shore-to-ship transfer pipelines from fuel production facilities, or in some cases ship-to-ship transfer.

4.1.5.1 *LNG bunkering infrastructure*

As shown above, LNG has become an increasingly popular fuel. Uptake of LNG-fuelled vessels has increased significantly in recent years, starting when four-stroke gas engines (dual-fuel or gas only) were adopted from the year 2000 onwards. Until then, LNG was used only by LNG carriers capable of burning boil-off-gas in their steam turbines.

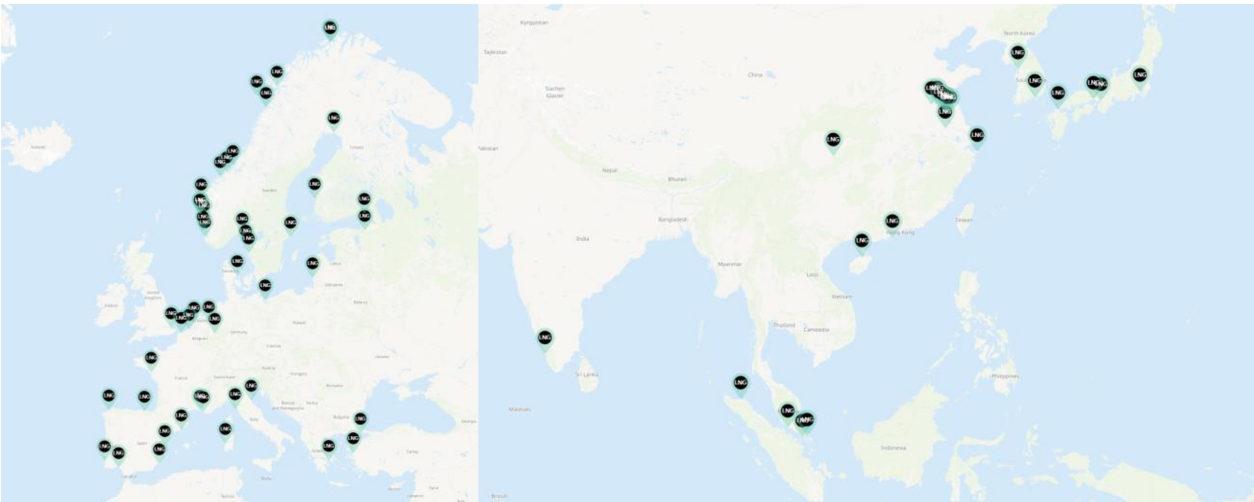
Today, LNG is transitioning from the most common alternative fuel, with over 300 ships in operation, excluding LNG carriers (AFI, 2023). The LNG ecosystem has matured as LNG is now available globally and in large volumes. Currently, there are about 85 ports equipped with LNG bunkering facilities across the globe, with the highest concentration in Europe and Asia. Figure 4-4 shows the number of existing LNG bunkering ports by global region.

Figure 4-4: Number of LNG bunkering ports in operation by global region (AFI, 2023)



The location of the LNG bunkering ports in Europe and Asia is shown in Figure 4-5. There is a high density of LNG bunkering locations in Europe, and for Asia there are bunkering facilities for LNG in or near ports with high levels of deep-sea traffic.

Figure 4-5: Location of LNG bunkering ports in Europe (left) and Asia (right) (AFI, 2023)



In addition to the LNG bunkering ports described above, there are 43 LNG bunker vessels in operation (AFI, 2023). They operate mostly in Europe and Asia, but there are 6 LNG bunkering vessels operating around Florida and the Caribbean. The first LNG bunkering vessel in Singapore was delivered in January 2021 and provides LNG bunker to LNG-powered vessels that call at the port (Mandra, 2021). The Port of Rotterdam started LNG bunkering in 2011, and today LNG is available both for shore-to-ship and ship-to-ship delivery (Contessi, 2022). In 2021, Port of Rotterdam sold about 270,000 tonnes of LNG (Port of Rotterdam, 2022). We also see that there are several sea-going LNG bunker vessels operating out of Rotterdam that serve vessels at anchorage and in other ports in the vicinity.

4.1.5.2 *Biofuel bunkering infrastructure*

Biofuel as a marine fuel is most common today as a fuel blended in with fossil fuel, called bio-blended fuels. Biofuel can be blended in with many different marine fuels, such as MGO, VLSFO, and so on. It is possible to store and bunker biodiesels the same way as for MDO/MGO today, and there is consequently an established infrastructure for the former (IRENA, 2021).

The Port of Rotterdam grew its sale of bio-blended fuels from 0.3 Mt in 2021 to 0.8 Mt in 2022, a 160% increase (Port of Rotterdam, 2023). In 2022, the Port of Singapore reported bunker sales of 0.14 Mt bio-blended fuels distributed over 90 bunkering operations (Lerh, 2023). This surpassed its LNG bunker sales of 0.016 Mt. Also in 2022, Vitol bunker barges delivered bio-blended VLSFO for the first time to Singapore (Wainwright, 2022).

4.1.5.3 *Methanol bunkering infrastructure*

Today, methanol is available as a marine fuel in about 90 of the world's largest ports and is proven to be a viable alternative fuel. However, most methanol-fuelled vessels in operation today are chemical tankers and receive supplies of methanol into their dedicated slop tank as part of their cargo loading operation. Therefore, there is a need for further developing and scaling the bunkering infrastructure to facilitate the increase for methanol-fuelled vessels other than tankers.

In 2021, the world's first ship-to-ship methanol bunkering took place in the Port of Rotterdam, fuelling Waterfront Shipping's methanol dual-fuelled vessel. Over the last five years, their methanol dual-fuelled chemical tankers have been bunkering methanol via cargo shore pipelines near a production facility (Labrut, 2021).

Another ship-to-ship bunkering operation was completed in the Port of Gothenburg in January 2023. The methanol supplier Methanex Corporation supplied Stena Germanica, the world's first methanol-fuelled ferry (Bahtić, 2023).

4.1.5.4 *Hydrogen bunkering infrastructure*

Only a few known small vessels are reported to operate on hydrogen today, and the availability for hydrogen is limited. Two examples include:

- Sea Change, a 75-passenger fuel-cell-powered ferry operating in the San Francisco Bay using renewable hydrogen. It is refuelled with gaseous hydrogen truck-to-ship. (Blenkey, 2021)
- MF Hydra, a ferry operating in Norway, using liquefied hydrogen as fuel. The first bunkering operation has been completed. Further bunkering will take place every third week, where the hydrogen is transported by truck from Germany, until liquefied hydrogen is produced locally. As a connection point, a bunkering tower is placed between the hydrogen truck and the fuel tank, located at the top of the vessel.[18]

4.1.6 **Outlook on port and bunkering infrastructure for alternative fuels**

Bunkering availability of alternative fuels in key ports along main maritime traffic routes will be crucial to supply candidate fuels to ships. From the previous sections, we learned that a global fuel and gas oil bunkering infrastructure is in place, a global LNG infrastructure is developing, and bunkering infrastructure for other alternative fuels is almost non-existent.

In this section, we first assess the orderbook for ships, which indicates the demand that may induce infrastructure developments. Second, we inventory the currently known port and bunkering infrastructure projects, indicating how things will develop down the pipeline, presented as a list (Appendix 5). As there is no complete worldwide database of current port and bunkering infrastructure projects for alternative fuels, it is challenging to present a complete overview of these. Finally, we assess how to leverage existing infrastructure to speed up the availability.

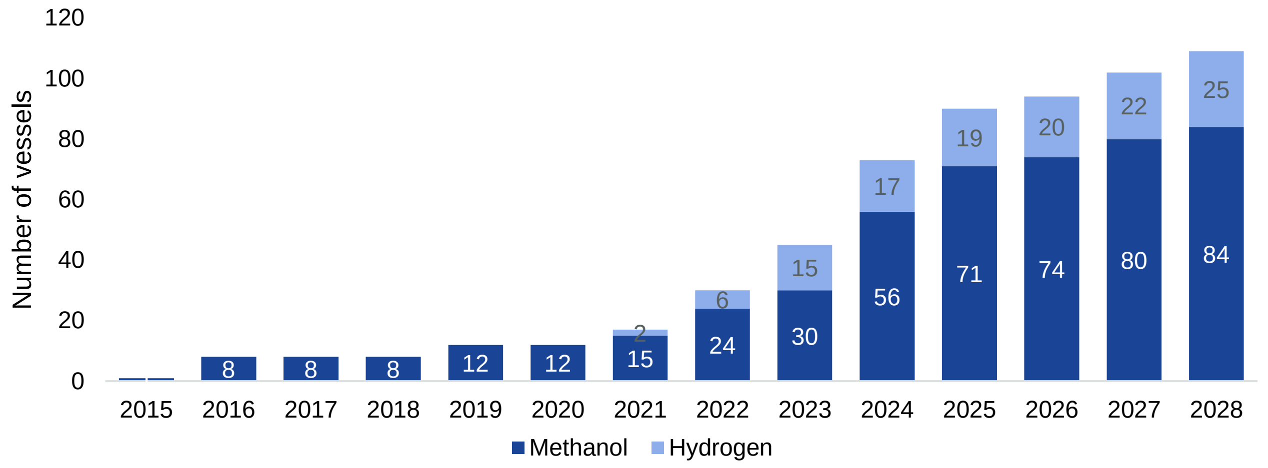
4.1.6.1 *Orderbook of alternative-fuelled vessels*

As different policy initiatives are being introduced and regulations to reduce GHG emissions are phasing in, shipowners are now deciding to build alternative-fuelled vessels, which helps to create demand pushing forward the port and infrastructure development. Two such shipowner initiatives are from A.P. Moller – Maersk, which has 19 methanol-fuelled vessels on order (MAERSK, 2022), and COSCO, which has 12 ultra-large, methanol container ships on order (The Maritime Executive , 2022), which will create demand to support methanol bunkering opportunities.

The orderbook for methanol-fuelled vessels and vessels with hydrogen installations is shown in Figure 4-6 (AFI, 2023), displaying an increase in such vessels towards 2028. In addition, there are known plans for numerous ammonia-fuelled vessels, though they are not yet in the orderbook.

[18] https://www.tu.no/artikler/mf-hydra-fyller-hydrogen-pa-tanken/521174

Figure 4-6: Annual delivery of hydrogen- and methanol-fuelled vessels according to the orderbook (AFI, 2023)



4.1.6.2 *Known port and bunkering infrastructure projects*

The list of port and bunkering infrastructure projects is mainly based on input from industry papers and announcements (Kilemo, Montgomery, & Leitao, 2022), and from the World Ports Climate Action Program (WPCAP, 2023) and the Nordic Roadmap project. The list includes bunkering vessel projects, bunkering infrastructure projects in ports, and announced green shipping corridor projects.

The identified projects are categorised based on fuel type, initiator (government, industry, or public-private), and location (region). We have also categorised the projects into three project categories: 1) green corridors, 2) bunker vessels, and 3) bunkering infrastructure projects. The status and time horizon of the projects are stated where this was accessible. The full list of projects can be found in Appendix 5.

We include in the list projects relating to the relatively new policy incentive of green shipping corridors. Since the Clydebank Declaration during COP 26 in 2021[19], this concept has received increasing interest and attention, recently at the COP 27 climate conference (el-Sheikh, 2022). Green shipping corridor initiatives and plans indicate a demand for fuels in the ports involved. Several of the major bunkering ports have already announced participation in a green shipping corridor, including Singapore, Rotterdam, Busan, Antwerp and Houston, as well as key container ports such as Los Angeles and Shanghai[20]. Green shipping corridors can help overcome barriers to the uptake of alternative fuels and become a key enabler to accelerate the uptake of alternative fuels and force the development of required bunkering infrastructure (Slotvik, 2022).

A total of 48 port and bunkering infrastructure projects were identified by this study. An example of a bunker vessel project is the 4,000 DWT chemical and oil tanker that will join GET's fleet at the end of 2023, carrying biofuel and methanol, operating out of the Port of Singapore (Executive, 2022). For bunkering infrastructure projects, ports in the US and Europe have announced plans for supplying ammonia (e.g. Hamburg and Houston (Taylor, 2023)) and hydrogen (e.g. Amsterdam (Hydrogen Central, 2023; Durakovic, 2022; Hydrogen Central, 2022) and Corpus Christi (Pekic, 2022)). In addition, Port of Amsterdam plans to develop a LOHC import terminal and a plant for the continuous large-scale production of hydrogen.[21] The development of hydrogen value chains connected to the port of Amsterdam can contribute to the decarbonisation of European industries.

Figure 4-7 shows how the number of projects is distributed by project category and fuel type, and by status of development and fuel type**.** For the project's status of development, the **initiation** phase refers to projects

[19] https://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors/cop-26-clydebank-declaration-for-green-shipping-corridors The Green shipping corridors concept aims to kick-start maritime's transition to carbon-neutral fuels, facilitating adoption and bunkering infrastructure development of alternative fuels. The Clydebank Declaration set a goal of enabling six green shipping corridors by 2025 and "many more" by 2030. More than 20 countries have signed this declaration and are committed.

[20] Note that in this list of projects in Appendix 0 we have counted a green corridor project as *one* bunkering infrastructure project.

[21] Port of Amsterdam is working with Gasunie to develop a hydrogen pipeline connecting IJmuiden and Amsterdam. This will be directly connected to the Netherlands' national hydrogen 'backbone'. Developing the basic infrastructure is a precondition for the subsequent setting up and scaling up hydrogen projects. https://www.portofamsterdam.com/sites/default/files/2021-10/Hydrogen%20Hub%20NZKG_uk_v06_LR%2005-10.pdf

where only announcements are made, the **feasibility** phase refers to projects where feasibility assessments are ongoing or finished, and the **planning** phase refers to projects that are under planned development.

Compared with the orderbook, there is a low number of methanol bunkering projects, while a high number of hydrogen projects have reached the planning stage. As many of the green corridors are at an early phase (initiating phase where only announcements are made), this category is dominated by unknown fuel type, or the project is still considering all or multiple options.

Figure 4-7: Number of port and bunkering projects included in the list developed in this project, sorted by three project type categories (left) and by fuel type and status of development (right). A total of 48 projects were identified (see Appendix 5)

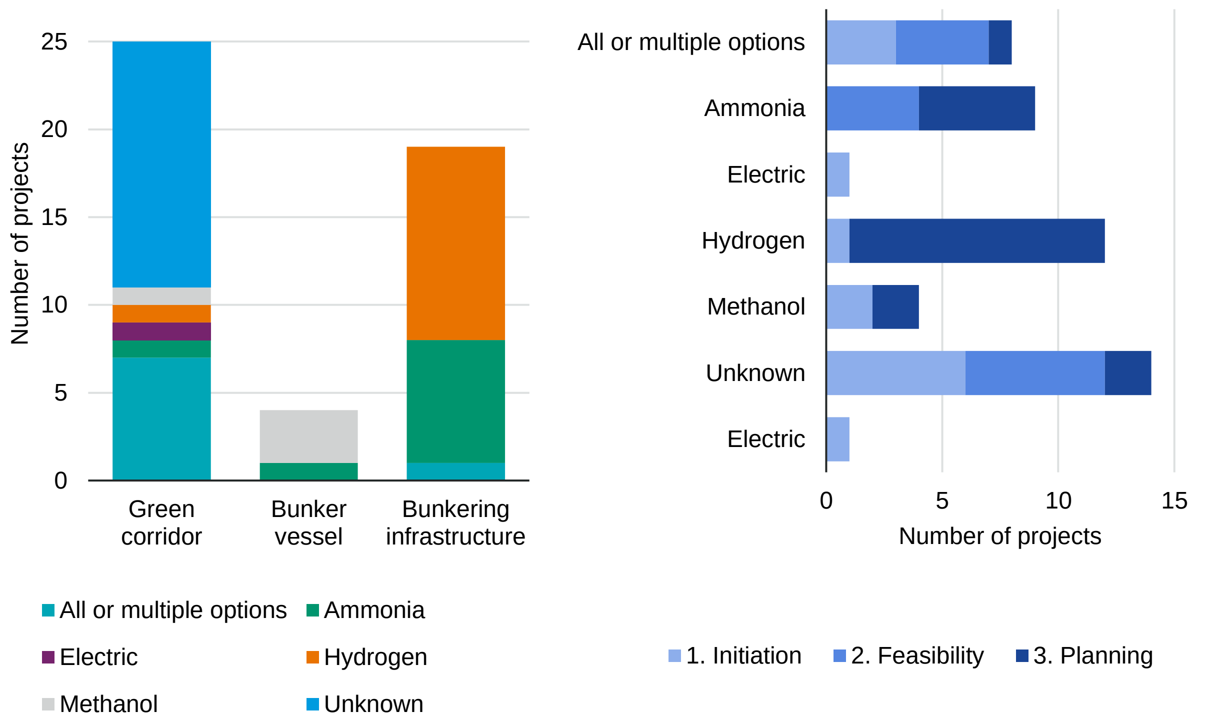
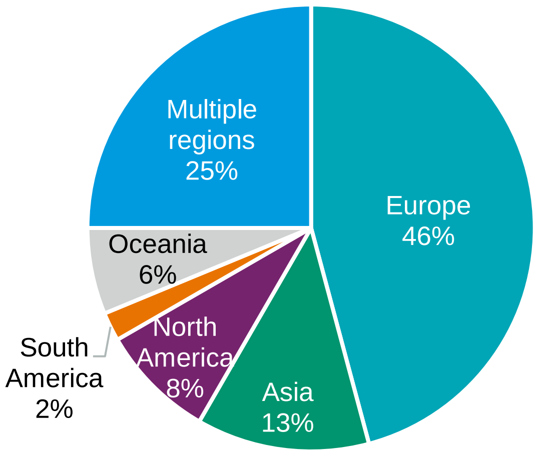


Figure 4-8 presents the location of the projects. The overall picture shows highest activity in Europe, followed by Asia and Oceania. The activity involving multiple regions is mainly green corridor projects. Green shipping corridors typically have low maturity, as most corridors are only announced by the partners involved and no further public assessment is available. For bunkering vessels, the location is flexible, but it is the region of planned operation that is stated in the list. Bunkering infrastructure projects are referring to stationary projects where there is planned development of the infrastructure and supply chain of the alternative fuels, often initiated by ports.

Figure 4-8: Identified port and bunkering infrastructure projects, by region. See Appendix 5 for the list of projects.



4.1.6.3 *How to leverage existing infrastructure to speed up bunkering availability for future fuels*

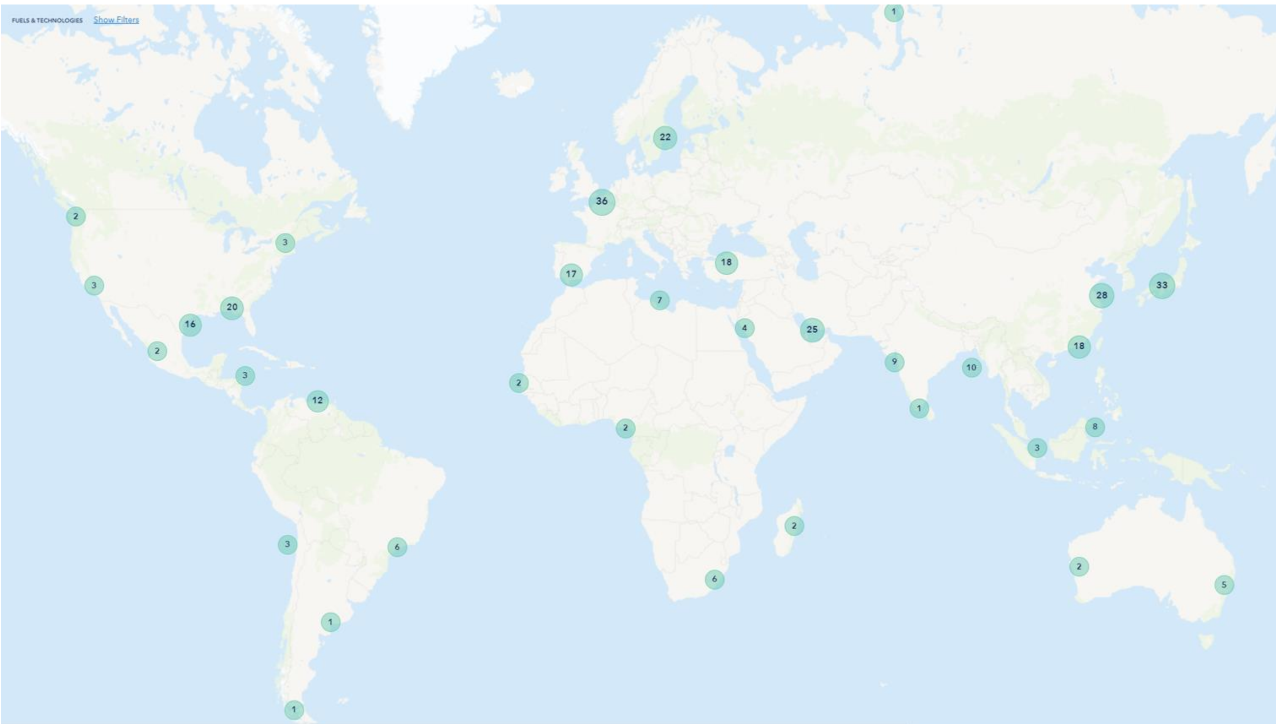
In this section we have performed a high-level assessment of what can be done to speed up availability of bunkering infrastructure for the future candidate fuels, and to what degree existing distribution and storage can be leveraged in the future. This can be done to a varying degree depending on the fuel type.

The new fuels for shipping, such as ammonia, hydrogen, and methanol are incompatible with the current bunkering infrastructure of conventional fuels, and development needs to be adjusted according to the specific fuel type. The fact that the different candidate fuels have different characteristics adds complexity to the infrastructure development. We may anticipate a need to shift away from refuelling being dominated by a small number of major bunkering hubs in the future, as some of the candidate fuels have lower energy density, reducing the range for the vessels.

Bio-MGO and e-MGO can use existing fuel oil infrastructure, and liquified biomethane and e-methane can use the developing LNG infrastructure. Assuming availability for such fuels, the bunkering infrastructure, distribution, and storage capabilities are ready and sufficiently developed today.

There is already a significant shipping network for transporting in the order of 50 Mt annually of ammonia and methanol combined. Around 18–20 Mt of ammonia are transported annually by ship, and around 170 ammonia carriers are in operation, of which 40 carry ammonia on a continuous basis (IRENA, AEA, 2022). Seaborne transport of methanol was 30 Mt in 2018 (Dolan, 2019), and methanol is already available in more than 100 major ports today, with 47 of these having storage facilities in excess of 50,000 tonnes (Methanol Institute, 2020). Figure 4-9 shows the locations of ammonia and methanol terminals globally, where the clusters indicate number of terminals in that area. In total there are around 215 existing ammonia terminals and around 120 existing methanol terminals with storage infrastructure. This infrastructure can possibly serve as a starting point for a distribution network for the use of ammonia and methanol as fuels for shipping, bringing down the 'last-mile' distribution cost. The ammonia and methanol stored and distributed today are mainly produced from fossil-based sources.

Figure 4-9: Map showing the geographical distribution of existing ammonia and methanol terminals, the clusters indicate the number of terminals in the area (AFI, 2023)



For hydrogen, the distribution network is not developed, and only small-scale transportation of hydrogen exists today. However, there is one ship that has successfully transported liquefied hydrogen. In January 2021, the Susio Frontier, the world's first liquid hydrogen carrier ship sailed from Australia to Japan with liquefied hydrogen as cargo for the first time (HESC, 2022). In addition, five ports (Amsterdam, Brünsbuttel, Rotterdam, Wilhelmshaven in Europe, and Kobe in Japan) are developing hydrogen import plans. For storing compressed or liquefied hydrogen, new dedicated bunkering infrastructure will be required.

Table 4-1 shows a high-level screening of the different candidate fuels, based on fuel type, addressing two elements: distribution and storage, and the bunkering infrastructure of the fuel type – assuming there are no issues related to feedstock availability and production. The high-level screening is given for three readiness levels; 1) mature and proven, 2) solutions identified, and 3) barriers remain. LNG and MGO (bio- and e-fuels) have mature bunkering options for shipping, while methanol has proven bunkering operations but needs further investment in bunkering facilities and scale-up. For ammonia, there is still a way to go regarding port and bunkering infrastructure, and hydrogen poses immature solutions for both distribution and bunkering infrastructure. For shipowners to choose candidate fuels, the fuels must be available in relevant ports, and coordinated plans must be made to increase bunkering availability.

Table 4-1: High-level screening of status regarding distribution and storage and bunkering infrastructure for candidate fuels

Fuel types	Distribution and storage	Bunkering infrastructure
Fuel oils (e-diesel, biodiesel)	Can use existing distribution and storage facilities for distillate fuel	Can use existing bunkering infrastructure for distillate fuel
Gaseous fuels (e-methane, biomethane)	Can use existing (and still developing) distribution and storage facilities for LNG	Can use existing (and still developing) LNG infrastructure
Methanol (e-methanol, biomethanol)	Can build on existing storage and distribution infrastructure from	Demonstration bunkering operations have been successful, ship-to-ship bunkering proven.

Fuel types	Distribution and storage	Bunkering infrastructure
	global network of terminals, used for global methanol trading/transport	Partially developed bunkering infrastructure at 90 ports worldwide.
Ammonia (e-ammonia, blue ammonia)	Can build on existing storage and distribution infrastructure from global network of terminals, used for global ammonia trading/transport	No bunkering infrastructure today, and no bunkering operations demonstrated. Barriers remain to be solved.
Hydrogen (e-hydrogen, blue hydrogen)	No existing distribution infrastructure	No existing bunkering infrastructure Local bunkering operations have been demonstrated. Barriers remain to be solved.

The high-level screening is given for 3 readiness levels:
Green: Mature and proven; Amber: Solutions identified; and Red: Barriers remain.

4.2 SHIPYARD CAPABILITY

Key findings

- There is an increasing number of alternatively fuelled vessels being built.
- The number of shipyards delivering alternative-fuelled vessels is diversifying.
- There is capacity in the industry to scale up the production and installation of energy converters, energy efficiency technologies and onboard carbon capture plants over short time periods once demand is clear.
- Provided that there is a demand for candidate fuels and energy efficiency improvements, the shipyard industry can be expected to follow a similar learning curve as for LNG and move into an upscaling phase with accelerated growth in capacity.

4.2.1 **Method**

In this section, historical delivery rates, and planned deliveries of new vessels are used to assess the capacity to support the accelerated uptake of vessels able to use candidate fuels in to 2050. To assess the future shipyard capacity for building vessels running on candidate fuels, we utilise shipyards' historical delivery capacities of new vessels running on alternative fuels (LNG, LPG, methanol, hydrogen, ammonia).

The analysis is based on the assumption that shipyards able to build LNG-fuelled vessels are also capable of building vessels running on candidate fuels such as ammonia or hydrogen. The assumption builds on the fact that LNG ships are more complex to build than conventionally fuelled ships, placing new requirements on both equipment suppliers and shipyards. While hydrogen-powered ships may be even more complex to build, building ships running on methanol and ammonia is expected to be less complex (Ebrahimi, 2021). Our method focuses on number of vessels instead of gross tonnage delivered, because the complexity of the fuel solutions is not directly linked to the vessel size.

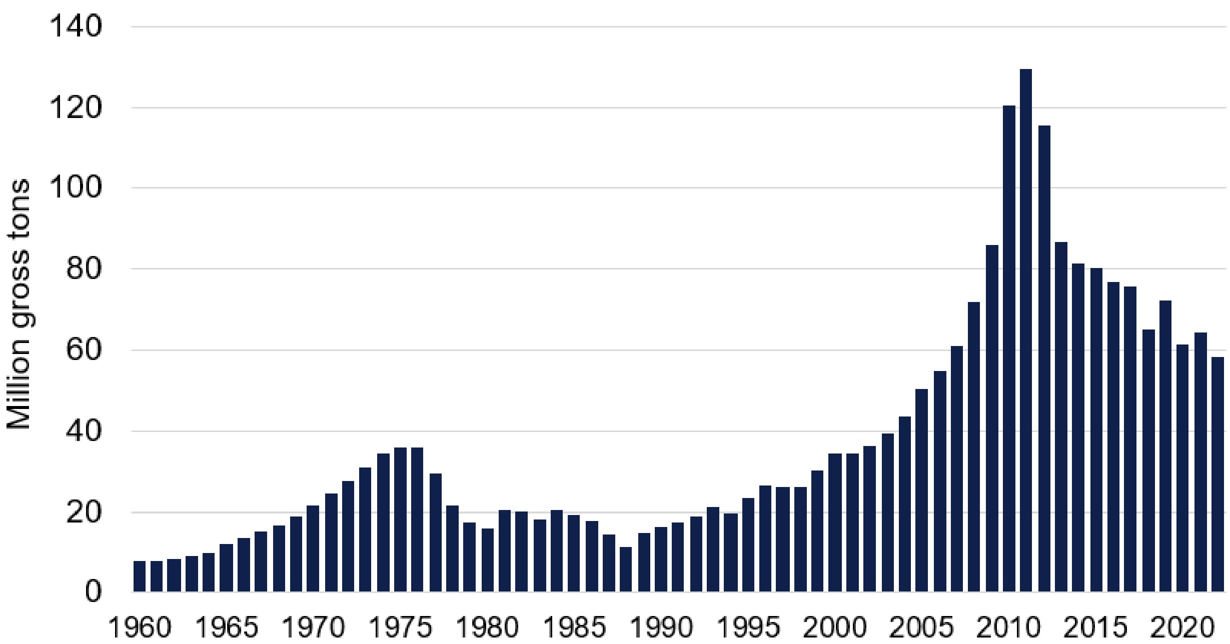
The basis for the analysis is the IHS Markit database (IHS Markit, 2023), covering all newbuilds above 1,000 GT for the world fleet delivered back to mid-20th century. For each newbuild, this database includes vessel-specific information such as country of shipyard, time of delivery, and vessel particulars. In addition, the IHS Markit database has been enriched with information from DNV's Alternative Fuels Insight platform (AFI, 2023) on vessels with alternative fuel systems.

4.2.2 **Background**

The shipbuilding industry has been drastically affected by demand fluctuations driven by changes in world GDP and other factors. Insight on the historical development of shipbuilding industry capacity has been provided by Stopford (2009). More recent work includes that of the OECD Council Working Party on Shipbuilding (OECD, 2023b) which has analysed capacity in the global shipbuilding industry, including projection towards 2030; for example, (Daniel, Adachi, & Lee, 2022; Daniel & Lee, 2022; Gourdon, 2019; OECD, 2017). Various studies analysing and modelling shipbuilding markets have recently been reported by Wada (2022).

The merchant shipbuilding industry has a volatile history as illustrated in Figure 4-10. Ship production trebled from 8 million GT in 1960 to 30 million GT in 1977, then halved to 16 million GT in 1980 and 1990. Then production increased to 50 million GT in 2005, reaching historical peak production at 130 million GT in 2011 before more than halving to 60 million GT in 2022 (IHS Markit, 2023). A recent study by Daniel & Lee (2022) shows that the shipbuilding industry still faces excess capacities.

Figure 4-10: Shipbuilding output 1960–2022 in gross tons for vessels above 1,000 GT (IHS Markit, 2023)

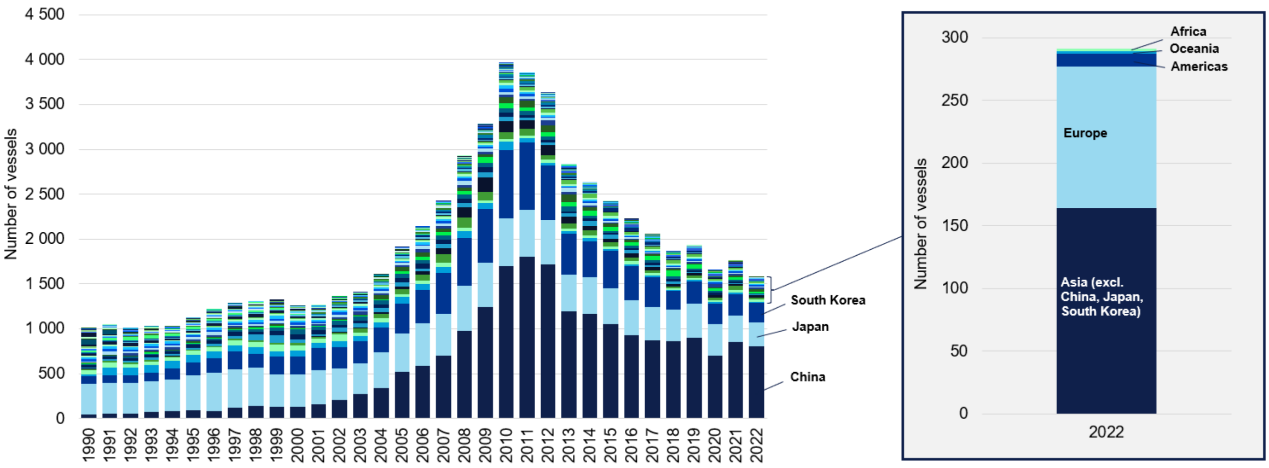


This development was accompanied by a realignment of regional shipbuilding capacity, where Europe's market share fell while Asia's grew. Today, some 30 countries have a significant shipbuilding industry, with China (45%), South Korea (30%) and Japan (17%) dominating the industry, accounting in total for around 92% of the world's newbuild deliveries in 2022 in GT terms. China tripled its production in GT delivered between 2000 and 2005, and is now the largest shipbuilding economy in both ship completions and new contracts (Daniel & Lee, 2022).

Figure 4-11 shows the number of vessels above 1,000 GT delivered per country in the years 1990 to 2022. China dramatically increased its shipbuilding deliveries in the years from 2000, peaking in 2011. South Korea also shows a peak in shipbuilding in the period before and after 2011, but not of the same scale as China. Japan, on the other hand, shows a steadier trend of newbuild deliveries, ranging typically between 300 to 500 vessels delivered annually from 1990 to 2022. Beyond China, South Korea, and Japan we see that other countries in Asia and Europe dominate shipbuilding.

Figure 4-11: Number of newbuilds delivered per country with respect to number of vessels above 1,000 GT from 1990 to 2022 (IHS Markit, 2023)

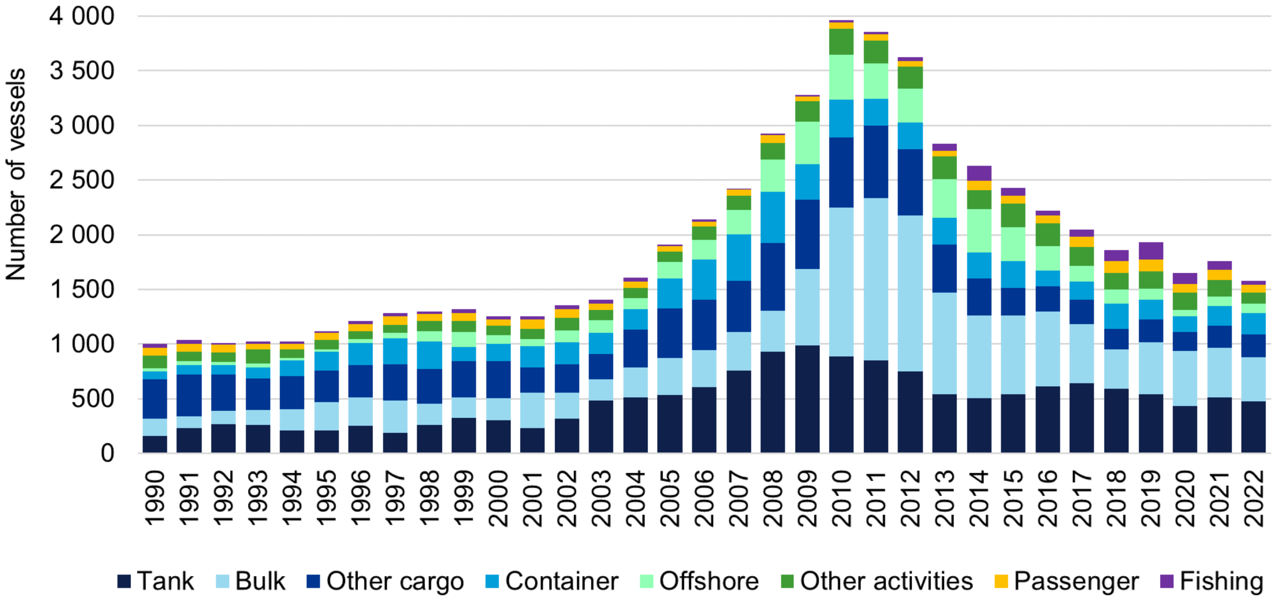
Zoom box shows countries other than China, Japan, and South Korea, delivering newbuilds of greater than 1,000 GT in 2022



4.2.3 Historical newbuild development

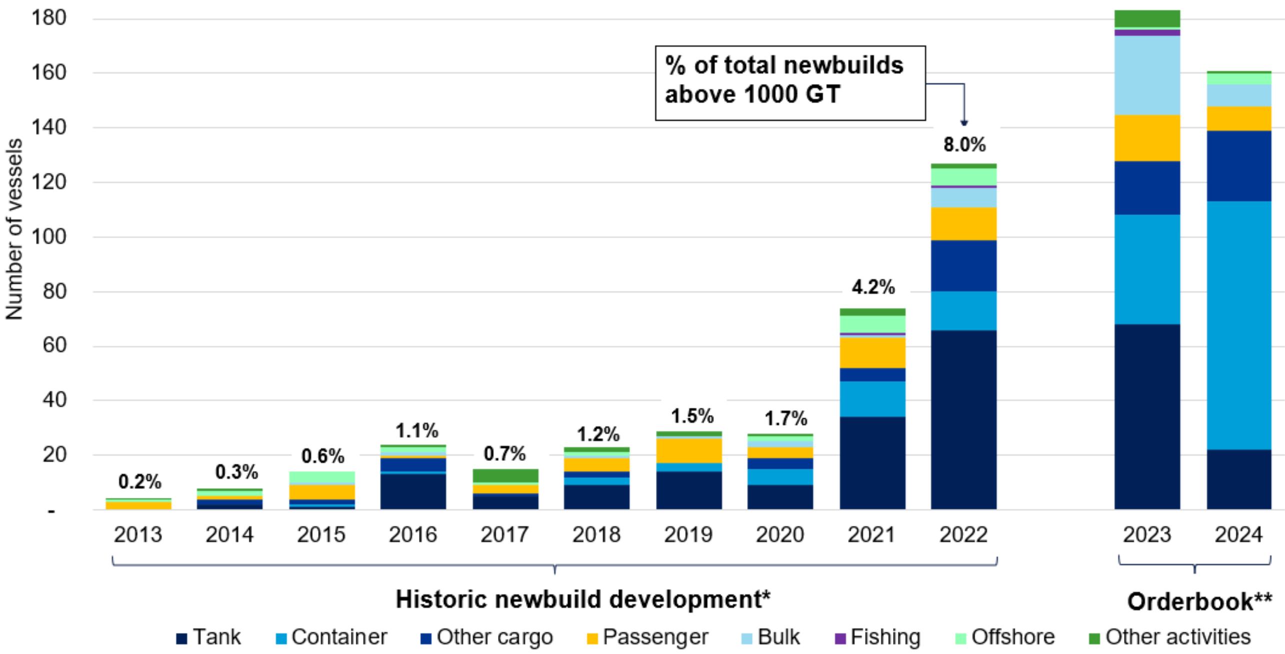
Figure 4-12 shows the development of newbuilding activity in number of vessels from 1990 to 2022 per ship type (IHS Markit, 2023). The figure shows a large peak in the years 2010, 2011 and 2012, driven mainly by a steep increase in the number of bulkers being built in this period. If focusing on the decade from 2013 to 2022, we see that bulker and tanker vessels comprise around 50% of the newbuilds being delivered.

Figure 4-12: Newbuilds delivered per ship type in number of vessels above 1,000 GT from 1990 to 2022 (IHS Markit, 2023)



Moving our focus to uptake of newbuilds with alternative fuel systems, Figure 4-13 shows a slow increase in the size of the vessels using alternative fuels being built from 2013 to 2020, while in 2021 and 2022 we see a large increase with LNG leading the way. The number of LNG-fuelled vessels delivered in recent years has increased sharply. They represented 0.5% in 2013, but 8% of all newbuilds above 1000 GT in 2022, of all newbuilds above 1,000 GT. The total share of newbuilds on alternative fuels increased from 1.7% in 2020, to 4.2% in 2021 and 8% in 2022. Looking at the orderbook for 2023 and 2024, the trend of building alternative-fuelled vessels continues into 2023, but slightly decreases with current 2024 numbers. However, it is still possible that more vessels will be added in the alternative fuel orderbook for 2024. Note that only vessels built to run on alternative fuels from newbuild stage are included in Figure 4-13; it excludes retrofits.

Figure 4-13: Historic delivery of newbuilds on alternative fuels from 2013 to 2022 (IHS Markit, 2023), and the current orderbook for ships on alternative fuels in 2023 and 2024 (AFI, 2023)

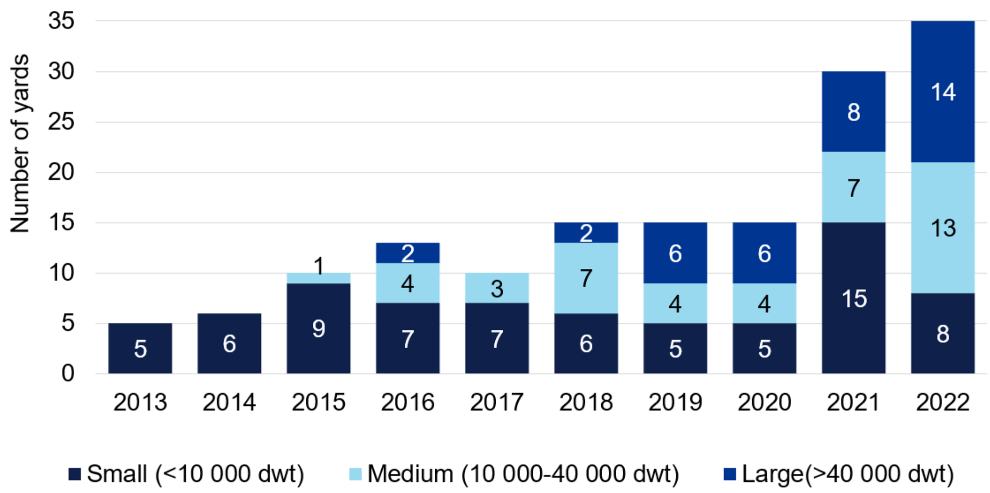


The figures on top of the bars from 2013 to 2022 indicate the percentage of all newbuilds built above 1,000 GT that are for alternative fuels (LNG, LPG, methanol).
**Historic newbuild development only shows vessels above 1,000 GT*
***Orderbook also includes vessels below 1,000 GT*

4.2.4 Developments in shipyard capability

Even though modern shipyards are highly flexible in the type of ships they build, physical and commercial factors tend to subdivide the shipbuilding market into a number of sectors. Stopford (2009) categorises the world's shipyards into three segments – small (building vessels below 10,000 dwt), medium (building vessels between 10,000 and 40,000 dwt) and large (building vessels above 40,000 dwt). Figure 4-14 presents the distribution of yards building small, medium, and large vessels from 2013 to 2022 to run on alternative fuels.

Figure 4-14: Number of yards that have delivered small, medium, and larger vessels above 1,000 GT per year from 2013 to 2022 to run on alternative fuels (IHS Markit, 2023)



The shipyards are categorised in size groups based on the largest vessel delivered for the specific year.

Figure 4-14 shows that there has not only been an increase in the number of vessels on alternative fuel delivered in the period 2013 to 2022, but that there has also been an increase in the number of yards delivering these vessels. In addition, it shows an increase in the number of yards building large vessels above 40,000 dwt. For comparison, around 400 yards delivered vessels annually in the years 2020 to 2022, during which around 90 yards delivered vessels above 40,000 dwt.

4.2.5 Equipment suppliers and installation

Beyond shipbuilding capacity and capability, the global marine equipment industry is a key supplier and input sector to shipbuilding production processes. The cost of equipment and materials ranges between 55% and 60% of total shipbuilding cost, but the sector is highly fragmented and heterogeneous (OECD, 2023a). When considering shipyard capacity, it is critical also to consider supply of marine equipment such as energy converters and storage (e.g. engines, fuel cells, batteries, tanks, fuel supply systems).

This study does not analyse the capacity for providing equipment to the ships. Beyond the alternative fuels systems, for the capacity to produce and install onboard CCS plants and other energy efficiency measures, we can use the uptake of exhaust gas cleaning systems (EGCS) as an indicator of capacity. The development and implementation of EGCS were driven by the adoption of the revised MARPOL Annex VI in 2008, which set a requirement of maximum 0.5% sulphur content in marine fuels from 2020, unless the ship was equipped with an EGCS. The IMO reviewed and finally confirmed the regulation in 2016, after which the uptake of EGCS accelerated. From 2017 to 2020, the number of ships equipped with EGCS increased from around 400 to almost 4,400 (AFI, 2023).

4.2.6 Expected future shipyard capability and capacity

Several factors could impact the future capacity to build ships running on candidate fuels, and to produce and install CCS plants and energy efficiency technologies both on newbuilds and existing vessels.

The historical data presented above shows that there is capacity to build a large number of vessels. Daniel et al. (2022) recently made an overall projection indicating potential overcapacity in the shipyard industry, also towards 2030. Hence, to increase the total capacity, it is critical to further increase the number of yards capable of delivering vessels to run on alternative fuels such as ammonia, methanol, and hydrogen.

The example of implementation of EGCS for the global sulphur limit requirement in 2020, indicates that there is a capacity in the industry to scale up the production and installation of CCS plants and energy efficiency technologies, and this is not expected to be a limiting factor provided that the technology is sufficiently mature and there is a demand for such solutions.

Retrofitting a ship to run on an alternative fuel system such as ammonia or methanol is more complex. Recently, more than 200 vessels have been built with various fuel-ready notations[22], indicating that these have been prepared to a certain degree for retrofitting at a later point in their lifetime (IHS Markit, 2023). This is expected to reduce the complexity of retrofitting, potentially increasing the number of yards capable of doing such retrofits.

Historical data shows that technology adoption often starts slowly, followed by exponential growth before gradually flattening out to follow an S-shaped curve as it approaches saturation (IEA, 2000). The shipbuilding industry is currently in a preparation phase for rolling out candidate fuels. Provided that there is a demand for candidate fuels and energy efficiency improvements, the shipyard industry can be expected to follow a similar learning curve as for LNG and to move into an upscaling phase with accelerated growth in capacity.

[22] See, for example, https://www.dnv.com/news/new-dnv-fuel-ready-and-gas-fuelled-ammonia-class-notations-provide-maximum-flexibility-to-tackle-shipping-s-carbon-curve-203646, https://marine-offshore.bureauveritas.com/magazine/introducing-our-ammonia-prepared-notation-and-rule-note and https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/design_and_analysis/210_lng_fuel_ready_vessels_2022/gas-and-lff-ready-guide-mar22.pdf

5 DEMAND FOR CANDIDATE FUEL ENERGY TO MEET THE DECARBONISATION SCENARIOS

Overview

- Two (high and low) seaborne transport demand projections to 2050 are selected from the Fourth IMO GHG Study 2020 to be used when estimating the energy demand under the BAU scenario.
- The energy demand of international shipping is estimated under the low and high growth BAU scenarios for each of the two selected seaborne transport demand projections.
- The potential reduction in energy demand from uptake of additional energy efficiency measures is estimated, and the potential for using shore power, beyond the uptake estimated in the BAU scenario.
- The energy that candidate fuels will need to supply to reach the GHG emission reduction targets in 2030, 2040, and 2050 is estimated for the three decarbonisation scenarios.

Key findings

- Seaborne transport demand projected to grow between 39% and 81% between 2022 and 2050, and Business as usual (BAU) energy demand by 2050 is expected to be 23-75% higher than 2022.
- In the low and high growth BAU scenarios, shipping will therefore require between 11.1 and 15.8 EJ of energy by 2050, which results in between 761 and 1068 MtCO_2e of GHG emissions. For comparison, the energy demand in 2022 – supplied almost exclusively with fossil fuels – was ~9.0 EJ.
- Additional energy efficiency measures beyond BAU including a 30% speed reduction are estimated to reduce energy demand by around 27% – between 2.9 and 4.3 EJ – in 2050, while potential use of shore power increases to 5% of energy demand for shipping by 2050.
- The remaining energy demand for candidate fuels is between 8.2 and 11.5 EJ in 2050 under the low and high growth BAU scenarios respectively, for decarbonisation by 2050 using the additional energy efficiency measures.

5.1 METHOD

This study uses 2022 as a baseline year for projecting emissions and energy need to 2050. The baseline is calculated using DNV's MASTER model (Mapping of Ship Tracks, Emissions and Reduction potentials) which uses global ship-tracking data from AIS, enriched with ship-specific data from other sources, to model baseline fuel consumption and emissions from ships and fleets (DNV GL, 2019; Mjelde, et al., 2019).

The total energy demand for international shipping in a certain year in the future is a function of the shipping activity (transport work per year) and the energy intensity (energy used per transport work). With a GHG emission target, there is a certain limit to the amount of energy that can be provided from fossil sources, and the remaining energy demand needs to be either covered by reducing the energy intensity through further uptake of energy efficiency measures and speed reduction, or by using candidate fuels with close to zero tank-to-wake GHG emissions. The energy required from candidate fuels is calculated using the total annual energy demand for the shipping fleet minus the maximum energy that can be provided by fossil fuels without exceeding the GHG emission target.

Estimating the future energy intensity of the fleet requires taking into account the technical and operational profile of the current and future fleet, logistical changes (e.g. ship sizes, new sea routes) and expected scrapping of older, inefficient ships and inclusion in the fleet of newbuilds with improved energy efficiency technologies which in turn is influenced by future fuel prices. The seaborne trade growth is a significant factor for achieving a GHG emission target, as under a high-growth scenario each ship will need to improve its energy and GHG intensity relatively more compared with a low seaborne trade growth scenario in order for international shipping in total to achieve the same GHG emission target.

The uptake of energy efficiency measures and speed reduction are other significant factors for determining the energy demand. Under the BAU scenarios, the uptake is based on compliance with currently adopted policies (EEDI, EEXI, CII and SEEMP), assuming that the CII reduction factors increase by 2 percentage points per year between 2027 and 2030. In addition, measures that are cost-effective (i.e., positive net present value) in themselves due to fuel cost savings are applied. Under the decarbonisation scenarios, we could expect a higher uptake of energy efficiency measures as fuel costs increase and through further policies, reducing the demand for candidate fuels. We estimate the potential energy efficiency improvements and resulting energy demand reduction that can be achieved with all ships implementing speed reductions up to 30% and all newbuilds implementing the latest energy efficiency measure packages.

To take into these factors into account, we apply a detailed fleet modelling using DNV's Pathway Model (DNV, 2022c; DNV GL, 2020; Eide, Chryssakis, & Endresen, 2013; Eide, Longva, Hoffmann, Endresen, & Dalsøren, 2011) to estimate the uptake of energy efficiency technologies, LNG, and LPG in the fleet to 2050, and use that to estimate the required energy in total and the energy required to be provided by candidate fuels to achieve a certain decarbonisation target.

Further details on the calculation method, the Pathway Model and key inputs are found in Appendix 2.

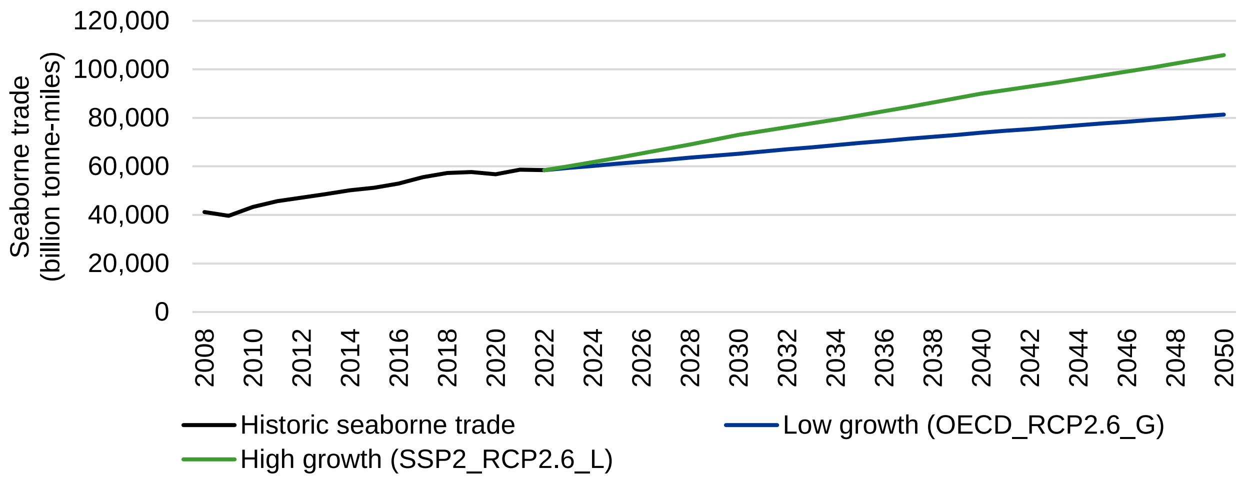
5.2 SEABORNE TRANSPORT DEMAND

The future seaborne transport demand determines the shipping activity to 2050, which has a large impact on the total demand for energy from the shipping fleet. We select two representative seaborne transport demand scenarios from the Fourth IMO GHG Study 2020 to provide a high and a low projection of shipping activity:

- **Low growth**: Uses the OECD_RCP2.6_G scenario projecting a **39% growth** in seaborne trade between 2022 and 2050
- **High growth**: Uses the SSP2_RCP2.6_L scenario projecting an **81% growth** in seaborne trade between 2022 and 2050

This study uses 2022 as the base year while the projections in the Fourth IMO GHG study use 2018 as base year. The estimated seaborne transport demand in 2022 of about 58,500 billion tonne-miles (Clarksons Research, 2023) is lower than projected by both scenarios for 2022. The estimated seaborne transport demand also includes domestic shipping. Rather than target the same absolute transport demand in 2050, we apply the same annual growth rates per segment as projected in the Fourth IMO GHG Study 2020 in the respective scenarios from 2022 to 2050, assuming that the transport demand for international shipping is the same as for all shipping covered by the seaborne transport demand estimates. This also results in the projected seaborne transport demand in 2050 in this study being lower than projected in the Fourth IMO GHG Study 2020, because the starting point in 2022 is lower.[23] The resulting projections are shown in Figure 5-1. Further explanation of the rationale for selecting the two scenarios is found in Appendix 3.

Figure 5-1: Historic and projected low- and high-growth seaborne transport demand 2008–2050. Note that the numbers include both international and domestic shipping



The historic data from 2008 to 2022 are from Clarksons Research (2023) *and the future projection are based on the two selected scenarios from the Fourth IMO GHG Study 2020.*

[23] This study has not analysed the impact of COVID-19 on the projected growth. Depending on the recovery, seaborne trade in the next decades may at most be a few per cent less than projected. In all, the impact of COVID-19 is likely to be smaller than the uncertainty range of the presented scenarios.

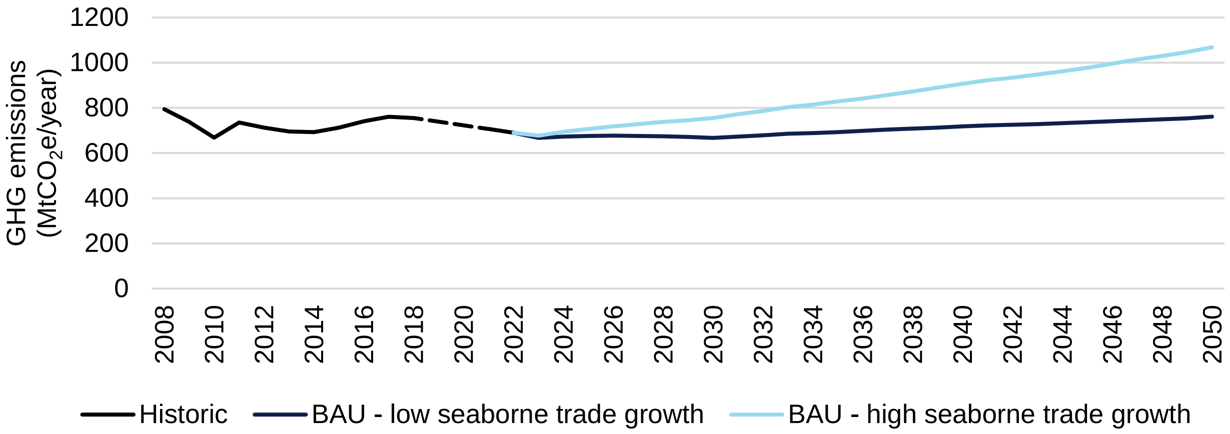
5.3 GHG EMISSIONS AND ENERGY DEMAND IN THE BAU SCENARIOS

The GHG emissions from international shipping in 2022 using the voyage-based allocation method is calculated to 690 $MtCO_2e$, of which 1.1% were CH_4 (7.5 $MtCO_2e$) and 1.5% N_2O (10.2 $MtCO_2e$). This is a 13% reduction compared with 2008. Towards 2050, the GHG emissions are expected to increase to 761 $MtCO_2e$ (10%) and 1068 $MtCO_2e$ (55%) in the low and high growth BAU scenarios, respectively, which is a 10–55% increase compared with 2022, and a 4% reduction to a 35% increase if comparing with 2008.

In the BAU scenarios, the uptake of LNG is expected to continue, reaching 49–54% of energy use in 2050, with the high-growth scenario resulting in a greater share of LNG in the fuel mix. This increases the share of CH_4 in the total GHG emissions almost five-fold to 4.7–5.3 % in 2050, though the total GHG intensity of the fossil fuels reduces. Biofuels and e-fuels have a small share of the fuel mix, peaking in 2030 at about 2.4–2.6% before reducing to 0.6–0.7% in 2050. The reduction is due to policies not becoming more stringent after 2030, and as new and more energy-efficient ships replace the existing ships the need for biofuels and e-fuels reduces.

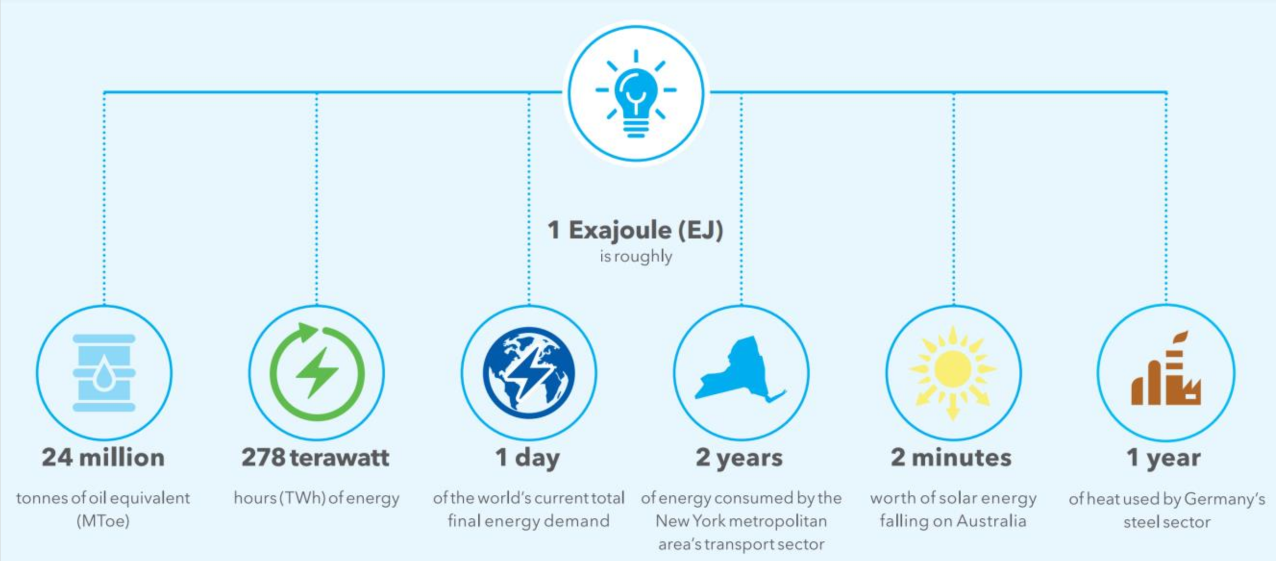
Figure 5-2 shows historic and projected GHG emissions per year to 2050 for the low- and high-growth BAU scenarios.

Figure 5-2: Historic and projected tank-to-wake GHG emissions 2008–2050 for the BAU scenarios with a low and high growth



Historic emissions for 2008 and 2012–2018 are based on the Fourth IMO GHG Study 2020 using the voyage-based allocated method, while the emissions for 2009–2011 are based on the annual changes from 2008 calculated by the Third IMO GHG Study 2014 using the vessel-based allocation method. Emissions from 2019–2021 are interpolated. Emissions from 2022–2050 are projected by this study.

Box: Energy demand and availability for the sectors are expressed in this paper in Exajoules



Source: DNV Energy Transition Outlook (2021b)

Figure 5-3 shows the energy demand of international shipping in 2022, 2030, 2040 and 2050 for the low- and high-growth BAU scenarios. The energy demand is projected through DNV's Pathway Model which models a future fleet towards 2050 able to meet seaborne transport demand and evaluating the uptake of energy efficiency measures and emission reduction measures. Under the BAU scenarios, the uptake (i.e. BAU energy efficiency) is based on compliance with the currently adopted policies EEDI, EEXI, CII and SEEMP.

The total energy demand was 9.0 EJ in 2022 or about 215 Mtoe. In 2050, the demand increases to 11.1 EJ and 15.8 EJ in the low- and high-growth scenarios, respectively.

Figure 5-3: Projected energy demand in the high and low growth BAU scenarios

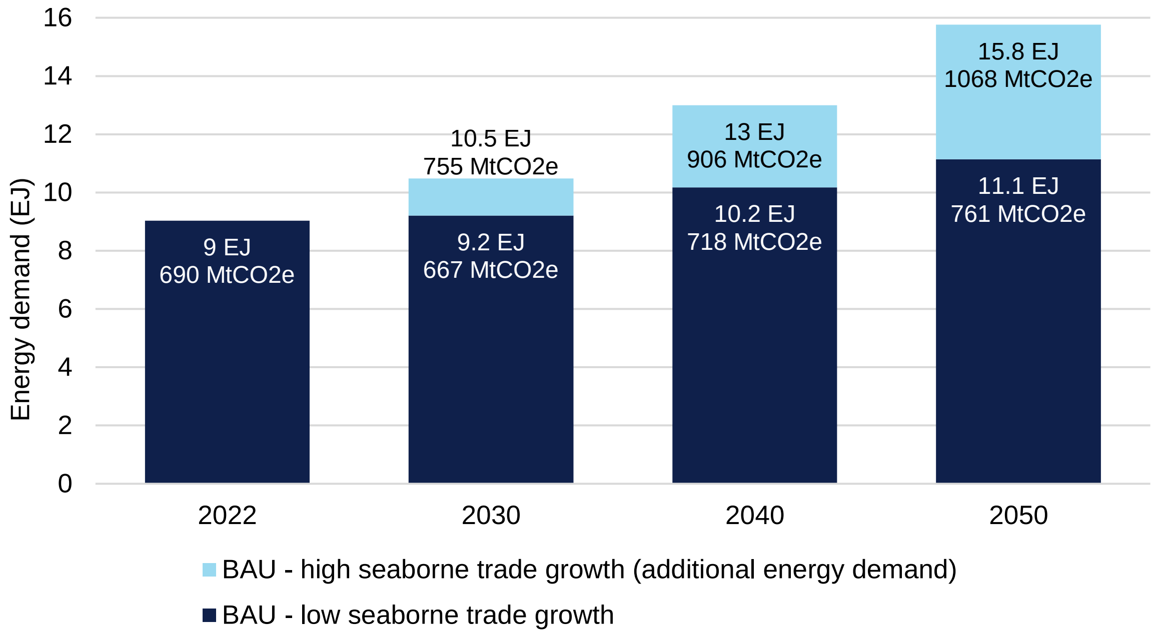
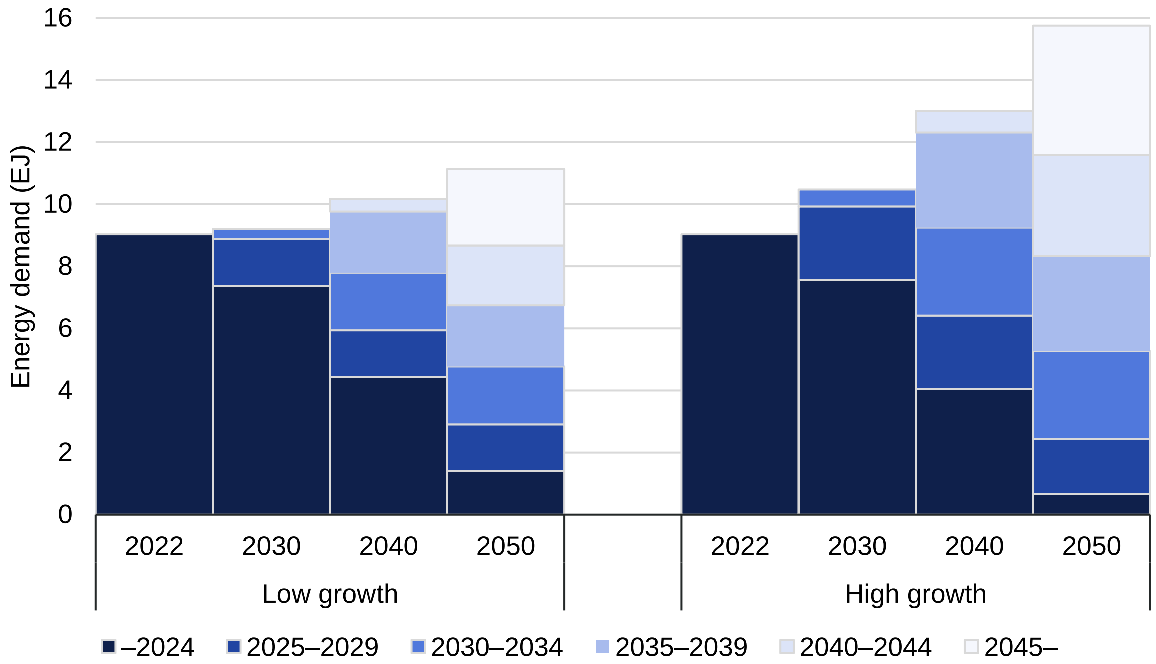


Figure 5-4 shows the energy demand group by build year for the ships in the fleet in 2022, 2030, 2040 and 2050. This shows how fast a new technology can be taken up in the fleet if it is included in all newbuilds from a certain year. For example, if all newbuilds from 2025 were built with a methanol or ammonia dual-fuel engine, the fleet in 2030 would be capable of using 1.8 EJ of methanol or ammonia in the low-growth BAU scenario and 2.9 EJ in the high-growth BAU scenario.

Figure 5-4: Energy demand per ship build years in the low- and high-growth BAU scenarios



5.4 POTENTIAL FOR ADDITIONAL ENERGY EFFICIENCY MEASURES AND USE OF SHORE POWER

The BAU scenarios assume a moderate uptake of energy efficiency measures (i.e. BAU energy efficiency measures) and no use of shore power. Further improvement of the fleet's energy intensity by uptake of additional energy efficiency measures will reduce total energy demand and consequently demand for candidate fuels. In this study, we estimate the potential for reducing energy demand if all new ships were to implement all applicable energy efficiency measures as they become available with a TRL of 10, and if all ships reduce speed by 30% (relative to a 2015 design speed average). The effect of 30% speed reduction varies across the fleet as it depends on the operational profile of the individual ships. A ship with long stretches at sea will see a larger impact than a ship with shorter voyages and more time in port. The modelling in this study takes the operational profile into account when estimating the effect.

Implementing 30% speed reduction and all available energy efficiency measures will likely require further policies to be implemented. The higher prices for candidate fuels are also expected to drive and maintain the uptake of energy efficiency measures.

The potential energy demand reduction in 2050 from additional energy efficiency measures is estimated to be 2.5 EJ (24% less than for BAU) for the low-growth scenario, and 3.7 EJ (23% less than for BAU) for the high-growth scenario. This should not be considered as the maximum potential for improving energy efficiency, as more measures can become available, or become more effective in the future. Further speed reduction to 50% may be possible but will require complex changes to the logistic supply chain (DNV GL, 2018).

Electricity is a candidate fuel that can be provided as shore power to ships at berth Using DNV's MASTER model for calculating emissions in 2022 based on AIS data (see Appendix 2), we estimate the fuel consumption from auxiliary engines for stationary ships to be about 11% of total fuel consumption for the fleet. Some of this time is waiting at sea with no option to connect to shore power. Data from the EU's MRV regulation shows that 5.5% of total fuel consumption was consumed at berth in 2020 (EC, 2021), though this reports the port consumption relative to voyages within, into, and out of the EU. DNV GL (2017) estimates that 30–70% of the fuel consumption at berth could be replaced by electricity from the land-grid towards 2050. This indicates potential to convert 4–8% of total fuel consumption to shore power by 2050. In this study, we assume that the implementation of shore power increases gradually from zero today to 1.4% in 2030, 3.2% in 2040, and 5% of the total consumption in 2050 after taking into account other energy efficiency measures. The use of shore power also results in an inherent efficiency gain for the onboard energy conversion, as we assume 90% efficiency for electricity conversion compared with 45% energy conversion for auxiliary engines on conventional fuels.

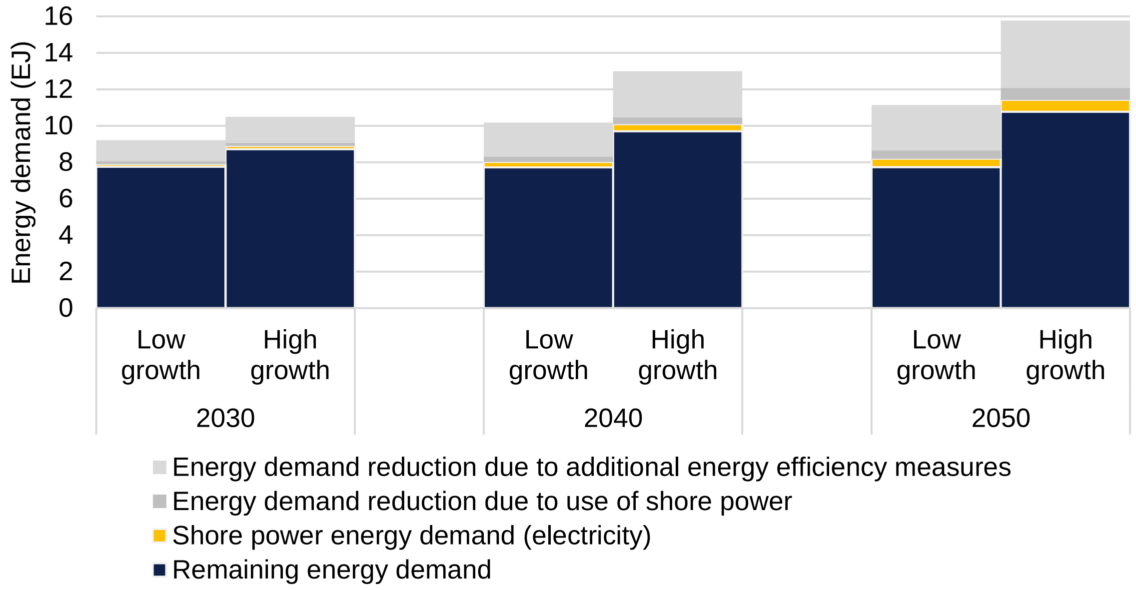
Table 5-1 shows the estimated potential for energy demand reduction from the additional energy efficiency measures, the potential shore power including the inherent energy demand reduction from using electricity rather than a liquid or gaseous fuel, and the total energy demand reduction. Figure 5-5 shows the same numbers including the remaining energy demand compared with the BAU scenarios.

Table 5-1: Potential for energy savings from additional energy efficiency measures and use of shore power compared with the BAU scenarios

Energy (EJ)	2030		2040		2050	
	Low growth	High growth	Low growth	High growth	Low growth	High growth
Energy demand – BAU energy efficiency (A)	**9.2**	**10.5**	**10.2**	**13.0**	**11.1**	**15.8**
Energy demand reduction due to further uptake of additional energy efficiency measures (B)	1.2	1.4	1.9	2.5	2.5	3.7
Shore power energy demand (electricity) (C = % of A – B)	0.12	0.13	0.27	0.34	0.43	0.60
Energy demand reduction due to use of shore power (equal to C[24])	0.12	0.13	0.27	0.34	0.43	0.60
Energy demand – additional energy efficiency (A – B – C)	**7.9**	**8.9**	**8.0**	**10.1**	**8.2**	**11.5**

Note that due to rounding, the total energy demand may differ from the sum of the values shown

Figure 5-5: Potential for additional energy demand reduction and use of shore power in the BAU scenarios for the low and high seaborne transport demand growth, and remaining energy demand



[24] Calculated as the fuel energy less the energy from the provided electricity. Due to different energy conversion efficiencies, 1 EJ of fuel energy is replaced by 1*0.45/0.9 = 0.5 EJ electricity and 0.5 EJ is saved.

5.5 CANDIDATE FUEL ENERGY DEMAND IN THE DECARBONISATION SCENARIOS

The GHG intensity of the fossil fuels determines the maximum amount of fossil energy that can be used without exceeding the GHG emissions targets in the decarbonisation scenarios. The maximum amount of fossil fuels for each scenario is calculated as the GHG target divided by the GHG intensity. The minimum amount of energy to be supplied by candidate fuels with zero or close to zero TtW GHG emissions is then calculated by subtracting the maximum amount of fossil fuels from the total energy demand in the BAU scenarios. A separate calculation on the minimum amount of candidate fuels is provided after taking into account reduction of energy demand from additional energy efficiency measures and the use of shore power.

Table 5-2 show the calculation steps and, together with Figure 5-7, the resulting fossil and candidate fuel energy demand for each decarbonisation scenario and year, for the high and low seaborne transport growth projections.

Table 5-2: Calculation steps and the resulting minimum amount of energy that needs be supplied by candidate fuels for the three decarbonisation scenarios with low and high seaborne transport demand growth

	Unit	Scenario	2030		2040		2050	
			Low growth	High growth	Low growth	High growth	Low growth	High growth
GHG targets (A)	$MtCO_2e$	RED50	606	606	502	502	397	397
	$MtCO_2e$	RED80	538	538	349	349	159	159
	$MtCO_2e$	ZERO	367	367	184	184	0	0
GHG intensity, fossil fuels (B)	gCO_2e/ MJ	-	72.4	72.0	70.5	69.7	68.3	67.8
Maximum fossil fuel energy use to stay below scenario target (C = A / B)	EJ	RED50	8.4	8.4	7.1	7.2	5.8	5.9
	EJ	RED80	7.4	7.5	4.9	5.0	2.3	2.3
	EJ	ZERO	5.1	5.1	2.6	2.6	0.0	0.0
Energy demand, BAU energy efficiency (D)	EJ	-	9.2	10.5	10.2	13.0	11.1	15.8
Required candidate fuel use, BAU energy efficiency (E = D – C)	EJ	RED50	0.8	2.1	3.1	5.8	5.3	9.9
	EJ	RED80	1.8	3.0	5.2	8.0	8.8	13.4
	EJ	ZERO	4.1	5.4	7.6	10.4	11.1	15.8
Energy demand reduction, additional energy efficiency and shore power (F)	EJ	–	1.3	1.5	2.1	2.9	2.9	4.3
Required candidate fuel use, additional energy efficiency (E – F)	EJ	RED50	0.0	0.5	0.9	2.9	2.4	5.6
	EJ	RED80	0.5	1.5	3.1	5.1	5.9	9.1
	EJ	ZERO	2.9	3.8	5.4	7.5	8.2	11.5

Scenarios: RED50 — Intital IMO GHG Strategy; RED80 — 80% reduction by 2050; ZERO — Decarbonisation by 2050

Note that due to rounding, the energy demand may differ from the sum of the values shown.

Figure 5-6: Ranges of required candidate fuel availability from low to high seaborne transport growth for the three decarbonisation scenarios, with BAU and additional energy efficiency (including use of shore power)

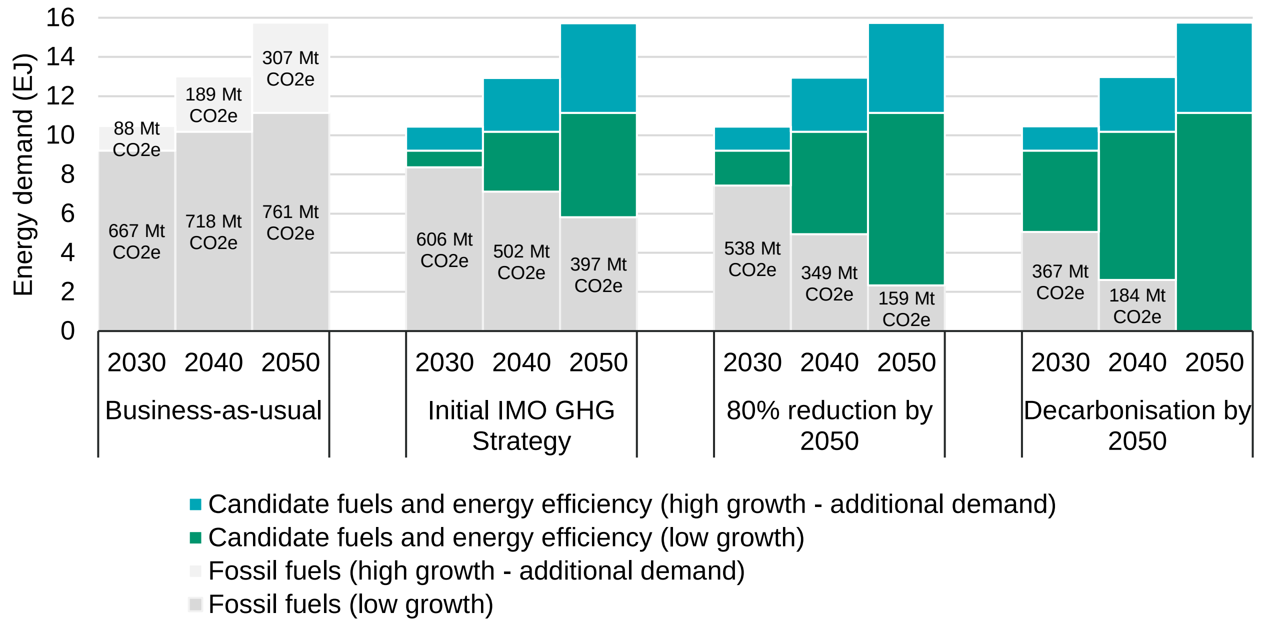
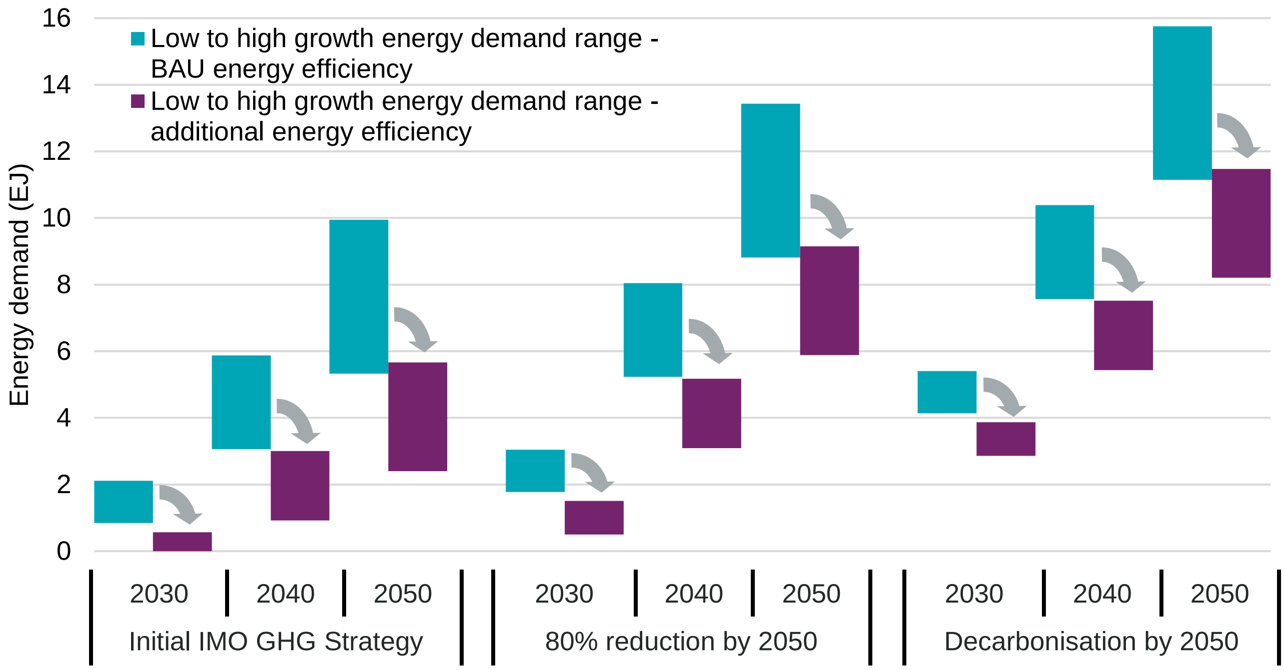


Figure 5-7 shows the ranges of required candidate fuel availability from low to high seaborne transport growth for the three decarbonisation scenarios, with BAU energy efficiency and additional energy efficiency. The energy demand ranges for candidate fuels with additional energy efficiency are: 0–3.8 EJ (2030), 0.9–7.5 EJ (2040) and 2.4–11.5 EJ (2050). The growth in candidate fuel demand between 2030 and 2050 is between 4 to 20% per year.

Figure 5-7: Ranges of required candidate fuel availability from low to high seaborne transport growth for the three decarbonisation scenarios, with BAU and additional energy efficiency (including use of shore power)

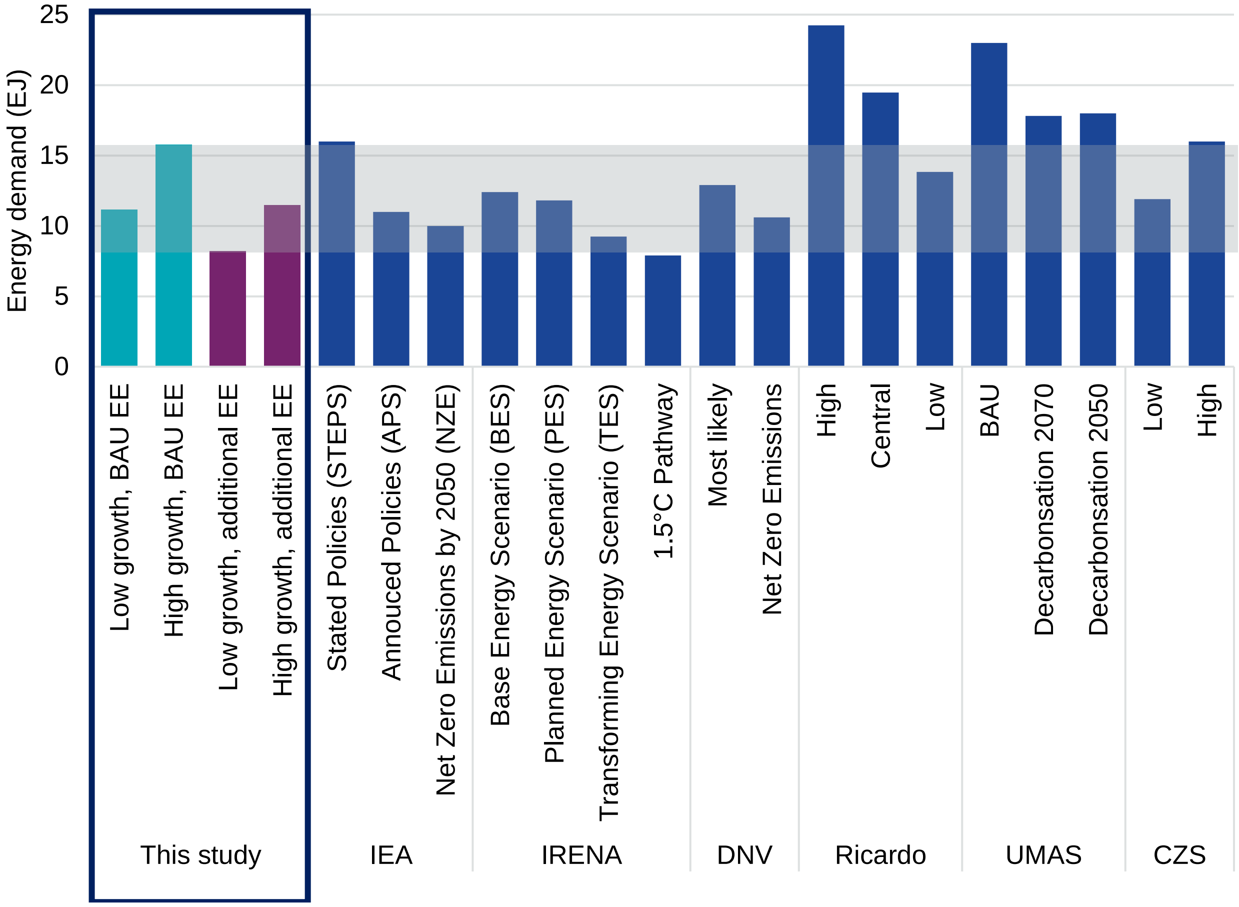


The upper, teal-coloured bars represent ranges of energy demand if no further energy efficiency measures are adopted, the arrows to the lower plum-coloured bars represent the ranges of energy demand if a maximum feasible uptake of energy efficiency measures is implemented.

Other studies have projected the GHG emissions and energy demand for shipping: The Fourth IMO GHG Study 2020 estimates an increase in CO_2 emissions over the period 2018–2050 of 6.2% and 47% for the low-and high-growth scenarios, respectively, while this study estimates equivalent increases of 6.4% and 48%, respectively, between 2022 and 2050. The GHG emissions have increased more due to the larger share of LNG in the fuel mix, with corresponding methane emissions. For the period 2020–2050, IRENA (2021) in its Base Energy Scenario (BES) projects increases of 35% for CO_2 emissions, 30% for energy demand, and 90% for seaborne transport demand. BES is close to the 81% transport demand increase in the high-growth scenario in this study, but this study has a much higher increase in energy demand of 76% and a somewhat higher CO_2 emission increase of 48%. IEA (2022c) projects a 53% increase in CO_2 emissions, and a 60% increase in energy demand from 2020 to 2050 in the Stated Policies Scenario (STEPS) but does not state the growth in seaborne trade. Ricardo (2022) projects a 22% increase in CO_2 emissions from 2020 to 2050 in their central estimate, which is the same as in the high-growth scenario in this study, while their low to high estimates range from a 13% decrease to a 43 % increase in emissions.

Figure 5-8 shows the projected energy demand from a range of studies and scenarios. The ranges estimated in this study covers most of the reviewed studies. The absolute numbers may not be directly comparable as some studies include domestic shipping and use different assumptions on growth in seaborne trade demand.

Figure 5-8: Comparison of energy demand in 2050 with other studies (IEA, 2022c; IRENA, 2021; DNV, 2022a; Ricardo, 2022; UMAS, 2020; Mærsk Mc-Kinney Møller ZCS, 2021)



6 POTENTIAL AVAILABILITY OF CANDIDATE FUELS

Overview

- The potential availability of biofuels, e-fuels and blue fuels to transportation and shipping in 2030, 2040, and 2050 has been estimated based on announced fuel production projects for 2030 and a review of energy system forecasts for 2040 and 2050.
- The potential for storing CO_2 captured from ships towards 2050 has been reviewed to access potential availability of onboard carbon capture to shipping in 2040 and 2050.
- The global availability of electricity for providing shore power to ships has been reviewed.
- The potential availability of sustainable CO_2 has been estimated.

Key findings

- The availability of candidate fuel for shipping is estimated to range from 0.2–2.5 EJ in 2030, 0.8–9.3 in 2040, and 1.3–19.7 EJ in 2050. These wide ranges represent significant additional potential supply beyond business as usual.
- A clear signal of demand is needed to encourage investments and reach the higher ends of these ranges of availability.
- The availability in 2030 could increase with the emergence of more fuel production projects and shortening of project lead-times, both on the planning and the commissioning phases.
- To reach the decarbonisation trajectories in 2050 an average annual growth rate in fuel production of 6-12% from 2030 is required, which is well below the historical sustained growth rates for solar and wind power generation.
- The availability of fuel for shipping depends on the decarbonisation of other sectors in two ways: demand from other sectors drives production but also competition for the same fuels.
- This assessment of availability does not represent a maximum availability but indicates a possible outturn if incentives and policies for scaling up production and a firm demand are agreed.

6.1 METHOD

The availability of energy sources and feedstock for fuel production, as well as setting up the production facilities and supply chain, impose the main constraints on the future availability of candidate fuels.

For the short-term availability of biofuels, e-fuels, and blue fuels in 2030 we use a database of existing, planned, and announced projects. To our knowledge, there is no public comprehensive global database containing data on all production projects for such fuels. We have compiled data from various databases and reports, each drawing on a variety of media articles, press announcements, and other industry literature and studies. The detailed list of sources is provided in Appendix 4. The projects are grouped into **Confirmed (*post-FID*) *projects,*** which are those where the final investment decision (FID) have been made, and ***All announced projects,*** containing all projects. In addition, we estimate the potential for ***Additional projects*** based on historical growth rates of similar technologies, assuming additional projects announced until 2024 could be commissioned and in operation by 2030.

The availability estimates for 2040 and 2050 of candidate fuels to the transportation sector are based on a review of energy system forecasting studies towards 2050 (Shell, 2021; BP, 2022; ExxonMobil, 2022; Bloomberg, 2022; Equinor, 2022). Scenarios from the forecasting studies describe possible futures based on widely different assumptions, especially with respect to decarbonisation ambitions. Because of this, we cluster the scenarios we consider in the study into two groups:

Business as usual (BAU) trajectories*:* scenarios where no decarbonisation ambitions are imposed. Such scenarios can typically represent a BAU or most likely outcome given current adopted regulations and policies. These scenarios are not consistent with 1.5–2.0 ºC limitation on global warming compared with pre-industrial levels. Specifically, some of the reviewed trajectories assume shipping decarbonises according to the 50% by 2050 pathway of the Initial IMO GHG Strategy.

***Decarbonisation trajectories**:* scenarios consistent with a limitation of global warming to a 1.5–2.0 ºC increase. There are still significant differences between the scenarios; while some decarbonise fully by 2050, others do not until decades lates. However, they are characterised by assumed stronger polices and incentivising renewable energy production and CCS increase in order to achieve the target, as opposed to the current policies scenarios.

It should be noted that these studies project the availability of various fuels based on the demand in each sector, which again is a function of the targets set in the case of the *Decarbonisation trajectories* group. The advantage of using these forecasts is that they consider the demand from all sectors against all potential energy production pathways, taking into account technology developments in production and end use, costs, and policies. They also consider the gap between current polices and what it requires to achieve the decarbonisation targets, which is useful when reviewing the potential availability of candidate fuels for shipping.

We start by estimating the potential availability of biofuels, e-fuels and blue fuels supplied for transportation. We then estimate how much of the supplied energy can be made available for international shipping taking into account decarbonisation efforts in other transport sectors. Conventional biofuels produced from food and feed crops can have significant emissions and sustainability issues related to direct and indirect land use change. As such, they are excluded as candidate fuels. In the availability analysis, we have included all available data on production capacity for biofuels, before estimating how much of this could come from advanced feedstocks based on projections by FAO (2022) and IEA (2022c).

The potential availability of onboard CCS is assessed based on a review of the capacity for permanently storing CO_2, and how much shipping can access of this storage capacity. The availability in 2030 is based on announced projects (IEA, 2022c; Global CCS Institute, 2022), and an estimate of the potential for additional projects based the current growth rate. For 2040 and 2050, the assessment is based on global energy system forecasts that have projected how the amount of CO_2 stored will trend (IEA, 2022c; IRENA, 2022; Bloomberg, 2022; BP, 2022; DNV, 2022a; Equinor, 2022; Shell, 2021).

The potential electricity availability for shore power and the availability of sustainable CO_2 for e-fuels are evaluated based on a literature review of the energy system forecasting studies.

We do not go into detail on availability of specific fuel types such as diesel, methanol, or ammonia, but focus on the high-level availability grouped into biofuels, e-fuels, blue fuels, electricity, and CO_2 permanent storage capacity. We do not consider the capacity for further processing of the energy to specific marine fuels, such a methanol synthesis and methane liquefaction. We only look at the global availability of candidate fuels, and do not review the availability on a regional level.

Based on the review, we provide three estimates for the availability in 2030, 2040, and 2050. This method does not provide the maximum production potential, and the estimates do not represent an upper limit on the candidate fuel availability for shipping.

The detailed method, assumptions, and sources are further described in Appendix 4.

6.2 CANDIDATE FUEL AVAILABILITY FOR THE TRANSPORT SECTOR IN 2030

In the compiled database, we focus on fuels relevant to the transportation sector. As such, where possible, we have only used projects tagged specifically to this sector. This was possible for blue hydrogen and green hydrogen, where IEA (2022e) is used for the main source of data. For methanol and ammonia, traded today as commodities, it was impossible to tie individual projects to intended end use.

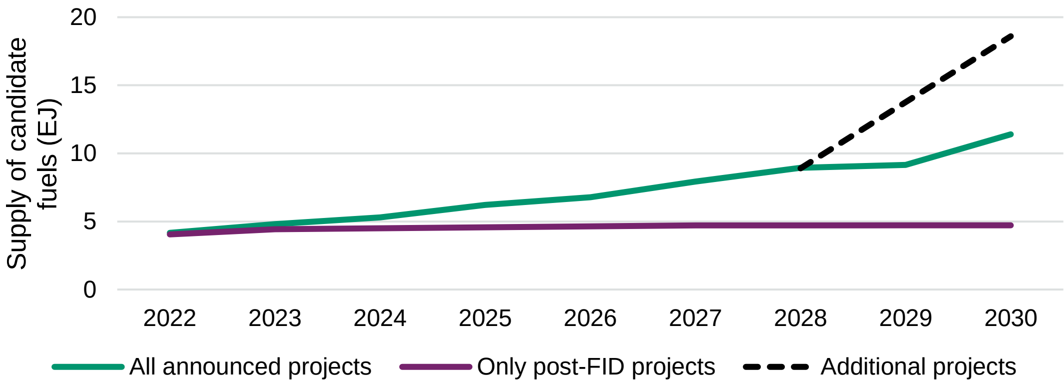
It is likely that at least a significant portion of production capacity of candidate fuel variants of these will be diverted to non-transportation uses such as fertiliser production in the case of ammonia, and chemicals in the case of methanol. In 2020, the demand for ammonia from the industrial sectors was 183 Mt or 3.4 EJ (ammonia) in energy terms (IRENA, AEA, 2022). Total methanol production stood at almost 100 Mt or 2.0 EJ, of which more than 80% was used for different industrial applications, while 17% was used within gasoline blending and combustion or the production of biodiesel (IRENA, Methanol Institute, 2021).

When applying the project database to assess the availability of fuels to transportation in 2030, we may miss out on projects that are yet to be announced but could become operational by then. This will depend on the lead-time of the given projects, and could potentially increase the fuel production towards 2030. Wappler et al. (2022) conclude that the duration of large (>1 GW) green hydrogen projects today is around 6–10 years, with 3–5 years until FID and an additional 3–5 years for construction and commissioning. This leaves a short time window for further projects to be announced, confirmed, and commissioned by 2030. According to the IEA, new projects increased the potential hydrogen production volume from all announced projects from 17 Mt/year in 2021 to 24 Mt/year in 2022, a 41% increase (IEA, 2022b; IEA, 2021b). Looking at historical growth rates of other technologies, wind and solar power generation grew by an average of 22% and 40%, respectively, per year between 1996 and 2020, while biofuel energy grew by 10% per year in the same period (BP, 2022). Odenweller et al. (2022) model a 39% annual growth in the emergence phase for the electrolysis market, but also point out that even larger growth rates above 100% have been observed historically (e.g. US Liberty ships, high-speed rail in China, smartphones), although achieving this would require significant regulation, policies, and funding to achieve.

Additional projects announced in 2023 and 2024 could, if using 6 years for the FID and construction phases, be commissioned and in operation by 2030. Assuming a continued 40% growth in e-fuel and blue fuel projects, and 10% growth in biofuel projects for two more years, this would add an additional 7.2 EJ/year of energy availability by 2030.

Figure 6-1 shows the estimated availability of candidate fuels for the transportation market towards 2030, based on i) fuel production projects where the final investment decision (FID) has been taken (post-FID), and ii) all announced future projects.

Figure 6-1: Potential availability of bio-, e- and blue fuels for the transportation sector from 2022 to 2030, based on the compiled database of candidate fuel projects and potential additional projects. See Appendix 4 for a full list of sources used.



The results show that there is a large span in the assessed availability of candidate fuels in the short term, depending on whether you take into account only projects where the FID has been taken, or all announced projects. Very few of the announced projects have reached the FID phase and if taking into account only post-FID projects the availability increases from 4.0 EJ in 2022 to 4.4 EJ in 2030, while if including all announced projects, the availability reaches 9.6 EJ in 2030. With the additional projects the potentially availability increases to 18.6 EJ. It should be noted that some fuel producers may not produce fuel at full capacity at the start, but increase production gradually as the market becomes more mature.

Since there is no comprehensive public database giving potential fuel production availability, it is challenging to directly compare our results with other sources. However, some literature sources provide potential availability based on announced projects for specific fuels. Below, we compare these sources with results from our database. Note that these sources consider all announced projects, regardless of when they are expected to be commissioned, and they are not limited to the period 2022–2030.

IRENA and Methanol Institute (2021) reports a potential availability for biomethanol of 0.06 EJ/year from announced projects. In our database, we have a total potential biomethanol availability of 0.09 EJ/year. The same study also indicates a potential availability for e-methanol of 0.014 EJ/year, compared with 0.1 EJ/year in our database. A key reason why our estimated production capacity is higher is due to a number of large projects being announced recently.[25] Laursen et al. (2022) reports that the announced e-ammonia projects add up to 2.5 EJ/year, while IRENA and AEA (2022) gives a value of 1.3 EJ/year. AEA (2023), a more recent source, reports almost 2.7 EJ/year from all announced projects. In our database, we see a total potential e-ammonia availability of 2.5 EJ/year, indicating that some projects are missing from our overview.

[25] See, for example, https://www.maersk.com/news/articles/2022/11/03/maersk-and-the-spanish-government-to-explore-large-scale-green-fuels-production

IRENA and AEA (2022) reports a potential availability of blue ammonia of 0.25 EJ/year[26], while AEA (2023) gives a figure of close to 0.5 EJ/year. This compares with our estimate of 0.2 EJ blue ammonia per year.

6.3 CANDIDATE FUEL AVAILABILITY FOR THE TRANSPORT SECTOR IN 2040 AND 2050

Table 6-1 gives the availability of candidate fuel for the transport sector, by fuel category, in 2040 and 2050, with the span and median for the two categories of forecasting scenarios.

Table 6-1: Projected availability of biofuels, e-fuels and blue fuels to the transportation sector in 2040 and 2050 by category of energy system forecasting scenario

Source	Scenario name		Biofuels (EJ)		E-fuels[a] (EJ)		Blue fuels[a] (EJ)	
			2040[b]	2050	2040[b]	2050	2040[b]	2050
(Shell, 2021)	Waves	BAU trajectories	12.3	20.6	1.3[c]	8.7[c]	0.0[c]	0.0[c]
(Shell, 2021)	Islands		11.8	21.2	0.0	0.0	0.0	0.0
(DNV, 2022a)	Most likely		9.6	10.0	3.0	9.5	1.2	2.8
(BP, 2022)****	New momentum		4.8	5.5	-	-	-	-
(Equinor, 2022)	Walls		6.6	6.4	1.0	1.9	0.0	0.8
(ExxonMobil, 2022)	Outlook for energy		12.2	18.5	-	-	-	-
(IEA, 2022c)	Stated policies		9.0	10.0	0.2	0.6	0.1	0.3
(BP, 2022)[d]	Accelerated	Decarbonisation trajectories	7.5	9.5	3.0	6.2	1.9	3.2
(Equinor, 2022)	Bridges		4.1	4.6	-	10.5	-	2.5
(IEA, 2022c)	Announced pledges		16.0	17.0	1.8	4.3	0.7	1.4
(Bloomberg, 2022)	Net zero scenario		15.0	18.3	-	-	-	-
(IRENA, 2022)	1.5C scenario		21.1	25.6	6.7[e]	12.4	3.3[e]	6.2
(Shell, 2021)	Sky scenario 1.5C		12.2	18.5	1.1[c]	2.7[c]	0.1[c]	0.8[c]
(BP, 2022)****	Net Zero		9.1	11.9	6.3	13.6	3.3	5.3
(IEA, 2022c)	Net Zero Emissions by 2050		12.0	10.0	4.8	10.4	2.1	3.8
(DNV, 2022a)	Pathway to Net Zero Emissions		7.4	5.7	3.9	12.1	1.1	5.0
Median and span (low-high) of BAU trajectories			**9.6 (4.8–12.3)**	**10.0 (5.5–21.2)**	**1.0 (0.0–3.0)**	**1.9 (0.0–8.7)**	**0.0 (0.0–1.2)**	**0.3 0.0–2.8**
Median and span (low-high) of decarbonisation trajectories			**12.0 (4.1–21.1)**	**11.9 (4.6–25.6)**	**3.9 (1.8–6.7)**	**10.5 (2.7–13.6)**	**1.9 (0.1–3.3)**	**3.5 (0.8–6.2)**

"-" is used to denote forecasting studies where the e-fuel / blue fuel availability for the transportation sector was not identified.

[a] The split between e-fuel and blue fuel availability is not given specifically for the transportation sector and has been calculated by considering the share of e- and blue hydrogen availability for all sectors projected by the study in that year.

[b] In some cases, the calculated value for 2040 is based on interpolation between 2030 and 2050.

[c] Share of hydrogen production via natural gas with CCS was calculated by translating total amount of CO_2 captured into equivalent hydrogen energy, assuming a capture rate of 90% and a CO_2 footprint of fossil energy reformation equal to 8.9 $kgCO_2/kgH_2$.

[d] We assume that all liquid biofuel is supplied to the transportation sector.

[e] We assume that distribution between blue fuel availability and e-fuel availability is the same as in 2050.

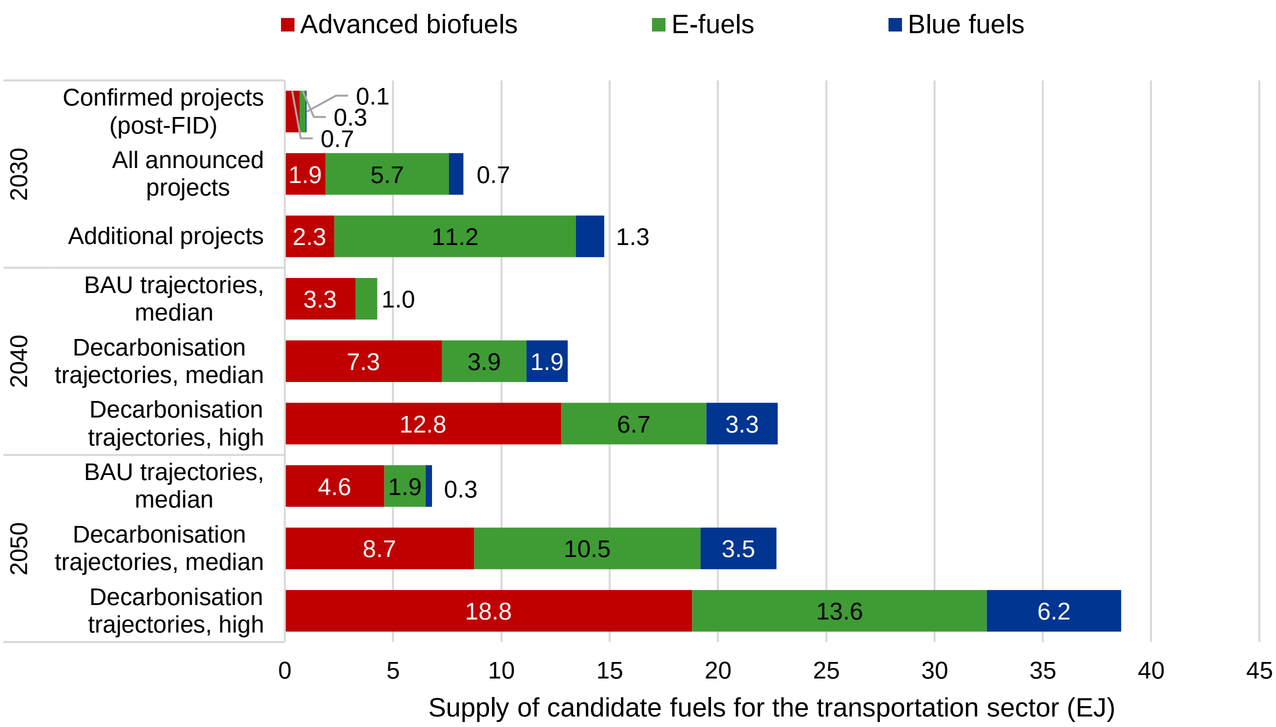
[26] Only accounting for projects where GHG savings are 70% or more relative to steam-methane reformation without CCS.

6.4 SUMMARY OF CANDIDATE FUEL AVAILABILITY FOR THE TRANSPORT SECTOR IN 2030, 2040, AND 2050

Figure 6-2 gives the total availability of candidate fuels, except onboard CCS and electricity, for the transportation sector, by fuel category, using results from the assessment of fuel availability in 2030, 2040, and 2050. The results show a significant span in candidate fuel availability: 1.1–14.7 EJ (2030), 4.3–22.8 EJ (2040), 6.8–38.6 EJ (2050).. Only the expected share of advanced biofuels is included in this overview. See Appendix 4 for the assessment in of advanced biofuel availability.

In most estimates, biofuels make up the largest fuel category, but we see that e-fuels make up a large share of candidate fuel availability when considering *All announced projects* and *Additional projects* to 2030, and the median *Decarbonisation trajectories* in 2050. We can also see that the availability of e-fuels in 2040 for both *Decarbonisation trajectories* are lower than in 2030 (*All announced projects*). This is because all the production projects hitherto announced already exceed the median availability forecasted in the *Decarbonisation trajectories* scenarios for the transportation sector in 2040.

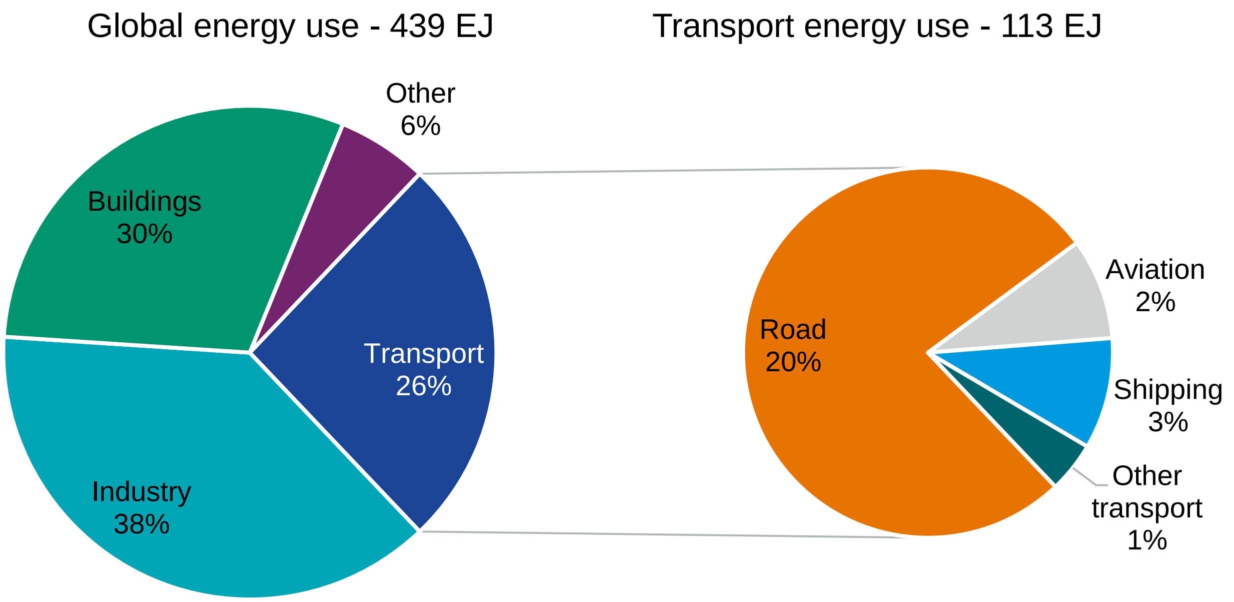
Figure 6-2: Total availability of candidate fuels, except onboard CCS and electricity, for the transportation sector, by fuel category, in 2030, 2040 and 2050.



6.5 SHARE OF TRANSPORT FUELS AVAILABLE FOR SHIPPING

The above estimates are for the transport sector which includes shipping, aviation, road and rail transport. Figure 6-3 shows the distribution of energy use globally and in the transportation sector. The final energy use globally amounted to 439 EJ in 2021, of which transportation used 113 EJ or 26% (IEA, 2022c). Of the 113 EJ, only 2 EJ was electricity. Road transportation used 87 EJ (77% of the transportation sector), followed by maritime with 11 EJ (10%), and aviation with 10 EJ (9%).

Figure 6-3: Share of energy use globally and within the transportation sector by transport-mode in 2021 (IEA, 2022c)



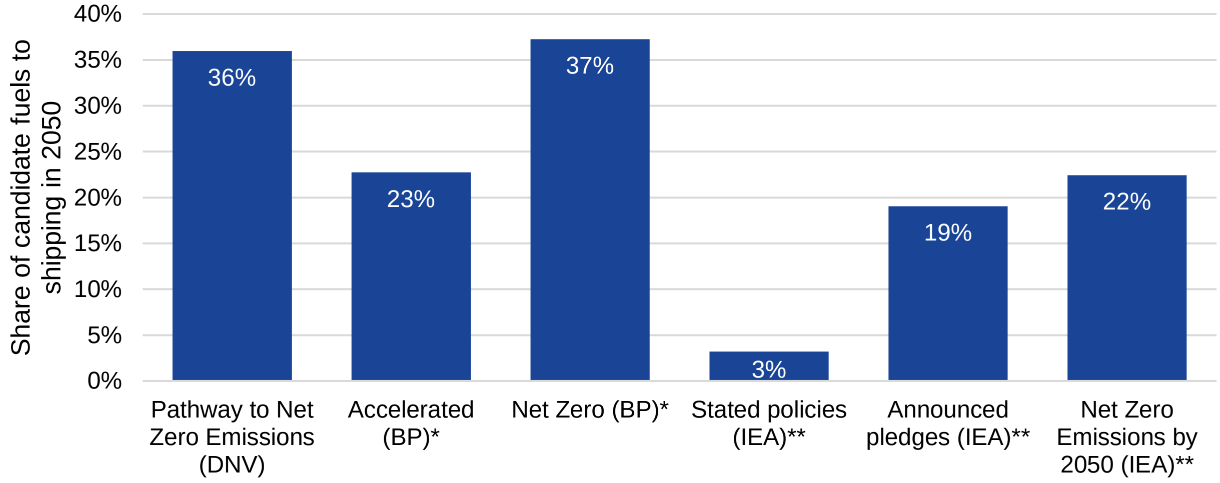
Although shipping currently uses a 10% share of energy for transportation, this could increase in the future. A key reason for this is due to electrification of energy consumption, in particular for road transportation.

Within the marine transportation sector, the vast majority of fuel is consumed by large sea-going vessels, with ships of size 15,000 GT and above estimated to account for more than 80% of CO_2 emissions in 2018 (DNV GL, 2019). Full electrification of shipping is feasible for some short-sea segments, but will likely not be feasible for large sea-going vessels (see, for example, (IRENA, 2021; LR and UMAS, 2020; DNV GL, 2019)). As a result, the candidate fuels remain one of few options for large sea-going vessels to fully decarbonise.

In contrast, electrification could serve as the most important decarbonisation option in the long term for road transportation. This is especially true for lighter-duty vehicles. In IEA's Net Zero Emissions in 2050 scenario the electricity use increases to 37 EJ, 48% of the total energy use for transportation. The impact is that the demand for biofuels, e-fuels and blue fuels for road transportation could decrease significantly in the future, increasing the share available for other hard-to-abate sectors such as shipping and aviation.

Based on the energy system forecasting scenarios that provide an energy share for shipping in 2050, Figure 6-4 shows the share of candidate fuel availability, excluding direct use of electricity, to the transportation sector supplied specifically to shipping. Depending on scenario, we see a span from 3% (IEA Stated policies scenario) which is a scenario with limited use of candidate fuels in the shipping sector and other sectors, to 37% (BP Net Zero scenario) where we see significant electrification in the road and rail sector and a larger share of candidate fuels, excluding electricity, that can be used by shipping. Based on this, our assessment is that shipping will use between 10% (current level) and 37% (highest projection) of candidate fuels supplied to transport, excluding direct use of electricity.

Figure 6-4: Share of candidate fuel energy use, excluding direct use of electricity, of shipping out of the total transportation sector (DNV, 2022a; BP, 2022; IEA, 2022c)



**We assume that 10% of biofuels for the transportation sector is used by shipping.*
***Does not include biomethane (bio-LNG)*

6.6 AVAILABILITY OF ONBOARD CARBON CAPTURE AND STORAGE CAPACITY, ELECTRICITY, AND SUSTAINABLE CARBON FOR E-FUELS

This section assesses the availability of onboard carbon capture for ship based on global carbon storage capacity, electricity for shore power, and sustainable carbon dioxide for e-fuels, completing the estimate of the potential availability of candidate fuels for shipping in 2030, 2040, and 2050.

6.6.1 Onboard carbon capture and global storage capacity

The potential for onboard CCS to 2050 will depend on:

- the technical maturity of the onboard capture technology;
- the capacity to produce and install onboard CCS plants on newbuilds or retrofitting existing ships; and
- the infrastructure for receiving and permanently storing the carbon dioxide.

In Section 3.7 we project that the TRL of onboard carbon capture reaches 9 in 2030, and in Section 4.2 we assess that the shipyard and manufacturer capacity to produce and install CCS plants on board ships is not a limiting factor based on previous experience with, for example, exhaust gas cleaning systems.

On the infrastructure, the Global CCS Institute (2022) reports that the current global capture capacity is at 0.043 GtCO_2/year with an additional 0.01 GtCO_2/year in construction. Only 9 of the current 30 facilities comprised dedicated storage, while most of the installed capacity is for the purpose of Enhanced Oil Recovery (EOR), in which the injected CO_2 is used for rejuvenating the production of oil at mature oilfields. The storage capacity of CCS projects in the pipeline increased by 44% from 2021 to 2022. Assuming all currently announced projects are realised, the global storage capacity could be around 0.25 GtCO_2/year in 2030 (IEA, 2022c; Global CCS Institute, 2022). As for fuel production projects, we assume that additional projects announced in 2023 and 2024 could be commissioned and in operation by 2030. Assuming a continued 44% growth CCS projects for two years, this would add an additional 0.27 GtCO_2/year for a total of 0.52 GtCO_2/year storage capacity by 2030. Although this is a high growth rate, the total storage capacity is around the median of the projected capacity in 2030, as indicated in the following paragraph and Table 6-2.

Several of the energy system forecasts have projected how the amount of CO_2 stored will trend (IEA, 2022c; IRENA, 2022; Bloomberg, 2022; BP, 2022; DNV, 2022a; Equinor, 2022; Shell, 2021), as summarised in Table 6-2. We look specifically at CO_2 stored and not captured and reused, as we assume that the CO_2 captured on board ship should be permanently stored to contribute to the decarbonisation targets. However, some forecasts do not explicitly separate between stored and reused carbon dioxide. The median projection is 0.5 GtCO_2 in 2030 increasing to 6.0 GtCO_2 in 2050. The planned capacity from projects in the pipeline must be doubled in order to reach this projection in 2030. Again, it should be noted that these are forecasts which are driven by decarbonisation targets, and that significant polices are needed in order to scale up the infrastructure capacity.

Table 6-2: Projected global CO_2 capture and storage in 2030, 2040 and 2050

Source	Scenario-name	$GtCO_2$ stored		
		2030	2040[a]	2050
(BP, 2022)	Accelerated	-	2.1	4.2
(Equinor, 2022)	Bridges	3.0	4.8	6.5
(IEA, 2022c)	Announced pledges	0.5	2.4	4.3
(Bloomberg, 2022)	Net zero scenario	-	3.5	7.0
(IRENA, 2022)	1.5C scenario	-	4.2	8.4
(Shell, 2021)	Sky scenario 1.5C	0.4	2.2	4.0
(BP, 2022)	Net Zero	-	3.0	6.0
(IEA, 2022c)	Net Zero Emissions by 2050	1.2	3.7	6.2
(DNV, 2022a)	Pathway to Net Zero Emissions	0.4	3.2	5.9
Median and span of global capacity		**0.5 (0.4–3.0)**	**3.2 (2.1–4.8)**	**6.0 (4.0–8.4)**

[a] *2040 numbers are interpolated between 2030 and 2050 for the scenarios*

Estimating how much shipping can access this is challenging. We expect that there will be infrastructure around the storage site, but shipping would need its own specialised infrastructure for receiving the CO_2 from the ship and transporting it to the storage sites or reception facilities. Today, shipping uses 11 EJ out of 494 EJ or 2.2% of fossil primary energy (coal, oil and gas) (IEA, 2022c). Taking into account that shipping is a hard-to-abate sector for which CCS could be considered a relatively more important mitigation option than for other sectors, we assume that shipping could access 5% of the global storage capacity.

This results in an estimated potential shipping capacity of 13 $MtCO_2$/year stored in 2030 based on *announced projects*, and 26 $MtCO_2$/year for *additional projects*. We do not include any confirmed capacity in 2030 as onboard CCS would require a shipping specific infrastructure to be set up which is not confirmed yet. The projected capacity increases to 158 and 238 $MtCO_2$ in 2040 and 300 and 420 $MtCO_2$/year in 2050 for the *median* and *high decarbonisation trajectories* projections respectively.

Table 6-3 shows how this can be calculated as the energy use that would produce this amount of CO_2. To achieve close to zero TtW GHG emissions we assume that onboard carbon capture is used with a 70% fossil and 30% advanced biofuel or e-fuel blend. The use of onboard CCS will increase the total energy demand by 20%, meaning that this energy use is 20% higher than what would be needed for a ship without onboard CCS. In order to make the onboard CCS energy use numbers comparable to the energy demand and availability from other candidate fuels we do not include the additional energy in subsequent tables and charts. However, we keep track of the required amount of advanced biofuel or e-fuel needed to achieve close to zero TtW GHG emission, which means that the remaining additional energy can be covered by 100% fossil fuels.

Table 6-3: Potential for onboard CCS based on estimated storage capacity available for shipping

	Unit	2030		2040		2050	
		Announced projects	Additional projects	Median	High	Median	High
Storage capacity (announced projects / median capacity)	$MtCO_2$	0.013	0.026	0.160	0.238	0.300	0.420
Maximum fossil energy use based on storage capacity and 70% capture rate (A)	EJ	0.24	0.50	3.22	4.86	6.39	8.95
Additional energy use (included in max.) (B = A / 1.2)	EJ	0.20	0.41	2.69	4.05	5.32	7.45
Energy use without onboard CCS (potential comparable to other candidate fuels) (C = A – B)	**EJ**	**0.04**	**0.1**	**0.5**	**0.8**	**1.1**	**1.5**
Required use of advanced biofuels or e-fuels (C = A * 0.3)	EJ	0.1	0.1	1.0	1.5	1.9	2.7

6.6.2 Electricity for shore power

Total global electricity generation is, according to IEA (2022c), estimated to grow to 126–139 EJ in 2030 and to 180–263 EJ in 2050, depending on the scenario. The potential annual demand for shore power electricity is in Section 5.4 estimated to be 0.15–0.17 EJ in 2030, increasing to 0.45–0.65 EJ in 2050. In all cases the share of total electricity generation is less than 0.4%, and our assessment is that the electricity availability will not be a constraint for the use of shore power by ships to 2050, provided there is infrastructure to provide the electricity in ports. It should be noted that the GHG intensity of the grid electricity varies considerably, and although the TtW GHG emission are zero, the WtW GHG emission may increase compared with using fossil fuels, until more renewable energy sources are included in the grid mix.

6.6.3 Sustainable carbon dioxide for e-fuels

Producing hydrocarbon e-fuels such as e-methane, e-methanol, and e-diesel requires combing hydrogen from electrolysis with CO_2 from biogenic sources or direct air capture (DAC). About 69–75 $MtCO_2$ is needed to produce 1 EJ of methanol, methane, or diesel.

IEA forecast in their Sustainable Development Scenario (SDS) that 189 Mt of captured CO_2 will be reused in 2030, increasing to 877 $MtCO_2$ in 2050, of which 60% is from industrial processes, bioenergy, and DAC (IEA, 2020c). In their Net Zero Emissions by 2050, they project that 234 $MtCO_2$ is stored in 2030, and 1526 Mt in 2050 through CCS from biofuel production and DAC, but without specifying if any CO_2 is reused (IEA, 2022c). IRENA estimates that 5,000 Mt of the captured CO_2 in 2050 comes from biogenic sources, but does not estimate if any this is reused (IRENA, 2022).

Using the IEA numbers indicates a global potential of hydrocarbon e-fuels of 1.5–1.6 EJ in 2030, and 7.0–7.6 EJ in 2050 if all the sustainable CO_2 is used for e-fuels. However, as shown above, the estimates in the various studies are not very specific and show a large span.

6.7 CANDIDATE FUEL AVAILABILITY FOR SHIPPING

Through the assessment of the production project database and the literature review of energy system forecasting scenarios we have identified key uncertainties that will influence the potential amount of candidate fuels for the transportation sector and shipping in the medium and long terms:

- How many additional projects will be announced in the coming year, and how many of the announced projects will progress to the operational phase by 2030?
- How much of the production capacity will be utilised?
- The development of renewable and nuclear energy production projects, including level of public support.
- To what degree will candidate fuels, with clear alternative uses other than as fuel for the transportation sector (e.g. ammonia and methanol), be supplied to the transportation sector, including shipping, and not other end-use markets?
- The proportion of candidate fuels that can be made available to shipping, taking into account the potential for electrification in other transport sectors.
- The development of the CCS industry, and potential adaption of onboard CCS on vessels and reception facilities onshore.
- The availability of sustainable CO_2 for hydrocarbon e-fuels.
- The long-term development of decarbonisation policies and ambitions driving the demand for candidate fuels.

In order to address these uncertainties, we make three availability scenarios, giving a range in the potential availability of candidate fuels for shipping in 2030, 2040, and 2050. The main assumptions for the low and high availability scenarios are given in Table 6-4.

Table 6-4: Key assumptions behind the availability scenarios for shipping

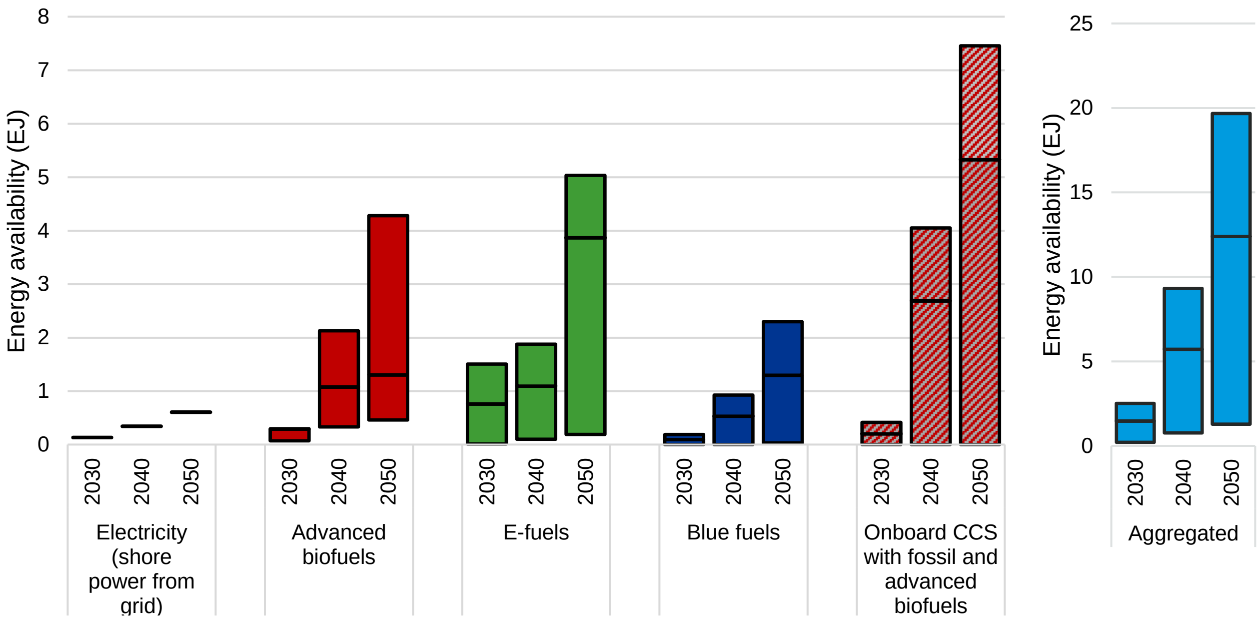
Scenario	2030
Confirmed projects	• Only the projects where a final investment decision (FID) has been taken progress to the operational phase by 2030 • 20% of production capacity of the candidate fuels ammonia and methanol is supplied to the transportation sector • 10%[a] of the total candidate fuel availability to the transportation sector is available to shipping • Shipping cannot access global CO_2 storage capacity
Announced projects	• All announced fuel production and CCS projects are commissioned by 2030 • 80% of production capacity of the candidate fuels ammonia and methanol is supplied to the transportation sector • 19% of the total candidate fuel availability to the transportation sector is available to shipping[b] • Shipping can access 5% of global CO_2 storage capacity
Additional projects	• An additional 96% growth (40% per year over two years) in announced fuel production projects • An additional 107% growth (44% per year over two years) in CCS projects • All announced and additional fuel production and CCS projects are commissioned by 2030 • 80% of production capacity of the candidate fuels ammonia and methanol is supplied to the transportation sector • 19% of the total candidate fuel availability to the transportation sector is available to shipping[b] • Shipping can access 5% of global CO_2 storage capacity

Scenario	2040 and 2050
BAU trajectories, median	• Median of *BAU trajectories* scenarios to estimate availability for the transportation sector • 10%[a] of the total candidate fuel availability to the transportation sector is available to shipping Shipping cannot access global CO_2 storage capacity
Decarbonisation trajectories, median	• Median of *Decarbonisation trajectories* scenarios to estimate availability for the transportation sector • 28% (2040) and 37% (2050) of the total candidate fuel availability to the transportation sector is available to shipping[b] • Shipping can access 5% of global CO_2 storage capacity
Decarbonisation trajectories, high	• High range of *Decarbonisation trajectories* scenarios to estimate availability for the transportation sector • 28% (2040) and 37% (2050) of the total candidate fuel availability to the transportation sector is available to shipping[b] • Shipping can access 5% of global CO_2 storage capacity

[a]10% is the current share of energy consumed for shipping, as a share of total transportation energy consumption.
[b]37% is the maximum share of candidate fuel uptake for shipping, from studies evaluated (see Figure 6-4). The numbers for 2030 and 2040 are based on linear interpolation from 10% (2020) to 37% (2050)

The span of estimated availability per candidate fuel for shipping in 2030, 2040, and 2050, is shown in Figure 6-5. Availability of e-fuels are projected to grow significantly after 2040. Advanced biofuels also show potential, but the median of the energy system forecasts is lower than for e-fuels in 2050. The availability of onboard CCS starts to grow after 2030.

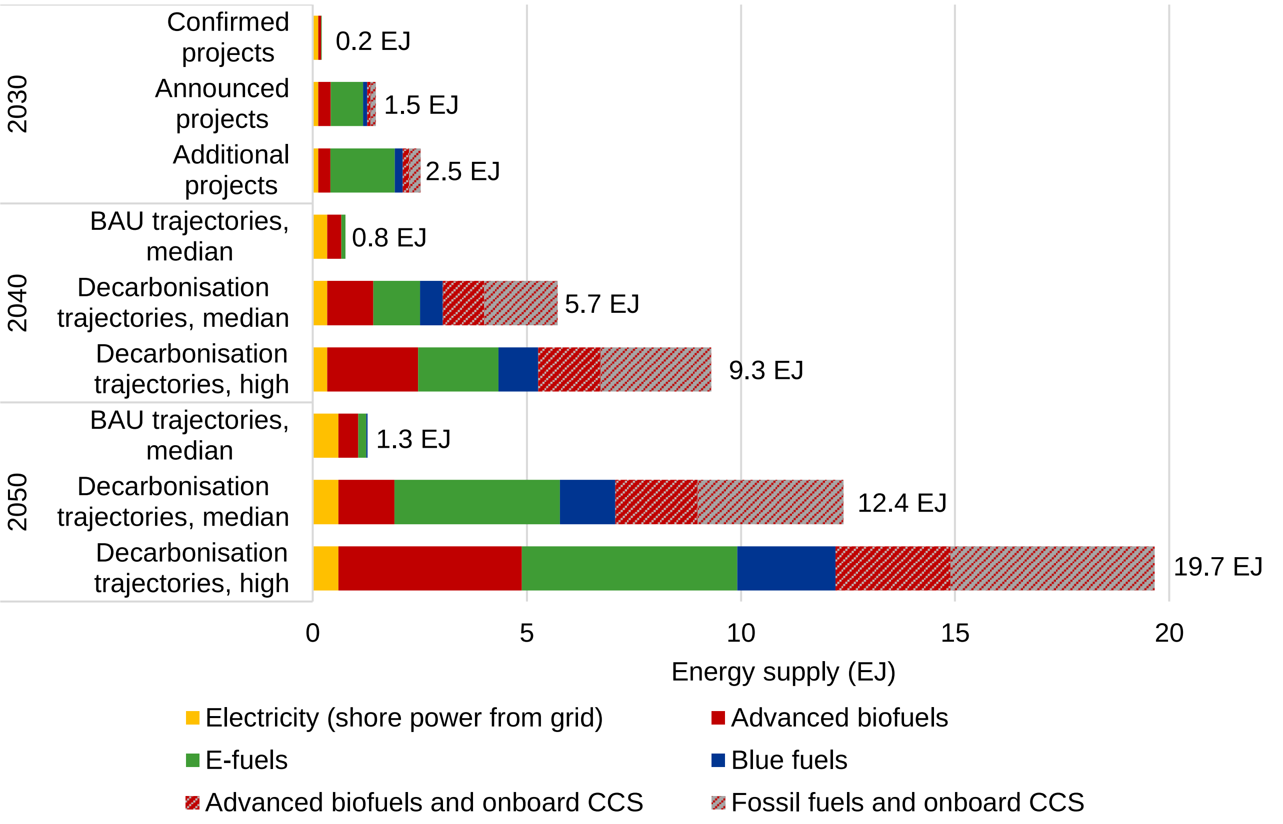
Figure 6-5: Span of estimated availability per candidate fuel (left) and aggregated for all candidate fuels (right) for shipping in 2030, 2040, and 2050



Bottom range: Confirmed projects / BAU trajectories
Median line: Announced projects / Decarbonisation trajectories, median
Top range: Additional projects / Decarbonisation trajectories, high
Note the required amount of advanced biofuels for onboard CCS is deducted from the indicated amount of available advanced biofuels (solid red).

Figure 6-6 shows the aggregated availability of all candidate fuels for shipping. The results indicate a span from 0.2–2.5 EJ in 2030, 0.8–9.3 in 2040, and 1.3–19.7 EJ in 2050. We indicate an availability of sustainable CO_2 for producing hydrocarbon e-fuels equal to 1.5–1.6 EJ in 2030, and 7.0–7.6 EJ in 2050 if all the sustainable CO_2 is used for e-fuels. Note that this does not come in addition to the e-fuel availability indicated in Figure 6-6.

Figure 6-6: Estimated aggregated availability of candidate fuels for shipping in 2030, 2040, and 2050



Note that the advanced biofuels indicated with onboard CCS can also be used without CCS

The large spans in the availability reflect the uncertainty in key factors such as the degree to which announced fuel and CCS projects will come to fruition; the long-term development of decarbonisation policies and ambitions driving investments in renewable electricity, fuel production, and CCS; and the pace of decarbonisation in other sectors which drives both production demand but also competition for the same fuels..

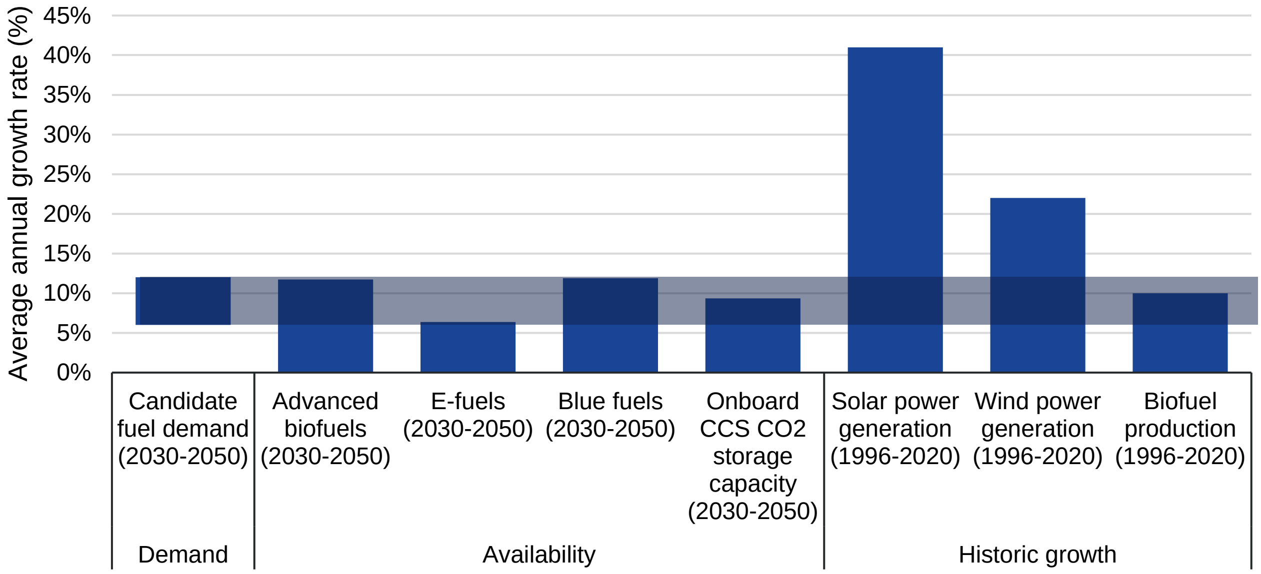
To enable the higher availability scenarios, key premises are a significant upscale of:

- collection of sustainable biomass for production of biofuels;
- renewable electricity production, grid capacity, and electrolyser capacity; and,
- CCS infrastructure for production of blue fuels and reception facilities for ship CO_2 from ships.

Currently *announced projects* for production of e-fuels are already close to the median of *Decarbonisation trajectories* in 2040, indicating that there is a significant body of projects in planning, but there are few confirmed projects due to the uncertainty on demand. The energy system forecast reports which address the gap between expected trajectories and a net zero scenario all highlight the need for significant policies in order to scale up the availability. IEA (2022c) highlights that policymakers also need to provide signals on the demand side and to develop the clean technology supply chain. IRENA (2022) points to the need for stronger policy focus on end uses such as heating, cooling, and transport. DNV (2022a) reports that technological and market developments are insufficient drivers of the change needed for net zero, and that massive early policy actions across regions and sectors are needed.

Figure 6-7 shows a comparison of the growth in demand for candidate fuels between 2030 to 2050 across low and high growth and decarbonisation scenarios, with the projected growth in availability in this study, and with historic growth rates for solar and wind power generation and biofuel production (BP, 2022). To reach the decarbonisation trajectories in 2050 an average annual growth rate of 6-12% from 2030 is required, which is well below the sustained growth rates seen for solar and wind power generation historically.

Figure 6-7: Comparison of annual growth in availability and demand for candidate fuels (this study) with historic growth rates for solar and wind power generation and biofuel production (BP, 2022)



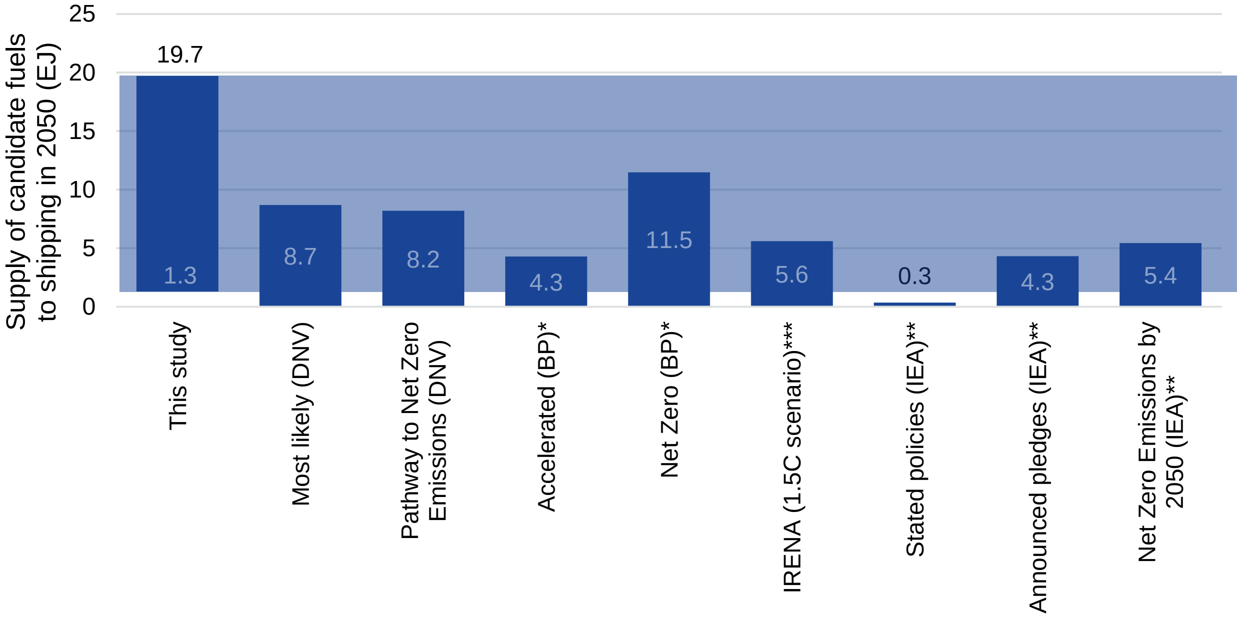
Note: The fuel availability growth numbers are relative to the announced projects availability in 2030.

It is important to note that the *Additional projects / Decarbonisation trajectories, high* scenario in Figure 6-6 does not represent an upper limit on candidate fuel availability for shipping. The availability in 2030 could increase with the emergence of more fuel production projects and shortening of project lead-times in both the planning and commission phases. As the energy system forecasts are based on matching the demand with availability, they do not represent the maximum growth possible in fuel production. Other transport modes may compete for the supply, or in the case of road transportation use electricity directly, and their paths to decarbonisation and which fuels they will seek are not determined.

In Figure 6-8: Comparison of this study's assessment of candidate fuel availability for shipping in 2050 with other selected studies

we show the projected 2050 availability for shipping for the energy system forecasting scenarios that explicitly provide this. Note that the total energy demand may include domestic shipping. The results show that most forecasting studies fall within the span estimated in this study. The reason for this study having a higher estimate that all other studies is that we take the high projection for each of the candidate fuels (biofuels, e-fuels, and blue fuels), while the studies in comparison match the availability with the demand from shipping in their projections. This study also includes the potential for onboard carbon capture and storage.

Figure 6-8: Comparison of this study's assessment of candidate fuel availability for shipping in 2050 with other selected studies



**We assume that 10% of biofuels for the transportation sector is applied for shipping*
***Does not include biomethane (bio-LNG)*
****Based on results from* (IRENA, 2021)

7 COSTS ASSOCIATED WITH CANDIDATE FUELS

Overview

- The increased capital costs of the vessels that can use the candidate fuels are considered.
- The costs of candidate fuels are compared against the conventional fuels.
- The increased costs are reviewed as to whether this will present a barrier to uptake for the shipping industry.

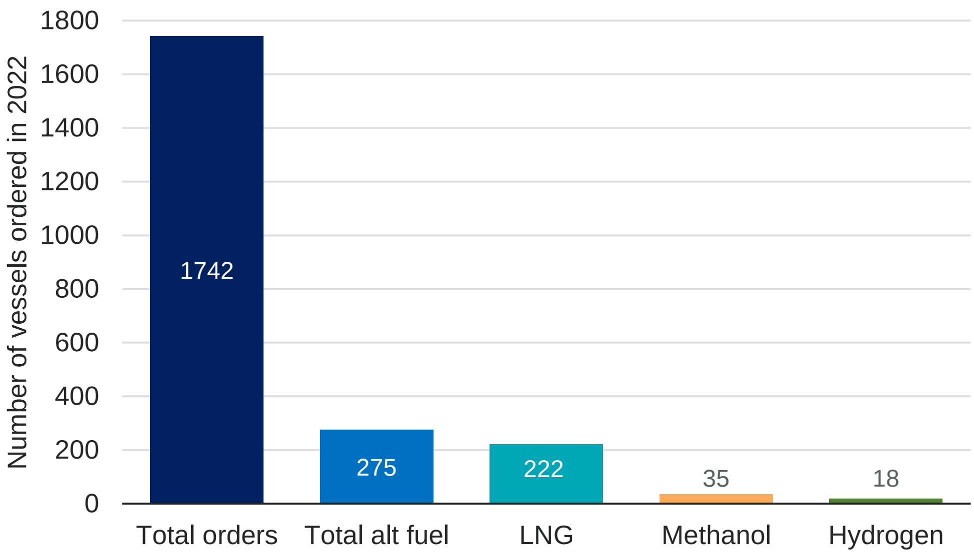
Key findings

- The increased capital costs of vessels using candidate fuels will not be a significant barrier to adoption.
- Upfront costs of some alternatively fuelled vessels can already be managed today.
- The high capital costs of onboard carbon capture systems are anticipated to be a barrier to adoption.
- It is not the higher prices of candidate fuels on their own that pose a barrier to their uptake for the shipping industry: it is the current uncertainty, in the absence of a clear demand signal, of when and by how much fuel prices could change, and the extent that these are stepped, unplanned and uneven between different segments and geographies.

7.1 COSTS OF VESSELS USING CANDIDATE FUELS

Vessels using candidate fuels are expected to be more expensive that those using conventional fuels. The costs of fuel tanks, fuel preparation equipment, safety systems and the engine or fuel cell, as well as potential effects on cargo volume due to the space taken up by the fuel, will all contribute to the increased cost of the vessel. However, alternatively fuelled vessels are already being ordered – Figure 7-1 shows that 275 alternatively fuelled ships were ordered in 2022, 222 of which were for LNG and 35 were methanol (note that information in section 4.2 concerns shipyard deliveries rather than new orders in 2022). Alternatively fuelled vessels represent around 15% of the 1742 newbuild orders placed in 2022 (Clarksons, 2023). However, as many of the alternatively fuelled vessels have tended to be larger, they represent nearly 40% of DWT.

Figure 7-1 New vessel orders in 2022 by fuel type



SEA-LNG (2020) estimate that a newbuild 14,000 TEU LNG-powered vessel would cost between 7% and 10% more than a conventionally fuelled vessel (assuming a newbuild cost of around $150m). It is clear from the orderbook that despite the relatively higher capital expenditure (CAPEX), **when the right incentives are in place, the upfront costs of alternatively fuelled vessels can already be managed today**. The Mærsk McKinney Møller Center for Zero Carbon Shipping (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022) estimates that a newbuild 15,000 TEU ammonia-powered vessel will cost around 16% more than a conventional vessel, while a methanol powered vessel will cost around 11% more, which is similar to the cost premium of an LNG vessel. Given that these figures are in the same range as LNG, **it is reasonable to assume that for many segments of the market, the increased capital costs of candidate fuels will not be a significant barrier to adoption**.

As an alternative to switching fuels, onboard carbon capture has been considered. For a system with 90% capture rate on a Suezmax tanker, OGCI estimates that the installed cost would be in the region of $30m (OGCI, 2021). This represents a 35% increase in the vessel CAPEX. ZCS (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022b) estimates that onboard carbon capture would increase CAPEX by around 40% for many vessel types, but by ~70% for the 205,000 DWT bulk carrier studied by ZCS. These cost estimates are significantly higher than those for the candidate fuels discussed above, so represent a potentially greater barrier to adoption.

Future studies could review which vessel types will be most sensitive to the increased CAPEX associated with candidate fuels and onboard carbon capture, so that measures to ensure this market is not penalised can be designed. Future studies could also consider whether increased vessel CAPEX would have an adverse impact in some geographies, and identify appropriate measures.

7.2 PRICE OF CANDIDATE FUELS COMPARED TO FOSSIL FUELS

Maritime fuels have historically been very cheap compared to other energy sources – for example, aviation fuel is around double the price of IFO380 at the time of writing. Depending on the vessel type and price of fuel at the time, fuel costs can make up significantly more than half of the vessel OPEX per km. Therefore, it could be assumed that increases in fuel costs from switching to the candidate fuels could not be accommodated by the shipping industry without significant disruption. However, over the last ten years bunker fuel price has varied from a low of $144/t to a high of around $1100/t, ($3/GJ to $26/GJ), as shown in Figure 7-2 (Ship & Bunker, 2022), and these price variations have been accommodated by the industry (though not without some challenges).

Figure 7-2 Average global bunker price over 10 years. Data copyright ©: Ship & Bunker

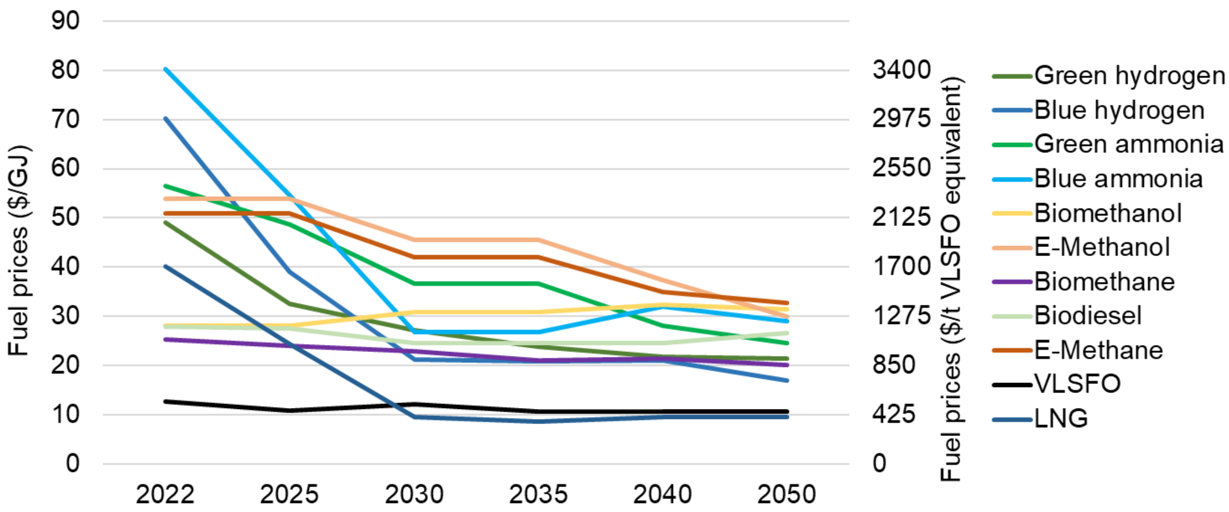
Undoubtedly, these fluctuations have caused knock-on impacts and disruption, potentially affecting pass-through costs and profitability, particularly when prices have risen unexpectedly over short periods. However, some experts interviewed did **not** view higher prices for candidate fuels on their own as a barrier to their uptake, within some provisos that any mandates or legislation are introduced:

- in a transparent manner;
- with sufficient time/warning to plan and factor in fuel price changes, including adopting efficiency measures to reduce the effect of fuel price increases;
- avoiding step changes, as this would be expected to cause disruption;
- fairly and equally, without unfairly disadvantaging certain sectors or geographies.

Recent changes can be used to observe however that (a) step changes in policy with implications for fuel prices have previously occurred (for example, the change coming into effect in 2020 of fuel sulphur content requirements of MARPOL Annex VI), and (b) unexpected price changes were possible to accommodate in the market (for example, customers paid more to ship goods during the COVID shipping crisis).

Forecasting of the price of globally traded commodities such as shipping fuels is challenging as global events can cause wild fluctuations in values, with little relation to the actual production cost. Therefore, some caution must be applied to the values projected for prices of future shipping fuels. Many price forecasts were made before the ongoing military conflict between the Russian Federation and Ukraine, so do not include the exceptional prices for natural gas and associated blue fuels. IEA (2022b) was the only source identified to explicitly detail the effect of these prices on the price of blue hydrogen, so this is the single source for 2022. Blue ammonia prices were adjusted to reflect the underlying price of the hydrogen feedstock. The 2025 blue fuels prices have been interpolated between the 2022 values and the averaged 2030 values (which did not include the effect of the conflict in Ukraine). Figure 7-3 compares the forecast price per GJ of the candidate fuels with the fossil fuels VLSFO and LNG, expressed as the midpoint of a range of values assessed in the literature (see APPENDIX 7):

Figure 7-3 Forecast prices for fossil and candidate fuels



Future prices for the candidate fuels will be dependent on a range of external factors. Recent policy measures, such as the USA Inflation Reduction Act, are intended to increase availability and reduce costs of hydrogen and hence hydrogen-based fuels. In addition, some geographies are aiming for production of very low-cost hydrogen, much of which is intended for export, potentially as shipping fuels. These elements both have the potential for lower e-fuel costs than the forecasts from the literature survey. The production of biofuels is dependent on the availability of suitable feedstocks, particularly for advanced biofuels using waste feedstocks and where there may be demand from other sectors, as noted in Section 6.7. Similarly, carbon-containing e-fuels require a supply of renewable CO_2, while blue fuels rely on the capacity to store CO_2.

Based on the values identified in this research, all candidate fuels are forecast to be more expensive per unit of energy than the incumbent fuels until 2050. There is some uncertainty as to whether marine fuel oils will increase in price towards mid-century as fossil fuels are used less for all transport modes, leading to less refinery capacity and fewer residual products, which have historically been used to minimise marine fuel costs. For much of the period studied, the least expensive candidate fuels are biofuels, particularly biodiesel and biomethane. However, if demand from shipping and aviation outstrips supply, the price of these fuels will undoubtedly rise. Of the other candidate fuels, blue hydrogen could become competitive with biofuels from 2030. However, hydrogen is unlikely to be suitable for larger transoceanic vessels due to its low volumetric energy density. For smaller vessels, blue hydrogen could be a suitable option. Blue and green ammonia are forecast to become more competitive with biofuels from the 2030s, which could be a suitable path for larger vessels. The data show e-methane and e-methanol to be the most expensive fuels for the majority of this timeframe. The price of these fuels is strongly affected by not only the price of both electricity for electrolysis (as per the hydrogen feedstock) but also the cost of the CO_2 feedstock, which vary significantly by region, technology, and legislation under which the fuels are considered acceptable. As the forecast of the commercial development of the various carbon capture technologies is unclear, there is some uncertainty over how the CAPEX and OPEX of these technologies will change, leading to some uncertainty in fuel price.

Figure 7-4 Forecast increase in fuel prices of candidate fuels vs. VLSFO

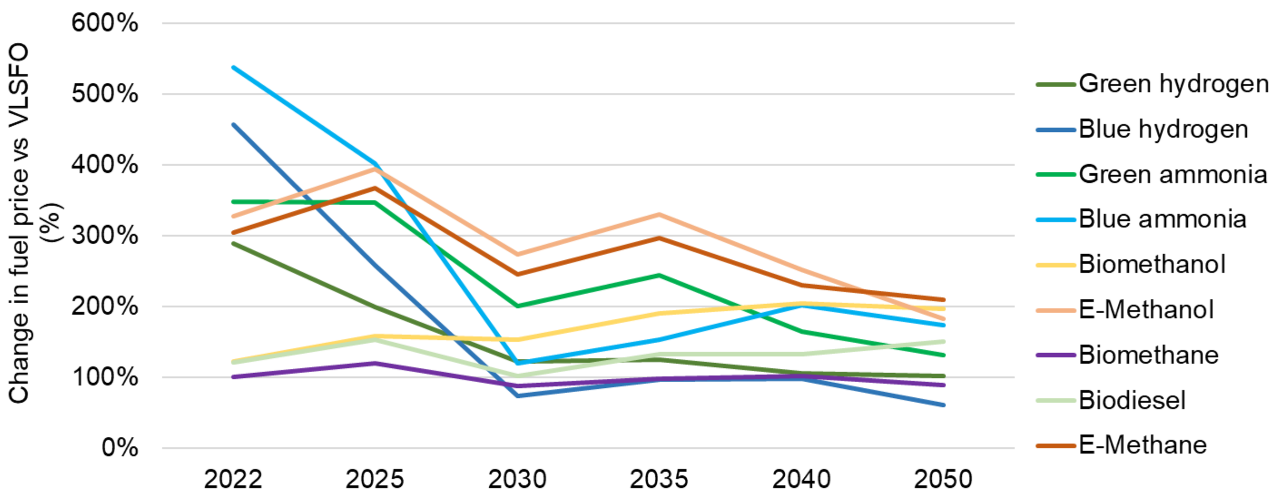
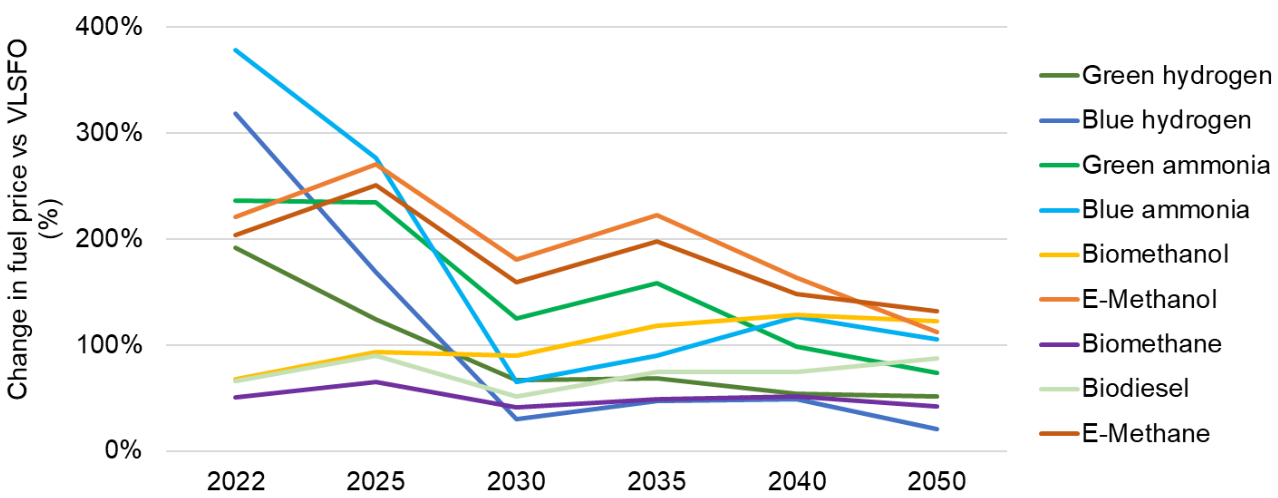


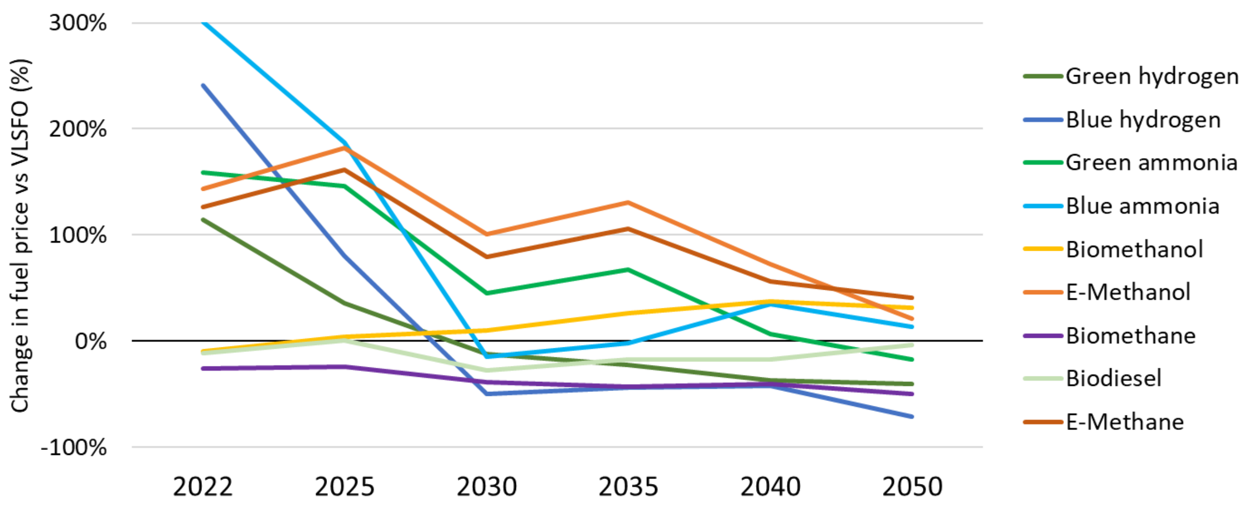
Figure 7-4 shows the forecast increase in fuel prices for the candidate fuels compared with VLSFO assuming the same energy use. Increases of this magnitude would cause challenges in the market if introduced suddenly. During previous price shocks, vessel operators quickly adopted efficiency measures such as slow sailing. Experts consulted for this study confirmed the expectation that with higher costs of fuels (e.g. with candidate fuels), higher levels of adoption of energy efficiency measures could be anticipated. The efficiency measures modelled in section 5.4 used a ~25% efficiency improvement. It should be noted that the level of efficiency improvement, and the measures that can be adopted will vary depending on the vessel type, its route and whether it is newbuild or retrofit. When this improvement is included, the increase in relative price of the candidate fuels with efficiency measures compared to VLSFO without efficiency measures is reduced, as seen in Figure 7-5.

Figure 7-5 Forecast increase in fuel prices of candidate fuels with 25% efficiency improvement



With efficiency improvements, between 2025 and 2040 many of the fuels fall to within a price doubling compared the VLSFO, which is within the proportion of fluctuations that have been seen in the recent past, and could be better accommodated, provided the changes were gradual, according to interviews with experts. However, in many cases, vessel operators and owners will not voluntarily choose to use a more expensive fuel without an incentive. The EU ETS carbon price is €100/tonne of CO_2 at the time of writing. Figure 7-6 shows that if the price of fuel had to incorporate that carbon price, once efficiency measures are implemented the majority of the candidate fuels would be similar to or in some cases cheaper than VLSFO from 2030 onwards. Therefore, this analysis suggests a carbon price of €100/tCO_2 could be sufficient to drive adoption of the candidate fuels

Figure 7-6 Forecast increase in fuel prices assuming efficiency measures and €100/tCO_2e



Comparing the prices of the candidate fuels against onboard carbon capture is important to help understand which approach may be more prevalent and what effect subsidies or levies may have. However, this is challenging to do in practice as the technology and associated costs are still immature. ZCS (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022) and OGCI (OGCI, 2021) have both released reports on onboard carbon capture in the last 18 months, yet use different boundary conditions and present their data in a way which make them difficult to compare. The reports show that, depending on the vessel type, fuel type and carbon capture rate, between 20% and 53% more fuel is estimated to be required to drive the carbon capture system (see APPENDIX 1 for further discussion).

A worked example of indicative costs for a notional vessel using a carbon capture system with 70% capture rate is shown below:

Fuel consumption (at 70% capture rate)			
Propulsion fuel consumption	1 tonne	Onboard carbon capture fuel use	20%
Cost of CO_2 sequestration/t	$20	EU ETS carbon price @€100	$107
CO_2 emissions per tonne of fuel			
Propulsion CO_2 emissions	3.1 tonnes	Propulsion CO_2 captured	2.17 tonnes
Propulsion CO_2 released	0.93 tonnes	CCS system CO_2 captured	0.43 tonnes
CCS system CO_2 released	0.19 tonnes	Total CO_2 released	1.12 tonnes
Costs			
VLSFO cost/t	$750	CCS fuel cost/t propulsion fuel	$150
$/t propulsion CO_2 captured	$69	Fuel % of CCS OPEX	70%
Total CCS OPEX/t propulsion CO_2	$99	CO_2 storage/t propulsion CO_2	$24
Total CCS OPEX/t propulsion fuel	$214	Carbon storage/t propulsion fuel	$52
OPEX + storage /t propulsion fuel	$256	EU ETS carbon cost /t propulsion fuel	$112
Total additional /t propulsion fuel if EU ETS applied		$368	49% increase

Comparing these values with Figure 7-6, the operating costs of onboard CCS are competitive with ammonia before the early 2030s but become more expensive than most candidate fuels after this time. Carbon capture systems can be run at lower capture rates for any period where the maximum capture rate is beyond that needed by any regulations. This leads to less additional fuel demand and hence lower operating cost. However, the high CAPEX may make this an expensive option per tonne CO_2. Where a system is specified at a lower capture rate than needed for regulations, an increasing proportion of bio- or e-fuel will need to be used to make up for the incomplete carbon capture. This will add further costs due to the higher fuel price, but could be a cost-effective solution in some cases. The high CAPEX costs of carbon capture technology, together with the differences in fuel consumption penalty by capture rate, vessel and route, means that a total cost of ownership approach is needed to fully compare the different fuel options.

8 FEASIBILITY OF MEETING DECARBONISATION SCENARIOS

Overview

- The feasibility of achieving the decarbonisation scenarios for 2030, 2040 and 2050 has been assessed by bringing together analysis of energy demand, technological maturity, availability and costs in previous sections. We compared the demand for candidate fuels against the expected availability to assess the potential gap to meet decarbonisation pathways.

Key findings

- None of the decarbonisation scenarios will be achieved under business as usual; action is needed.
- The analysis of feasibility by 2030, 2040 and 2050 is summarised in the table below. All three decarbonisation scenarios are expected to be feasible to the extent that policies with an increased level of ambition are implemented in the short term. The only significant gap was found for the *Decarbonisation by 2050* scenario by 2030, considering the need to increase the uptake of candidate fuels well beyond currently announced projects to meet this target by 2030. This gap does not, however, preclude achieving the targets for the pathway in 2040 and 2050. These conclusions are robust to the range considered of low and high growth in seaborne trade.

Decarbonisation scenario	2030	2040	2050
Initial IMO GHG strategy	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition
80% reduction by 2050	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition
Decarbonisation by 2050	✗ Major gaps	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition

- The feasibility of these decarbonisation scenarios, and particularly the most ambitious pathways, requires an early clarification of further policy targets and measures to help unlock investment in candidate fuels and their associated infrastructure.
- From a basket of candidate mid-term GHG reduction measures, both technical and economic measures are likely to be needed to ensure the feasibility of this transition, complementing each other. Technical measures can provide long-term clarity for the industry on expected level and scope of mitigation efforts. Economic measures with revenue raising and disbursement mechanisms could be deployed early in the transition to help smooth the cost increase, particularly for first movers and help develop economies of scale around the production, distribution and use of candidate fuels for the benefit of the rest of the market.
- The feasibility analysis does not point to significant gaps in terms of technology and commercial development for the achievement of decarbonisation pathways, particularly in the short term. Hence, availability of candidate fuels for the shipping sector is only expected to be sufficient to meet demand if there is firm demand from the sector and capacity to transition early on.
- Some additional barriers and possible mitigating actions to help achieve the decarbonisation scenarios have been identified.

8.1 FEASIBILITY ANALYSIS BY 2030

The three availability scenarios considered for 2030 are (as per assumptions in Table 6-4):

- the **Confirmed projects** availability scenario considers only the projects where a final investment decision (FID) has been made on projects publicly announced for developing new supplies of candidate fuels. Shipping can access 10% of that availability in line with current shares;

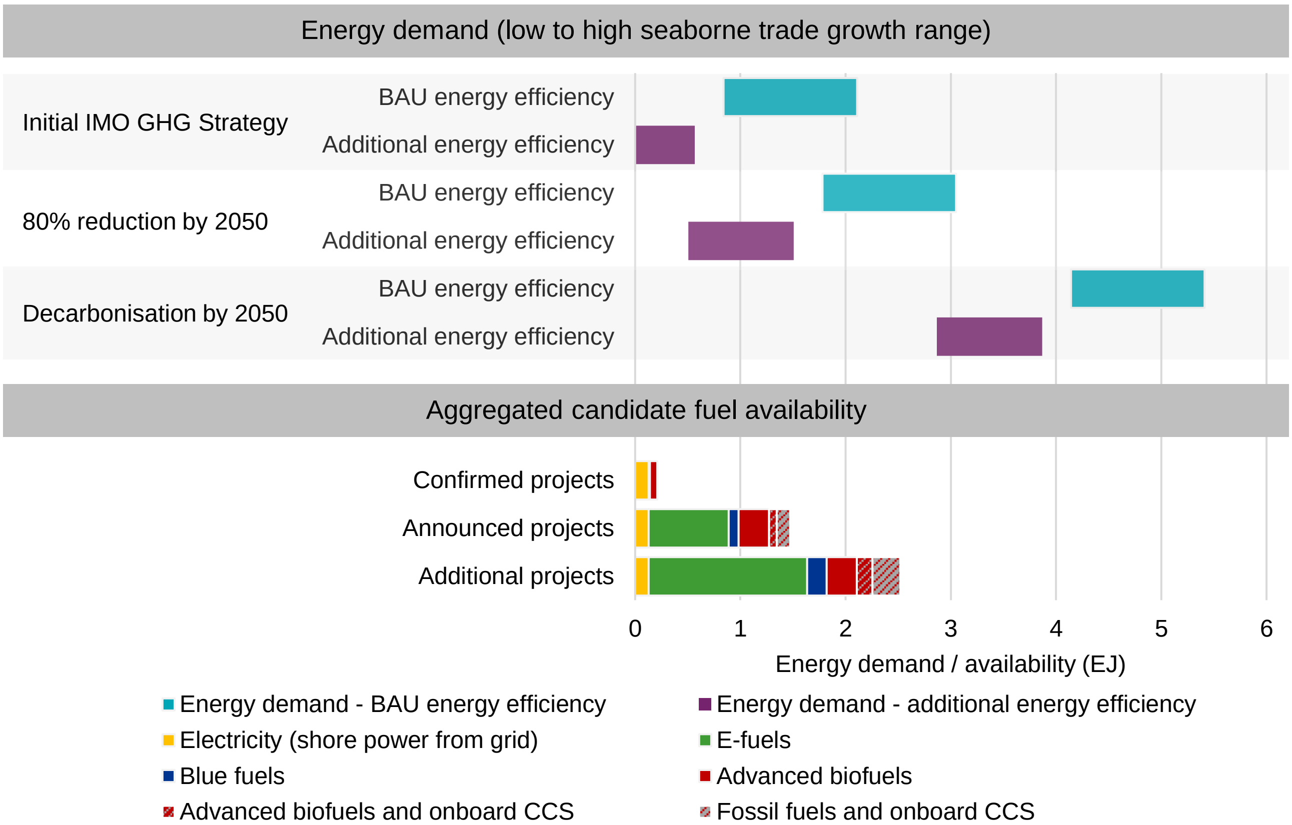
- the **Announced projects** availability scenario includes all currently announced projects i.e. also including those projects for which there has not been a final investment decision made. Taking into account that the road sector transitions to electricity, shipping can access 17% of the availability.
- The **Additional projects** availability scenario, in addition to currently announced projects, extrapolates an additional set of production projects to be announced until 2024, based on the current rate of announcements, and comparable with observed historical growth rates for solar power generation and biofuels. The date cut-off acknowledges the lead-in times needed for implementation. Shipping can access 17% of the availability.

As such, the **Confirmed projects** availability scenario is used to indicate the minimum availability expected as a matter of business as usual. The **Announced projects** availability scenario would be the availability if remaining announced projects receive final investment decisions, which may occur under business as usual but which are not guaranteed to proceed; it could be expected that with firmer signals of demand, more final investment decisions would likely be forthcoming, as well as with electrification in the road sector, more of the availability is available to shipping. The **Additional projects** availability scenario recognises that the Announced projects scenario is not a maximum: further availability could be considered likely to be realised if clear demand signals from the shipping sector are made through effective policy targets and measures.

Figure 8-1 compares the demand for candidate fuels for each of the decarbonisation scenarios and under the high and low growth seaborne trade scenarios, against the availability of candidate fuels under different scenarios by 2030. This shows the potential gap by 2030 between demand and availability for each decarbonisation scenario. The following conclusions can be drawn for each decarbonisation scenario by 2030:

- **Initial IMO GHG Strategy: Feasible with increased policy ambition**. Without additional energy efficiency measures, the target could be reached under low growth if some of the *announced projects* proceed (which may require additional policy action). With additional energy efficiency measures (i.e. expected to need additional policy action), the target could be achieved under the low growth scenario with the availability from the *confirmed projects*. Meeting this target under the high growth scenario would require a combination of energy efficiency measures and materialisation of the *announced projects*.
- **80% reduction by 2050: Feasible with increased policy ambition**. The demand for candidate fuels could be met with the *Additional projects* scenario under the low growth scenario and business as usual energy efficiency savings. If additional energy efficiency measures are adopted, it would be possible to meet the candidate fuel demand with the *announced projects* scenario, even under high growth. In this sense, the feasibility of this scenario by 2030 depends on revised policy measures and targets in the next years, leading to a firm demand for candidate fuels.
- **Decarbonisation by 2050: Major gaps**. The demand for candidate fuels under low or high growth scenarios cannot be achieved with currently *announced projects,* or with *additional projects* with expected growth rates. More fuel production projects should be added to meet this decarbonisation pathway by 2030, but the window is closing as the lead times to investment decision and commissioning are around 6-10 years. This means that additional measures and targets, beyond the current policy ambition, are required in the next 1-2 years to generate firm demand for additional projects supplying candidate fuels in the short term.

Figure 8-1: Top: energy demand for candidate fuels in 2030, without and with additional energy efficiency savings; Below: candidate fuel availability scenarios by 2030



Notes: For 'Additional energy efficiency', the potential energy savings from additional energy efficiency measures and use of shore power are deducted.

The required amount of advanced biofuels for onboard CCS is separated from the availability of advanced biofuels in the chart, although e-fuels may also be used. Onboard CCS does not show the 20% additional energy required assuming that this can be covered by fossil fuels (see Section 6.6). The candidate fuel availability shows the aggregated availability per fuel and should not be construed as a possible fuel mix.

Table 8-1 summarises the forecast maturity of fuel production pathways by 2030 in comparison to the expected availability of candidate fuels. As acknowledged in earlier sections, these forecasts are rooted in today's current (policy) situation and so could be considered as underestimates of the maximum pace of development, because if demand was higher for candidate fuels, it would be expected that fuel production and bunkering infrastructure roll-out would accelerate. There is no evidence of significant barriers in terms of technological development for fuel production pathways to meet supply requirements by 2030. The production of e-fuels with no carbon content (e.g. green ammonia) is expected to be at an early adoption stage but likely to reach a sufficient level of technological and commercial maturity on time for the implementation of announced projects if there is firm demand. The use of e-fuels *with* carbon content is expected to have a similar level of maturity but supply might be somewhat limited by the availability of sustainable carbon. The required amount of sustainable carbon to be combined with all available e-hydrogen in the *Announced projects* scenario to produce hydrocarbon e-fuels would require almost 50% of IEA's projected availability of sustainable carbon in 2030. 0.14 EJ of the advanced biofuel or e-fuel availability could be used in conjunction with onboard CCS. Electricity for shore power is already mature (though costly) but in 2030 may have high WtT emissions in some regions depending on the GHG intensity of the supplied grid electricity, and infrastructure needs to be significantly developed and expanded in the short term.

Distribution, storage and bunkering infrastructure for some candidate fuels would need to be further developed and expanded by 2030, compared to the current situation. Methanol bunkering infrastructure needs to be matured and expanded, while barriers remain for ammonia and hydrogen bunkering infrastructure. Existing distribution and storage infrastructure for methanol and ammonia, although not for marine fuels, can be used for initial availability. However, there is no existing hydrogen distribution and storage infrastructure to be used, which limits the capacity to deploy distribution and storage hydrogen infrastructure by 2030.

Table 8-1: Feasibility of fuel availability/production for candidate fuels by 2030

Candidate fuel		Fuel production readiness	Bunkering and distribution readiness	Expected availability per scenario
Biofuels	Biodiesel	Mature	Mature	0.1 EJ (confirmed projects) 0.4 EJ (announced projects) 0.4 EJ (additional projects)
	Biomethane	Mature	Mature	
	Biomethanol	Mature	Solutions identified	
E-fuels	Green hydrogen	Mature	Barriers remain	0 EJ (confirmed projects) 0.8 EJ (announced projects) 1.5 EJ (additional projects)
	Green ammonia	Deployment (early adoption)	Barriers remain	
	E-Methanol	Deployment (early adoption)	Solutions identified	
	E-Methane	Deployment (early adoption)	Mature	
	E-Diesel	Deployment (early adoption)	Mature	
Blue fuels	Blue hydrogen	Mature	Barriers remain	0 EJ (confirmed projects) 0.1 EJ (announced projects) 0.2 EJ (additional projects)
	Blue ammonia	Deployment (early adoption)	Barriers remain	
Shore power		Mature	Mature	0.1 EJ

Table 8-2 summarises the feasibility of the powertrains for the required use of candidate fuels, in terms of their retrofit potential and technological and commercial readiness. **Again, as noted earlier, technology and commercial readiness could be faster than shown here because if demand was higher for candidate fuels, it would be expected that the necessary development, demonstration and deployment would accelerate.**

Existing evidence suggests there may not be significant gaps in terms of technology maturity for the use of required powertrain types by 2030. If starting in 2025 it is possible to add newbuilds with candidate fuel systems. This would require a rapid acceleration of uptake and it may only be feasible for methane and possibly methanol ICE engines and fuel systems. Ammonia is not currently forecast to achieve a full uptake on new builds before 2030 and retrofitting may be the main mechanism for the use of ammonia on existing vessels. Remaining demand for candidate fuels would need to be covered by drop-in fuels, i.e. bio- or e-diesel.

Table 8-2: Feasibility of powertrain types for candidate fuels by 2030

Candidate fuel	Powertrain type	Retrofit Potential	Readiness
Bio or e-diesel	ICE (2-stroke)	Excellent	Mature
	ICE (4-stroke)	Excellent	Mature
Bio or e-methane	ICE (2-stroke)	Good*	Mature
	ICE (4-stroke)	Good*	Mature
	Fuel Cell#	Limited**	Deployment (early adoption)
Bio or e-methanol	ICE (2-stroke)	Excellent	Mature

Candidate fuel	Powertrain type	Retrofit Potential	Readiness
	ICE (4-stroke)	Excellent	Mature
	Fuel Cell#	Limited**	Deployment (early adoption)
E- or blue hydrogen	ICE (4-stroke)	Limited	Deployment (early adoption)
	Fuel Cell	Unlikely**	Deployment (early adoption)
E- or blue ammonia	ICE (2-stroke)	Good*	Deployment (early adoption)
	ICE (4-stroke)	Good*	Deployment (early adoption)
	Fuel Cell#	Unlikely**	Demonstration

*More likely for existing LNG-fuelled vessels than for conventionally fuelled vessels

**Except where vessels constructed with future powertrain conversion in mind – e.g., use of electrical propulsion

#Methane, methanol, and ammonia fuel cell includes direct use or reformation/cracking to hydrogen with a hydrogen fuel cell

Table 8-3 summarises the feasibility of onboard carbon capture. The use of onboard CCS in the *Announced projects* and *Additional projects* availability scenarios are currently expected to be from exhaust capture only, since this technology is currently forecast to be at an early adoption stage by 2030. However, evidence collected does **not** point to a fully scalable and commercially viable onboard CCS technology by 2030. Onboard CCS could be implemented by retrofits or on newbuilds but depends on access to storage infrastructure, which could the main limiting factor in the short term.

Table 8-3: Feasibility of onboard CCS technologies by 2030

Technology	Readiness	Expected availability of energy with onboard CCS*
Carbon capture (exhaust)	Deployment (early adoption)	0 EJ (confirmed projects) 0.2 EJ (announced projects) 0.4 EJ (additional projects)
Carbon capture (fuel reformation)	Demonstration	

*These are the supplies of energy that could be replaced by systems that include onboard carbon capture, for which an additional fuel penalty of 20% would apply.

Energy efficiency measures will be required by 2030 in all decarbonisation pathways. Table 8-4 shows the current forecasts of maturity of energy efficiency technologies and their potential energy reduction by 2030. Delivering the energy efficiency potential by 2030 requires a rapid uptake of voyage and vessel efficiencies (including speed reduction) in the short term, as well as vessel design optimisation continuing to play a role. The use of wind and sun assistance technologies is currently forecast to have a limited contribution by 2030.

Table 8-4: Feasibility of energy efficiency measures by 2030

Measures		Readiness	Potential energy reduction
Energy reduction and energy efficiency measures	Vessel design optimisation	Mature	1.2 – 1.4 EJ
	Voyage and vessel efficiencies	Mature	
	Wind assistance technologies	Deployment (early adoption)	

8.2 FEASIBILITY ANALYSIS BY 2040

The three availability scenarios considered for 2040 are (as per assumptions in Table 6-4):

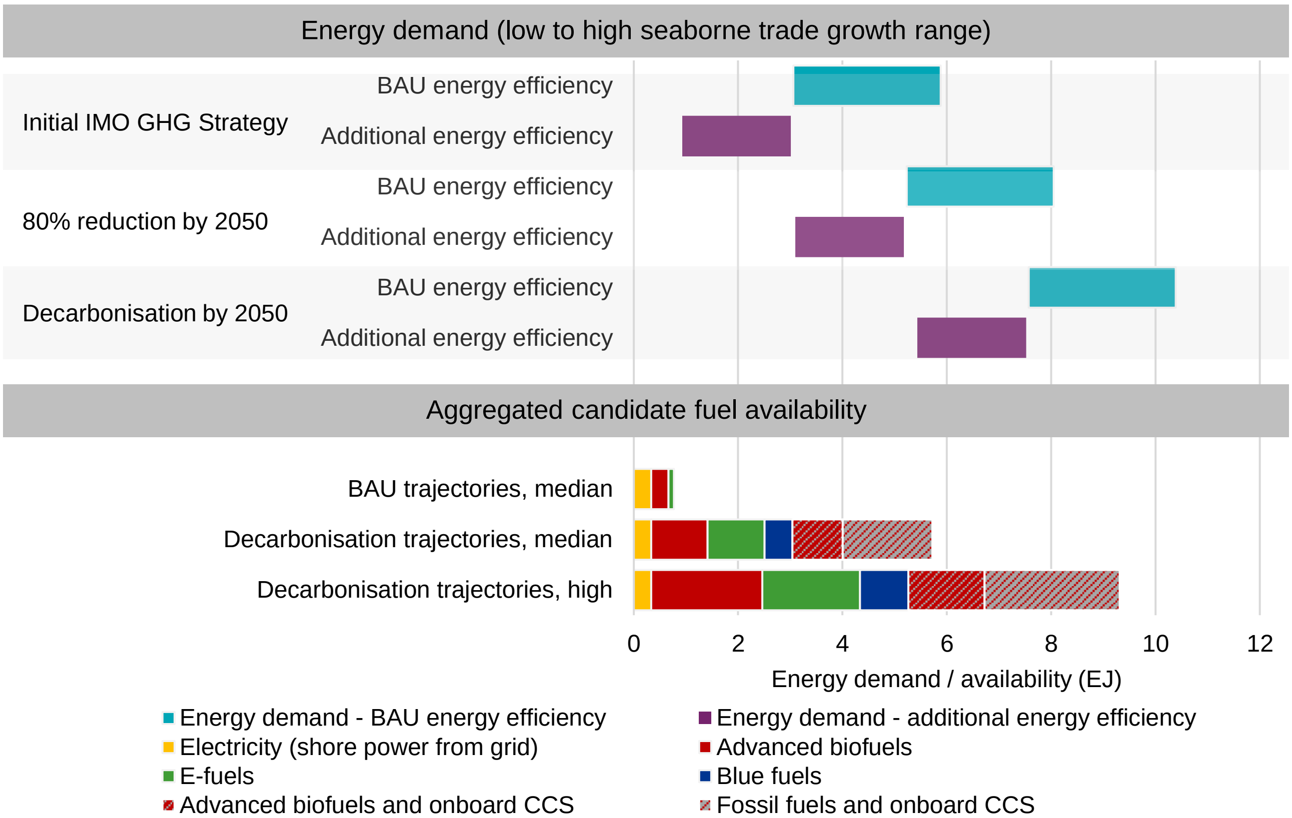
- The **BAU trajectories** availability scenario represents the median of various energy system forecasts of BAU scenarios identified among relevant studies. These do not consider any significant decarbonisation policies.
- The **Decarbonisation trajectories (median and high)** availability scenarios represent the median and highest of various forecasts of availability of candidate fuels under decarbonisation scenarios identified among relevant studies. The large spans in the availability reflect the uncertainty around decarbonisation policies and ambitions driving long-term investments in renewable electricity, candidate fuel production, vessel technology and CCS.

Figure 8-2 compares the demand for candidate fuels for each of the decarbonisation scenarios and under the high and low growth scenarios, against the different scenarios of availability of candidate fuels by 2040. This shows the potential gap by 2040 between demand and availability for each decarbonisation scenario.

The following conclusions can be drawn for each decarbonisation scenario by 2040:

- **Initial IMO GHG Strategy: Feasible with increased policy ambition**. A combination of energy efficiency measures and candidate fuels rollout under current policies (*BAU trajectory*) is not expected to be sufficient to meet this target, particularly under the high growth scenario. As such, additional policies beyond the current level of ambition are required to maximise uptake of energy efficiency measures and/or increase the rollout of new candidate fuel production projects. The *median of decarbonisation trajectories* is expected to be sufficient to achieve the target under a high growth scenario, even with no further energy efficiency measures.
- **80% reduction by 2050: Feasible with increased policy ambition**. The demand for candidate fuels can be achieved with a combination of energy efficiency measures plus an uptake of candidate fuels in line with availability scenarios driven by decarbonisation policies. In the absence of further energy efficiency measures, the target can be achieved with the *median of decarbonisation trajectories* under a low growth scenario. However, under a high growth scenario, further energy efficiency measures or a higher uptake of candidate fuels would be needed.
- **Decarbonisation by 2050: Feasible with increased policy ambition**. The demand for candidate fuels will require a combination of energy efficiency measures and a high uptake of candidate fuels. Under a low growth scenario, a rapid uptake of candidate fuels in line with the *higher end of decarbonisation trajectories* could meet demand even in the absence of energy efficiency measures. Achieving the target under a high growth scenario would require both the full potential of energy efficiency measures and availability of candidate fuels in line with the *higher end of decarbonisation trajectories*.

Figure 8-2: Top: energy demand for candidate fuels in 2040, without and with additional energy efficiency savings; Below: candidate fuel availability scenarios by 2040



Notes: For 'Additional energy efficiency', the potential energy savings from additional energy efficiency measures and use of shore power are deducted.

The required amount of advanced biofuels for onboard CCS is separated from the availability of advanced biofuels in the chart, although e-fuels may also be used. Onboard CCS does not show the 20% additional energy required assuming that this can be covered by fossil fuels (see Section 6.6). The candidate fuel availability shows the aggregated availability per fuel and should not be construed as a possible fuel mix.

Table 8-5 summarises the maturity of fuel production pathways by 2040 in comparison to the expected availability of candidate fuels. Currently *announced projects* for production of e-fuels are already close to the median of *Decarbonisation trajectories* in 2040, indicating that there is a significant body of projects in planning, but there are few confirmed projects due to the uncertainty on demand. All candidate fuel production pathways are expected to be (or are capable of being) commercially mature by 2040[27]. Hence, fuel production technology is not expected to be a barrier for the availability of low carbon fuels by 2040. Sustainable carbon for hydrocarbon e-fuels would require about 30-35% of IEA's projected availability. 1 EJ of the advanced biofuel or e-fuel availability could be used in conjunction with onboard CCS. Electricity from shore power is likely readily available and it is expected to play a role in reducing energy demand at berth. However, it should be noted that, shore power may still have high WtT emissions in some regions, if electricity is produced from non-renewable sources.

Bunkering infrastructure can be expected to be mostly available in 2040, although there may remain gaps for certain fuel types and across different geographies.

[27] The timescale for commercial maturity of e-methane was found to be unclear in section 3.5.2, although this was not due to lack of technical readiness (with first commercial operations commencing already) but uncertain demand limiting investment. All other fuel production pathways are forecast to reach commercial maturity by the late 2030s or sooner.

Table 8-5: Feasibility of fuel availability/production for candidate fuels by 2040

Candidate fuel		Fuel production readiness	Range of availability
Biofuels	Biodiesel	Mature	0.3 EJ (BAU) 2.0 EJ (decarbonisation median) 3.6 EJ (decarbonisation high)
	Biomethane	Mature	
	Biomethanol	Mature	
E-fuels	Green hydrogen	Mature	0.1 EJ (BAU) 1.1 EJ (decarbonisation median) 1.9 (decarbonisation high)
	Green ammonia	Mature	
	E-Methanol	Mature	
	E-Methane	Deployment (early adoption)	
	E-Diesel	Mature	
Blue fuels	Blue hydrogen	Mature	0 EJ (BAU) 0.5 EJ (decarbonisation median) 0.9 (decarbonisation high)
	Blue ammonia	Mature	
Shore power		Mature	0.3 EJ

Vessel powertrain technologies for candidate fuels are expected to be commercially mature by 2040, except for ammonia fuel cell powertrains, which are currently forecast to be at an early adoption stage (Table 8-6). As such, evidence available suggests there may not be technical barriers for scaling up number of ships with candidate fuel systems to 2040.

Table 8-6: Feasibility of powertrain types for candidate fuels by 2040

Candidate fuel	Powertrain type	Retrofit Potential	Readiness
Bio or e-diesel	ICE (2-stroke)	Excellent	Mature
	ICE (4-stroke)	Excellent	Mature
Bio or e-methane	ICE (2-stroke)	Good*	Mature
	ICE (4-stroke)	Good*	Mature
	Fuel Cell#	Limited**	Mature
Bio or e-methanol	ICE (2-stroke)	Excellent	Mature
	ICE (4-stroke)	Excellent	Mature
	Fuel Cell#	Limited**	Mature
E- or blue hydrogen	ICE (4-stroke)	Limited	Mature
	Fuel Cell	Unlikely**	Mature
E- or blue ammonia	ICE (2-stroke)	Good*	Mature
	ICE (4-stroke)	Good*	Mature
	Fuel Cell#	Unlikely**	Deployment (early adoption)

*More likely for existing LNG-fuelled vessels than for conventionally fuelled vessels

**Except where vessels constructed with future powertrain conversion in mind – e.g., use of electrical propulsion

#Methane, methanol, and ammonia fuel cell includes direct use or reformation/cracking to hydrogen with a hydrogen fuel cell

The technology of onboard CCS is forecast to be fully developed by 2040. However, the extent to which onboard CCS technologies will be fully scalable and commercially available by 2040 is still rather unclear (Table 8-7). This will largely depend on its cost-effectiveness (compared to candidate fuels) and its retrofitting potential. In addition, the availability of storage infrastructure at ports could still be limited. There is therefore a risk of this technology not being fully capable to deliver significant emission reductions by 2040.

Table 8-7: Feasibility of onboard CCS technologies by 2040

Technology	Readiness	Range of energy availability with onboard CCS
Carbon capture (exhaust)	Unclear	0 EJ (BAU) 2.7 EJ (decarbonisation, median) 4.0 EJ (decarbonisation, high)
Carbon capture (fuel reformation)	Unclear	

A further uptake of energy efficiency measures is expected to be needed by 2040. The commercial maturity of wind and sun assistance technologies by 2040 is still unclear. If this technology does not prove to be a cost-effective and fully scalable solution by 2040, further energy efficiency measures will need to entirely rely on further speed reduction and optimised design of newbuilt vessels.

Table 8-8: Feasibility of energy efficiency measures by 2040

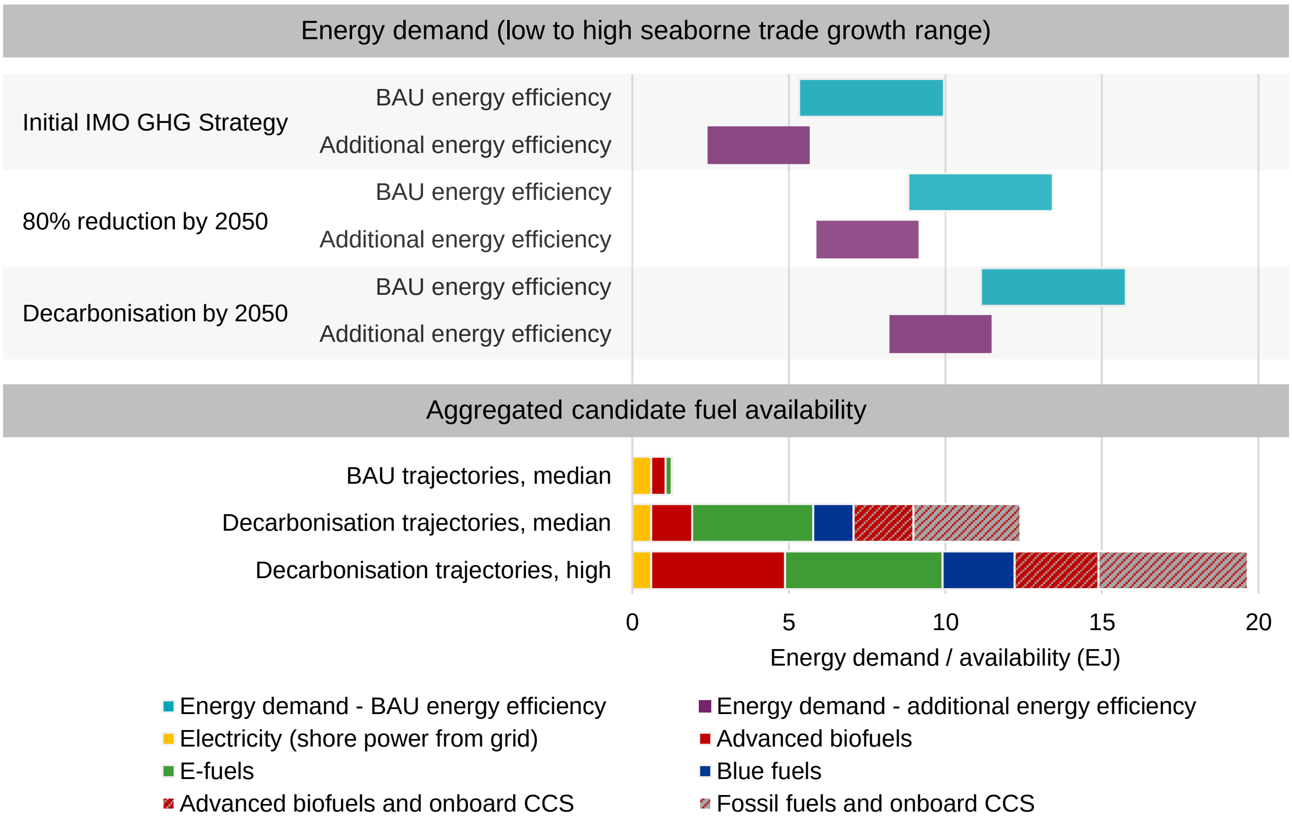
Measures		Readiness	Potential energy reduction
Energy reduction and energy efficiency measures	Vessel design optimisation	Mature	1.9 – 2.5 EJ
	Voyage and vessel efficiencies	Mature	
	Wind assistance technologies	Unclear	

8.3 FEASIBILITY ANALYSIS BY 2050

The comparison between demand for candidate fuels and expected availability scenarios in Table 8-3 leads to the following conclusions on the feasibility of the different decarbonisation scenarios by 2050:

- **Initial IMO GHG Strategy: Feasible with increased policy ambition**. A combination of energy efficiency measures and energy availability changes under current policies (*BAU trajectory*) is not expected to be sufficient to meet this target. As such, additional policies beyond the current level of ambition might be required to promote a significant uptake of candidate fuels by 2050. The *median of decarbonisation trajectories* is expected to be sufficient to achieve the target under a high growth scenario, even with no further energy efficiency measures.
- **80% reduction by 2050: Feasible with increased policy ambition**. The demand for candidate fuels can be achieved with a combination of energy efficiency measures plus an uptake of candidate fuels in line with availability scenarios driven by decarbonisation policies. Availability of candidate fuels in line with the *median of current decarbonisation trajectories* would be sufficient to meet the target, even in the absence of energy efficiency measures under moderate growth. Under a high growth scenario, either the full potential of energy efficiency measures or a higher uptake of candidate fuels would be needed.
- **Decarbonisation by 2050: Feasible with increased policy ambition**. The demand for candidate fuels would require a combination of energy efficiency measures and a high uptake of candidate fuels. The availability of candidate fuels from the *median of decarbonisation trajectories* is aligned with the demand, considering the full potential of energy efficiency measures. However, if the full potential of energy efficiency measures cannot be achieved, the availability of candidate fuels to meet the demand would need to be closer to the *higher end of decarbonisation trajectories*, particularly under the high growth scenario.

Figure 8-3: Energy demand for candidate fuels after deducting for potential energy efficiency savings, and candidate fuel availability by 2050



Notes: For 'Additional energy efficiency', the potential energy savings from additional energy efficiency measures and use of shore power are deducted.

The required amount of advanced biofuels for onboard CCS is separated from the availability of advanced biofuels in the chart, although e-fuels may also be used. Onboard CCS does not show the 20% additional energy required assuming that this can be covered by fossil fuels (see Section 6.6). The candidate fuel availability shows the aggregated availability per fuel and should not be construed as a possible fuel mix.

As seen at 2040, all candidate fuel production pathways are expected be (or are capable of being) commercially mature by the late 2030s, and so fuel production technology is not expected to be a barrier for the availability of low carbon fuels by 2050. Sustainable carbons for hydrocarbon e-fuels would require about 30-35% of IEA's projected availability in 2050. 1.9-2.7 EJ of the advanced biofuel or e-fuel availability could be used in conjunction with onboard CCS.

Port and bunkering infrastructure can be expected to be available in 2050 for relevant fuels, although there may remain gaps for certain fuel types and across different geographies.

Table 8-9: Feasibility of powertrain types for candidate fuels by 2050

Candidate fuel		Fuel production readiness	Expected availability
Biofuels	Biodiesel	Mature	0.5 EJ (BAU) 3.2 EJ (decarbonisation median) 7.0 EJ (decarbonisation high)
	Biomethane	Mature	
	Biomethanol	Mature	
E-fuels	Green hydrogen	Mature	0.2 EJ (BAU) 3.9 EJ (decarbonisation median) 5.0 (decarbonisation high)
	Green ammonia	Mature	
	E-Methanol	Mature	
	E-Methane	Unclear	

Candidate fuel		Fuel production readiness	Expected availability
	E-Diesel	Mature	
Blue fuels	Blue hydrogen	Mature	0 EJ (BAU) 1.3 EJ (decarbonisation median) 2.3 EJ (decarbonisation high)
	Blue ammonia	Mature	
Shore power		Mature	0.4 – 0.6 EJ

Scaling up the number of ships with candidate fuel systems should not be an issue by 2050. All powertrain technologies are expected to be fully mature, expect for ammonia fuel cells, which is still unclear (Table 8-10).

Table 8-10: Feasibility of powertrain types for candidate fuels by 2050

Candidate fuel	Powertrain type	Retrofit Potential	Readiness
Bio or e-diesel	ICE (2-stroke)	Excellent	Mature
	ICE (4-stroke)	Excellent	Mature
Bio or e-methane	ICE (2-stroke)	Good*	Mature
	ICE (4-stroke)	Good*	Mature
	Fuel Cell#	Limited**	Mature
Bio or e-methanol	ICE (2-stroke)	Excellent	Mature
	ICE (4-stroke)	Excellent	Mature
	Fuel Cell#	Limited**	Mature
E- or blue hydrogen	ICE (4-stroke)	Limited	Mature
	Fuel Cell	Unlikely**	Mature
E- or blue ammonia	ICE (2-stroke)	Good*	Mature
	ICE (4-stroke)	Good*	Mature
	Fuel Cell#	Unlikely**	Unclear

*More likely for existing LNG-fuelled vessels than for conventionally fuelled vessels

**Except where vessels constructed with future powertrain conversion in mind – e.g., use of electrical propulsion

#Methane, methanol, and ammonia fuel cell includes direct use or reformation/cracking to hydrogen with a hydrogen fuel cell

Decarbonisation availability scenarios consider a significant role for onboard CCS technologies. However, as in 2040, the commercial maturity and the availability of access to storage infrastructure remains uncertain (Table 8-11).

Table 8-11: Feasibility of onboard CCS technologies by 2050

Technology	Readiness	Expected energy availability with onboard CCS
Carbon capture (exhaust)	Unclear	0 EJ (BAU) 5.3 EJ (decarbonisation, median) 7.5 EJ (decarbonisation, high)
Carbon capture (fuel reformation)	Unclear	

The feasibility of further energy efficiency technologies is similar to that of 2040. By 2050, however, there may be less room for vessel design and optimisation and speed reduction, which means that the role of wind assistance technologies and shore power may be expected to play a more significant role. The commercial maturity of wind assistance technologies by 2050 is not fully clear (Table 8-12).

Table 8-12: Feasibility of energy efficiency measures by 2050

Measures		Readiness	Potential energy reduction
Speed reduction and energy efficiency measures	Vessel design optimisation	Mature	2.5 – 3.7 EJ
	Voyage and vessel efficiencies	Mature	
	Wind assistance technologies	Unclear	

8.4 SUMMARY OF FEASIBILITY ANALYSIS

The feasibility analysis by 2030, 2040 and 2050 is summarised in Table 8-13. **None of the decarbonisation scenarios will be achieved under business as usual; action is needed. All three decarbonisation scenarios are expected to be feasible to the extent that policies with an increased level of ambition are implemented in the short term. The only significant gap was found for the *Decarbonisation by 2050* scenario by 2030, considering the need to increase the uptake of candidate fuels well beyond currently announced projects to meet this target by 2030**. This gap does not, however, preclude achieving the targets for the pathway in 2040 and 2050. These conclusions are robust to the range considered of low and high growth in seaborne trade.

Table 8-13: Summary of feasibility analysis by decarbonisation scenario

Decarbonisation scenario	2030	2040	2050
Initial IMO GHG strategy	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition
80% reduction by 2050	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition
Decarbonisation by 2050	✗ Major gaps	✓ Feasible with increased policy ambition	✓ Feasible with increased policy ambition

9 POSSIBLE MITIGATING ACTIONS TO HELP ACHIEVE THE DECARBONISATION SCENARIOS

The feasibility of these decarbonisation scenarios, and particularly the most ambitious pathways, requires an early clarification of further policy targets and measures to help unlock investment in candidate fuels and their associated infrastructure. From a basket of candidate mid-term GHG reduction measures, both technical and economic measures are likely to be needed to ensure the feasibility of this transition, complementing each other, as being discussed at MEPC and ISWG-GHG. Technical measures can provide long-term clarity for the industry on expected level and scope of mitigation efforts. Economic measures with revenue raising and disbursement mechanisms could be deployed early in the transition to help smooth the cost increase, particularly for first movers and help develop economies of scale around the production, distribution and use of candidate fuels for the benefit of the rest of the market. The analysis in section 7 showed how a concept such as a carbon price, coupled with energy efficiency measures, could contribute to bring down the costs of candidate fuels relative to conventional fuels over the longer term. Economic measures could improve predictability of future fuel prices and reduce differences between sectors and regions if implemented at a global level.

The feasibility analysis does not point to significant gaps in terms of technology and commercial development for the achievement of decarbonisation pathways, particularly in the short term. At the same time, availability of candidate fuels for the shipping sector is expected to be sufficient to meet demand, if there is firm demand from the sector and capacity to transition early on. Nonetheless, some remaining risks would need addressing and could be mitigated with specific policy actions.

Table 9-1 provides a summary of the risks, along with potential topics for policy actions to mitigate them.

Table 9-1: Technology and fuel availability risks and potential policy actions

Risks	Description	Potential topics for policy actions
Insufficient availability of distribution and bunkering infrastructure for candidate fuels	There are barriers for rolling out distribution and storage infrastructure for hydrogen, and bunkering infrastructure for ammonia and hydrogen, which could limit the required infrastructure by 2030. These are forecast to be solved by 2040 and 2050, if there is firm demand for candidate fuels from the sector, but infrastructure rollout may not be available for all fuels in parallel.	• Bunkering safety standards and training • Revenue disbursement from economic measures allocated to enable infrastructure investments • Support for green corridors, shipping routes and maritime hubs
Reaching full maturity of onboard carbon capture technology and availability of storage capacity is still unclear	Onboard carbon capture technology is forecast to not reach commercial operation until the 2030s, but the pathway to full commercial maturity of this technology (compared to other solutions) is unclear.	• Framework for certified reception and storage facilities • Clarity in new technical measures of if/how carbon capture would be considered • Revenue disbursement from economic measures allocated to technology/commercial development • Safety standards
Reaching full maturity of wind propulsion assistance technologies is still unclear	Wind assistance technologies are forecast to be in commercial operation or development in the 2030s, but their pathway to full commercial maturity (compared to other solutions) is unclear. If wind assistance does not reach full maturity, energy efficiency improvements would need to entirely rely on vessel and voyage optimisation measures.	• Clarity in new technical measures of if/how wind assistance technologies would be considered • Improved incentives for wind in existing instruments (e.g. CII, EEDI) • Revenue disbursement from economic measures allocated to technology/commercial development

Risks	Description	Potential topics for policy actions
Insufficient uptake of energy efficiency measures	Increased uptake of energy efficiency measures reduces the pressure on fuel availability by lowering demand. With higher fuel prices comes a greater reliance on energy efficiency measures.	• Further, or strengthened technical measures requiring / promoting energy efficiency
Development and investment efforts allocated to potentially stranded assets	Lack of clarity on the scope of emissions to be covered by mid-term and long-term policies (i.e. which GHG emissions and whether these are calculated on a TtW or WtW basis) may lead industry players to focus development and investment efforts on solutions that may become stranded assets in the future with regulatory changes.	• Early clarification on the level of ambition of the Revised IMO GHG Strategy for 2030, 2040 and 2050 • Lifecycle guidelines that clarify the way TtW and WtW GHG emissions are considered • Early clarification on scope of emissions (TtW vs. WtW and GHG emissions) in the Revised IMO GHG Strategy and supporting technical and/or economic measures
Competition for candidate fuels with other sectors limits the availability for shipping	The capacity of shipping to use candidate fuels (and related feedstocks), which are demanded by other sectors as well, will depend on the technological and commercial maturity for shipping, availability of infrastructure and capacity of the sector to absorb additional costs in a gradual manner. As such, this supply risk is linked to considerations on readiness and cost barriers.	• Early clarification on the ambition level of the Revised IMO GHG Strategy for 2030, 2040 and 2050, as well as scope (TtW/WtW and GHG emissions) • Policies supporting technology/fuel readiness to reduce uncertainty of which fuels the shipping sector will demand and the scale of demand • Revenue raising and disbursement mechanisms
Higher cost of candidate fuels compared to conventional fuel	The challenges relate to the phasing of these. Clear policies and timetables address this. Full cost pass through would increase the price of shipping services to end users.	• Technical measures (e.g. GHG intensity standard of marine fuel / energy) to provide clarity of demand • Revenue disbursement from economic measures to help close price gaps, to ensure changes are smooth, planned and even across segments and geographies
Increased newbuild cost for candidate fuels / onboard carbon capture for specific vessel types	Whilst not a major barrier identified in section 7, there may be a need to support specific vessel types, operator types or geographies. Decisions would be needed on which technologies to fund. May need compensatory support to shipbuilders or buyers	• Revenue disbursement from economic measures • Finance/loan support, e.g. with scrappage schemes • Clarity on implications from the Revised IMO GHG Strategy for uptake of conventionally fuelled newbuilds by specific date
Lack of onboard safety requirements for candidate fuels	Interim guidelines have been developed or are under development for candidate fuels, but prescriptive regulations for onboard applications haven't yet been created. Lack of standards is a barrier for upscaling due to the effort needed to use alternative designs. Further, crews operating the ships need to have the necessary training and competence.	• Finalise interim safety guidelines for candidate fuels • Include further fuels into the IGF Code or other frameworks, as appropriate • Develop training standards and programs for crews.

10 CONCLUSIONS

Three decarbonisation scenarios have been considered as conceivable options to bound the potential Revised IMO GHG Strategy:

- the Initial IMO GHG Strategy (modelled as 50% reduction by 2050)
- 80% reduction by 2050
- Decarbonisation by 2050

Given the scale of seaborne trade growth anticipated, **none of the decarbonisation scenarios will be achieved without agreeing policy measures. Therefore, action is needed.**

Achieving a more ambitious decarbonisation pathway than business as usual is not seen as being limited by the technical and commercial readiness of candidate fuels and technologies, nor infrastructure and shipyard readiness, but rather by the clarity provided to the sector by the ambition level and the policies in place to decarbonise the sector. The currently expected availability of candidate fuels for the shipping sector is limited and, without action, will lead to insufficient availability to meet demand.

A clear signal of demand is needed to enable sufficient availability of candidate fuels. That signal of demand could come from the forthcoming Revised IMO Strategy setting revised levels of ambition in combination with the policies needed to drive the transition to the revised ambition. Currently, policies are not yet in place supporting the Initial IMO GHG Strategy ambition to reduce GHG emissions by at least 50% by 2050. The policies to transition the sector from the current business as usual pathway to the forthcoming Revised Strategy decarbonisation pathway need to be agreed to firm up the demand.

All three decarbonisation scenarios are expected to be feasible in 2040 and in 2050 if policies to deliver an increased level of ambition are implemented in the short term. However, achieving the *Decarbonisation by 2050* scenario 2030 interim target would appear to be challenging to meet, considering the need to increase the uptake of candidate fuels well beyond currently announced projects to meet the 2030 target of this scenario.

Hence, **the clear signal of demand is needed very soon** to enable the sufficient availability of candidate fuels early enough to meet a steep transition pathway. Policies to achieve that ambition would need to come into effect by 2025 in order to meet the 2030 targets of the decarbonisation scenarios.

Several additional aspects[28] are needed for this clearer signal of demand, including:

- Which pollutants with GWP (e.g., CO_2, CH_4, N_2O in this paper) will be considered.
- Whether a TtW or WtW approach will be adopted.
- How sustainability will be assessed (such as different feedstocks for biofuels).
- How certification will differentiate among pathways (and hence GHG intensity) for the same fuel.
- How carbon for e-fuels will be accounted.
- How CCS will be treated – both onboard and in fuel production.
- The extent of requirements/incentives on energy efficiency measures, as this impacts fuel demand directly. Conversely, if cheaper fuels were incentivised, the demand for energy efficiency measures (without policy requirements) would be lower, which ultimately limits the ability to decarbonise.

Whilst this paper has followed a Tank-to-Wake scope, its conclusions on availability versus demand are not strongly dependent on this choice. But the choice between TtW and WtW is important. This is because, for example, if fuels with a large WtW GHG impact were inadvertently incentivised by a scope focussed on TtW impacts, this could jeopardise decarbonisation efforts in other sectors by shifting the burden of responsibility for emissions upstream and lead to overall higher global GHG emissions.

While candidate fuels are and will be more expensive than currently used fuels, this is not a barrier to deployment if the demand signal is clear. Short term cost changes – such as the costs of switching to candidate fuels and investing in new vessels – are barriers to decarbonise in the current framework of policy measures and ambition level. But with a clear signal of demand over defined timescales, increased costs can be planned for.

[28] The Guidelines on life cycle GHG intensity of marine fuels (LCA Guidelines) currently being developed will start to resolve many of these issues.

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12 APPENDICES

APPENDIX 1 : WELL-TO-WAKE AND TANK-TO-WAKE GHG EMISSIONS FROM CANDIDATE FUELS

This study has made a high-level assessment based on available literature of the well-to-wake (WtW) and tank-to-wake (TtW) GHG emissions for the various candidate fuels.

It is beyond the scope to do a detailed literature review and we mainly rely on the recent literature review in a report by Brynolf et al (2023) for the Nordic Roadmap project and in a report by (Ricardo, 2022) for OGCI/Concawe. The reports are supplemented by other papers and reports where relevant, values provided in the Fourth IMO GHG Study 2020, the default emissions factors in the proposed FuelEU Maritime regulation in the EU (European Commission, 2021a), the typical well-to-tank GHG emissions factors in EU's Renewable Energy Directive (RED) (EC, 2018), and the various adopted and upcoming fuel and hydrogen standards and regulations in the US, the EU and China.

Comparing various sources are challenging due to different assumptions and metrics: Some sources use GHG emission per fuel energy and others GHG emissions per energy to the propeller. The GWP values vary as the IPCC have provided updated values for each assessment report. The GHG intensity of electricity used for the production of e-fuels, is sometime assumed to be zero and in other cases reflects the energy mix of the national or regional grid.

For each candidate fuel we provide a range of WtT, TtW and WtW GHG emissions per unit of fuel energy. For TtW, we provide two values: one assuming that CO_2 emissions from combustion of biogenic carbon or carbon from DAC are considered zero, and one where the actual CO_2 emissions are included regardless of carbon source (denoted TtW').

For onboard CCS the GHG emission factors are corrected for the additional energy use needed for the onboard capture and storage. We correct for values that includes the energy conversion onboard (i.e. GHG emissions per propeller energy output), as well for values given in GWP20. Otherwise, we do not endeavour to correct the values from the literature review to be consistent with the assumptions in this study.

We do not distinguish between the possible fuel types that can be made from each candidate fuel, although the ranges should reflect the best to worst case of production pathway, fuel type and energy converter. To achieve the lower end of the GHG emission range, further requirements may have to be set on the production pathway and onboard energy conversion.

TTW GHG EMISSION FACTORS PER FUEL TYPE

Independent of the production pathway and well-to-tank emissions the various fuels will emit GHG emissions depending on the energy converter such as internal combustion engine, fuel cells and steam turbines. Ammonia, methanol and methane running in a dual fuel combustion engine will require a pilot fuel, assumed to be biodiesel or e-diesel. Other technologies exist such as using hydrogen from reformed ammonia as pilot fuel, fuel cells, and spark-ignited engines which can run without pilot fuel.

Table 12-1 shows an overview of TtW emission for various fuel types. The ranges include all type of energy converters. For methane the range is based on engine with a methane slip up to 4 g/kWh which is consistent with the emission conversion factors using the fleet modelling for the projection of emissions and energy demand to 2050 (see Appendix 2).

For TtW GHG emissions for bio- and e-fuels we provide two values: one assuming that CO_2 emissions from combustion of biogenic carbon or carbon from DAC are considered zero, and one where the actual CO_2 emissions are included regardless of carbon source. Table 12-1 provides the full TtW GHG emissions for the various as well as a separate line with the TtW CO_2 emissions. For biofuel and e-fuels the CO_2 emissions are deducted from the GHG emissions in the last row.

Table 12-1: Overview of the TtW GHG emissions for various fuel types. Values in gCO_2e/MJ

Report	HFO	LFO	MGO/diesel	Methane	Methanol	Ammonia	Hydrogen
(Ricardo, 2022)	77.6	-	-	60–85	76.1	0	0
(Brynolf, et al., 2023)*	-	-	78–79	55–66	69–71	0–14	0-5
Fourth IMO GHG Study 2020			76–78	67–80	69.3	N/A	N/A
FuelEU Maritime	78.1	77.7	76.3	59–67	71.6	2.6	0
CO_2 emissions only[29]	76.9	76.5	75.1	57.3	69.1	N/A	N/A
TtW range for fossil fuels	78	78	76–79	55–85	69–76	N/A	N/A
TtW range for bio- and e-fuels	-	-	1–4	0–28	0-7	0–14	0–5

**) Includes main and pilot fuel*

FOSSIL FUELS

Table 12-2 summarises a review of WtT GHG emissions for fossil HFO, LFO, MGO and LNG and the resulting WtW ranges.

Table 12-2: Overview of the WtT and WtW GHG emissions for fossil fuels. Values in gCO_2e/MJ

Report	HFO	LFO	MGO	LNG
(Ricardo, 2022)	9.6	-	-	16–19
(Brynolf, et al., 2023)	-	-	12.4	19.5*
FuelEU Maritime	13.5	13.2	14.4	18.5
WtT range	10–14	13	12–14	16–20
WtW range (combined with Table 12-1)	88–92	91	88–93	71–105

**) Includes MGO as pilot fuel*

BIOFUELS

The well-to-tank GHG emissions from biofuels is complex to estimate due to emissions related to direct and indirect land-use. In this study we split the biofuels into two categories based on feedstock: conventional biofuels which is based on biomass from food and feed crops, and advanced biofuels which is based on waste feedstocks. Table 12-3 shows an overview of the WtT GHG emissions based on a literature review by Ricardo (2022) and the typical GHG emission from cultivation, processing, transport and distribution in the EU's Renewable Energy Directive (2018). Similar to e-fuels it should be possible to decarbonise the production of biofuels by using renewable electricity. However, since this is not found in the literature review, we have not included this potential in the assessed ranges.

[29] Based on MEPC.308(73) – 2018 Guidelines on the method of calculation of the attained Energy Efficiency Design Index (EEDI) for new ships.

Table 12-3: Overview of the WtT GHG emissions for biofuels. The values do not include a deduction due to the stored biogenic carbon in the fuel. Values in gCO_2e/MJ

Report	Conventional			Advanced		
	Diesel	Methane	Methanol/ Ethanol/ DME	Diesel	Methane	Methanol/ Ethanol/ DME
(Ricardo, 2022)	75–112	53.1	-	8-15	(-61)* 16–28	(-40)* 2–19
(EC, 2018)**	33–63	26–41	20–60	2-17	(-103)* 10–25	15–16
WtT range	33–112	26–53	20–60	2-17	10–25	2–19
WtW range (combined with Table 12-1)	34–116	26–81	20–67***	3-21	10–53	2–26***

** The value in the brackets is the lower value if including methane emission reduction from landfill and liquid manure. This is not included in the WtT ranges.*

*** Includes the provisional default land-use change emissions in Annex VIII of the RED. Includes animal fats and waste cooking oil under advanced biofuels although these are not categorised as advanced feedstocks according to Annex IX of the RED. Excludes methane based on open digestate processes which release methane during production.*

**** Combined with WtT GHG emission factors for methanol.*

The U.S. Environmental Protection Agency (EPA) (U.S. EPA , 2023) has defined four categories of renewable fuels where advanced biofuels must meet a criterion of at least 50% GHG emission reduction (46.5 gCO_2e/MJ), and for cellulosic biofuels at least 60% reduction (37.2 gCO_2e/MJ). The EU's Renewable Energy Directive (RED) sets a criterion of 65% GHG emission reduction (32.9 gCO_2e/MJ) for sustainable biofuels (proposed increased to 70% or 28.2 gCO_2e/MJ) and provides a list of advanced feedstocks which mostly includes waste feedstock and algae. These standards refer to lifecycle or WtW GHG emissions and be expected to promote biofuels with GHG emission below these criteria.

E-FUELS AND BLUE FUELS

E-fuels and blue fuels are all either hydrogen or hydrogen-derivatives such as ammonia, or e-diesel. The hydrogen for e-fuels is produced by electrolysis using electricity that should as far as possibly come from renewable sources such as wind and solar, or from nuclear. The energy can also come from the grid when there is excess production capacity which would otherwise not be used. The hydrogen for blue fuels is produced by methane reforming with CCS with a capture rate of 90% (Brynolf, et al., 2023; DNV, 2022a; IEA, 2020c). Hydrogen for direct use need to be liquefied, while other derivatives such as ammonia or e-diesel requires further processing which increases the energy use. Lindstad et al (2021) reports the WtW energy use for e-ammonia to 84% of liquid e-hydrogen (i.e. a 16% lower energy use), and further for other derivatives containing carbon to 22 to 42% additional energy. This assumes that the carbon capture was done with renewable energy, and also include the energy conversion onboard.

Various standards and regulations are developed or under development, setting GHG emission thresholds for hydrogen. In the US, under the Inflation Reduction Act the threshold for clean hydrogen (e- or blue) that can receive tax credit is 4 kg CO_2e/kgH_2 which is equal to 33.3 gCO_2e/MJ. (Bipartisan Policy Center, 2022)

In the EU, the proposed threshold for renewable fuel of non-biological origin (RFNBO), recycled carbon fuels and sustainable biofuels to be considered for the targets under the Renewable Energy Directive (RED) is at least 70% lifecycle GHG emission savings compared to the fossil fuel comparator of 94 gCO_2e/MJ, which is 28.2 gCO_2e/MJ.[30] In addition, the EU defines criteria for when electricity can be considered renewable and count as zero emission.

The China Hydrogen Alliance defines thresholds for the GHG emission during production to 14.5 gCO_2e/kgH_2 (120 gCO_2e/MJ) for low-carbon hydrogen and to 4.9 gCO_2e/kg H_2 (40.8 gCO_2e/MJ) for clean hydrogen. In

[30] Figures obtained by: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0557 and https://energy.ec.europa.eu/system/files/2023-02/C_2023_1086_1_EN_ACT_part1_v5.pdf

addition, there are criteria use for renewable energy for green hydrogen (Liu, Wan, Xiong, & Gao, 2021). Similarly, the CertifHy project defines labels for green (from renewable sources and low-carbon (non-renewable including nuclear and fossil with CCS) with a threshold of 36.4 gCO_2/MJ (CertifHy, 2023). This is however expected to the be updated when the EU's RED is revised.

For this study we assume that the future blue and e-hydrogen will be produced with lower emissions than the least stringent thresholds in the standards and regulations above (i.e. 40.8 gCO_2e/MJ). Further, we assume that e-fuels can reach zero emissions while blue fuel production is constrained by the GHG emissions from fuel extraction and the carbon capture rate and can only be produced down to 28 gCO_2e/MJ which is the proposed threshold in the EU. Based on this, the WtT emissions in this study are assumed to be 0-41 gCO_2e/MJ for e-ammonia and e-hydrogen and 28-41 gCO_2e/MJ for blue fuels. For e-fuels containing carbon, we increase the upper end GHG emission factor by 22-42%, reflecting the additional energy needed for production of hydrocarbon e-fuels (Lindstad, Lagemann, Rialland, Gamlem, & Valland, 2021).

Table 12-4 shows an overview of the WtT GHG emissions factors of blue and e-fuels.

Table 12-4: Overview of the WtT GHG emissions for e-fuels and blue fuels. Values in gCO_2e/MJ

Report	E-fuels			Blue fuels	
	Hydrogen	Ammonia	Diesel, methane, methanol	Hydrogen	Ammonia
(Ricardo, 2022)	-	0–45	-	-	12.8
(Brynolf, et al., 2023)	1–43	5–36	1–33	8–156	21–54
Sustainable RFNBO – EU RED (proposed)	28.2	28.2	28.2	28.2	28.2
Clean hydrogen – US Inflation Reduction Act	33.2	-	-	33.2	-
Clean hydrogen – China Hydrogen Alliance	40.8			40.8	
WtT range used in this study	0–41		0–58*	28–41	
WtW range (combined with Table 12-1)	0–46	0–55	0–79*	28–46	28–55

** Estimated based on additional 22% (methanol), 24% (methane) and 42% (diesel) energy required for production of hydrogen-derivatives, from Lindstad et al (2021).*

It should be noted that production of blue hydrogen through reforming of fossil natural gas with CCS, at the same time as producing, although separately, hydrocarbon e-fuels with hydrogen from electrolysis and sustainable CO_2 will require two carbon capture processes. It may be more efficient energy and emission-wise to use the natural gas as LNG directly instead of using it for reforming and store the sustainable CO_2 instead. The total stored CO_2 remains the same, while less energy is needed with only one capture process, as well as removing the reforming process, potentially reducing emitted CO_2 further. However, as the carbon capture and storage will then be a separate process from the onboard use of fossil LNG, to achieve a decarbonisation for shipping such optimisation will require a form of offsetting or book-and-claim system. The effect of this is not explored in this study.

ELECTRICITY FOR SHORE POWER

Electricity for shore power is assumed to be provided from the local grid. The WtT emission factor reflects the GHG intensity of the energy used to produce the grid electricity. IEA (2022) reports the current average GHG intensity of major regions in 2020 to between 63-200 gCO_2e/MJ, although in local grids the GHG intensity could be as low as 3 gCO_2e/MJ .[31] As renewable energy is added to the grid, the GHG intensity is expected to be reduced to 2050 (DNV, 2022a).

In this report we assess the WtT GHG emission range for electricity for shore power to 0-200 g CO_2e/MJ. The TtW GHG emission factor is zero.

ONBOARD CCS

There are few literature reviews of emissions and energy use from onboard CCS and a more detailed review has been conducted for this study. Onboard carbon capture rates could achieve the same capture rate of 90% as onshore facilities. However, other considerations such as installation size and energy use could reduce the practical capture rate, as well as the size of the CO_2 storage tanks. During initial testing Wärtsilä has achieved more than 65% capture rate for their system which fits into the existing funnel (CIMAC, 2022). In a case study, MMMCZCS uses an 82% capture rate at 18 to 42% additional energy use depending on fuel and ship type (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022). OGCI & Stena Bulk (2020) estimate a 90% capture rate at 53% additional energy use although without optimising the energy use. In a feasibility study, Einbu et al (2022) find that a 90% capture rate can be achieved with 6-12% additional energy including using thermal energy from the exhaust. Law et al (2021) report a 90% capture rate with 22% additional fuel consumption.

Based on the above, for the purposes of the WtW and TtW assessment as well as the reduction potential and energy demand for the total fleet, we assume in this study a practical capture rate of 70% with a 20% additional energy use for capture and storage. This is a general assumption for the purpose of evaluating the potential for use of CCS to achieve the GHG emission reduction targets in this study. In practice individual ships could use CCS plants with lower or higher capture rates.

To achieve 100% TtW CO_2 emission reduction, the fossil fuel would need to be blended with 30% biofuels or e-fuel. The storage of biogenic CO_2 or from DAC would count as a negative emission and the total TtW GHG emissions would be close to zero. The TtW' factor is the same for both the 100% fossil fuel case and for the 30% biofuel blend case.

To compare the WtW and WtT GHG emissions with other candidate fuels, we adjust for the additional energy needed for capture and onboard storage by multiplying the WtT and TtW emission factors with 1.2. Then 70% of the CO_2 emissions are deducted.

This assessment does not include the emissions on land to transport and permanently store the CO_2. In a complete WtW assessment these emissions should also be included. Further, we have not considered the case where the CO_2 is reused to produce an e-fuel, and the issue of allocating the impact between the ship and the recipient of the carbon dioxide.

SUMMARY

Table 12-5 summarises the review of WtW GHG emission factors for the candidate fuels compared to fossil fuels as a reference. Note the WtW ranges take into account the underlying WtT and TtW ranges per fuel type and do not combine for example worst case methane in the WtT with worst case methanol in the TtW.

The large range of emissions factors identified in the literature review indicates that conditions need to be set both to the production and onboard energy conversion. The WtT have a large spread in particular for the biomass feedstocks, the electricity used for electrolysis to produce e-fuels and the carbon capture rate and storage for blue fuels. The TtW emission factors have a narrower range. In order to achieve the lower range of emissions more advanced energy converters such as fuel cells needs to be used.

[31] Figures obtained by: https://www.statista.com/statistics/1291750/carbon-intensity-power-sector-eu-country/

Table 12-5: Summary of well-to-tank (WtT), tank-to-wake (TtW), tank-to-wake including CO_2 emissions from biogenic cargo and carbon from DAC (TtW'), and well-to-wake (WtW) for fossil and candidate fuels. Values in gCO_2e/MJ

Fuel	**Description**	**Possible fuel types/energy carriers**	**GHG emissions factors**			
			WtT	TtW	TtW'	WtW
Fossil fuels (reference)	*Fossil fuels*	*HFO, LNG, LSFO, MGO*	*10-20*	*55-85*	*55-85*	*71-105*
Biofuels	Fuels made from conventional biomass feedstocks (food and feed crops)	biomethanol biomethane biodiesel	20-112	0-28	55-85	20-116
	Fuels made from advanced biomass feedstocks (e.g. waste, algae)		2-25			2-53
E-fuels	Fuels based on hydrogen produced by electrolysis using renewable or nuclear electricity, with no carbon content	e-hydrogen e-ammonia	0-41	0-14	0-14	0-55
	Fuels based on hydrogen produced by electrolysis using renewable or nuclear electricity, combined with carbon from biogenic sources or direct air capture	e-methanol e-methane e-diesel	0-58	0-28	55-85	0-79
Blue fuels	Fuels based on hydrogen made from fossil energy sources with carbon capture and storage (>90% capture rate)	blue hydrogen blue ammonia	28-41	0-14	0-14	28-55
Electricity	Electricity from grid, produced from a mix of fossil and renewable sources	Electricity provided as shore power	0-200	0	0	0-200
Fossil fuels and onboard CCS	Fossil fuels with onboard CCS.	HFO, LNG, LSFO, MGO	12-24	20-54	20-54	41-65
Fossil fuels blended with biofuels or e-fuels and onboard CCS	Fossil fuels blended with 30% advanced biofuels or e-fuels with onboard CCS.	HFO, LNG, LSFO, MGO – blended with biodiesel, biomethane, e-diesel or e-methane	9-26	0-33	20-54	12-59

APPENDIX 2 : MODELLING ENERGY DEMAND

The total energy demand for international shipping in a certain year is a function of the shipping activity (transport work per year) and the energy intensity (energy used per transport work) and can be expressed as follows:

$$Energy_{BAU,total} = EI_{BAU} \times TW_{BAU}$$

Where:

$Energy_{BAU,total}$: Total required energy in the BAU scenario [EJ]

EI_{BAU}: Energy intensity of the total fleet in the BAU scenario [EJ/trillion tonne-miles]

TW_{BAU}: Seaborne transport work demand in the BAU scenario [trillion tonne-miles]

We calculate the energy required from candidate fuel paths to achieve a certain GHG emission target in a certain year from the total energy need and the GHG intensity of fossil fuels (GHG emissions per MJ) in the BAU scenario. This takes into account that even in the BAU scenario there may be some candidate fuels in the fuel mix. The GHG intensity of the fossil is calculated as follows

$$GHGintensity_{BAU,fossil} = \frac{GHGemission_{BAU}}{Energy_{BAU,fossil}}$$

Where:

$GHGintensity_{BAU,fossil}$: Fossil fuel GHG intensity in the BAU scenario [Gt CO_2e/EJ]

$GHGemission_{BAU}$: Total GHG emissions from the fleet in the BAU scenario [Gt CO_2e]

$Energy_{BAU,fossil}$: Total energy provided by fossil fuels in the BAU scenario [EJ]

The energy required from candidate fuel paths can then be calculated as the total annual energy demand for the shipping fleet minus the maximum energy that can be provided by fossil fuels without exceeding the GHG emission target. The calculation can be expressed as follows:

$$Energy_{scenario,candidate} = Energy_{BAU,total} - \frac{GHGemission_{scenario}}{GHGintensity_{BAU,fossil}}$$

Where:

$Energy_{scenario,candidate}$: Required energy from candidate fuel paths for a specific scenario [EJ]

$GHGemission_{scenario}$: GHG emissions target for the fleet for a specific scenario [Gt CO_2e]

BASELINE

This study uses 2022 as a baseline year for projecting emissions and energy need to 2050. The baseline is calculated using DNV's MASTER model (Mapping of Ship Tracks, Emissions and Reduction potentials) which uses global ship-tracking data from AIS, enriched with ship-specific data from other sources, to model baseline fuel consumption and emissions from ships and fleets. Use of the MASTER model has been described previously (DNV GL, 2019; Mjelde, et al., 2019; Mjelde, et al., 2019).

AIS data provide a detailed and high-resolution overview of current sailing speeds, operating patterns, sailed distances (nautical miles) and time spent at sea by each vessel. The information from AIS is combined with technical databases (e.g. IHS database) for detailed information on the individual ships, such as installed power on main and auxiliary engines, machine configuration (diesel-electric versus diesel-mechanical / direct-driven), specific fuel consumption, ship design speed, tonnage, etc.

The main engine load is calculated based on the ship's design speed and observed actual speed over ground based on AIS signals. The model assumes that the design speed is achieved at 85% of the engine load. The engine loads at other speeds are calculated according to the "Cubic Rule" method where the engine power increases with speed raised to the third power.

The method applied in the MASTER model has been established in cooperation with the Norwegian Coastal Administration. The output of the MASTER model has been validated against actual reported fuel consumption from around 5,000 vessels of all types, showing an overall good correlation.

The scope is according to the voyage-based method. For the purpose of the abatement uptake and correct fleet growth in the fleet modelling, the baseline includes all ships and activities including those trading domestically.

The Fourth IMO GHG study estimated and filled data gaps for ships without matching IMO and MMSI numbers and ship marked as active in the IHS database but without registered AIS data. This study adds Type 3 and Type 4 type ships in the 2022 baseline for the relevant segments according to the share relative to Type 1 and 2 ships given in the detailed results table for 2018 in the Fourth IMO GHG Study (Table 35).

EMISSION CONVERSION FACTORS

The tank-to-wake GHG emissions for ships built to 2022 are calculated based conversion factors from the Fourth IMO GHG study (IMO, 2020), with some adjustments due to availability of data. For CO_2, the conversion factors are a direct function of the carbon content the fuel, while also taking into account that emission of CO_2 from of biogenic carbon or carbon DAC is zero. For CH_4 and N_2O the conversion factors are dependent on the engine type and engine load. For LNG fuelled ships we distinguish between 4-stroke Otto cycle engines, 2-stroke low pressure Otto cycle engines, 2-stroke high pressure diesel cycle engines, and steam turbines. All auxiliary power is assumed to be produced by 4-stroke engines. No correction taking into account that emissions increase at low loads is applied.

For CO_2 and N_2O, the same conversion factors are used also for ships built from 2023. The CH_4 emissions for LNG fuelled engines are improving and for all ships built from 2023 and onwards we use a reduced emissions factor based on a report by Sphera (2021). The conversion factors for CO_2, CH_4 and N_2O are provided in Table 12-6.

Table 12-6: Tank-to-wake emission conversion factors (Sphera, 2021; IMO, 2020)

Fuel	Engine type	CO_2 [gCO_2/g fuel	CH_4 [gCH_4/kWh]		N_2O [gN_2O/kWh]
		All	Built -2022	Built 2023-	All
HFO	All	3.114	0.01	0.01	0.031
LSFO/MGO	All	3.206	0.01	0.01	0.03
LNG	Otto 4-stroke	2.75	5.5	4	0.02
	Otto 2-stroke Low Pressure	2.75	2.1	1	0.02
	Diesel 2-stroke High Pressure	2.75	0.2	0.2	0.02
	Turbine	2.75	0.04	0.04	0.02
Methanol	All	1.375	0.001	0.001	0.003

FLEET MODELLING

The fleet, uptake of energy efficiency technologies and alternative fuels in the BAU scenario have been modelled to 2050 using DNV's GHG Pathway Model, a cost-based modelling tool for developing scenarios for decarbonisation of shipping (DNV, 2022c; DNV GL, 2020; Eide, Chryssakis, & Endresen, 2013; Eide, Longva, Hoffmann, Endresen, & Dalsøren, 2011). The Pathway Model is used for projecting a future fleet and to evaluate the uptake of energy efficiency measures and alternative fuels towards 2050. The projection is used to determine the energy intensity of the fleet and the GHG intensity of the fossil fuel mix, which again is used to calculate the energy demand from candidate fuels.

The Pathway Model comprises the following two core evaluation modules:

The fleet development module, in which the future fleet is simulated by adding and removing ships year-by-year. The objective is to provide the fleet supply capacity corresponding to the seaborne-trade demand projections used as input, taking into account a scrapping rate and lost capacity through speed reduction in the fleet. The starting point for the fleet development is the current fleet for the base year 2019, with associated ship activity deriving from actual ship movement data from the AIS tracking data, and fuel used based on data from the Alternative Fuels Insight (AFI) platform (AFI, 2023). Each newbuild is modelled as a copy of a random ship from the same segment in the 2022 baseline, including its operational profile and, technical particulars, adjusted for increase in the average size of newbuilds. The newbuild will be evaluated taking into account the latest available energy converters and energy efficiency measures.

The abatement uptake module in which the model evaluates available solutions for CO_2 emission reduction on all existing vessels and newbuilds for each year, including alternative fuels, energy efficiency measures, and speed reduction. The ships are fitted with the most cost-effective feasible combinations of measures that fulfil regulatory requirements imposed as input. Possible fuel transitions achieved through drop-in fuels or retrofit of engine and fuel system are added to the model input. The model takes into account measures already implemented since the base year.

The model includes two feedback loops: If speed reductions are adopted by a ship, thereby reducing the transport capacity of the fleet, the fleet development module ensures that additional ships are built to replace the lost capacity. The model will replace all lost transport capacity with newbuilds. In a second feedback loop, uptake of technical measures and fuels results in year-by-year technology learning, which reduces the costs for future installations. The output of the model is vessel specific and provides an overview of energy use, uptake of measures, associated costs, and other parameters.

COST CALCULATIONS

The net present value (NPV_{mg}), in US dollars, is calculated according to the equation below for each available and compliant measure group (*mg*) based on the capital costs (*CapEx*) plus the operational cost (*OpEx*), lost opportunity cost (*SpeedLO*) related to speed reduction, and fuel cost (*FuelEx*), over a certain investment horizon period *p* with discount rate *r*:

$$NPV_{mg} = -\,CapEx - (OpEx + FuelEx + SpeedLO) \times \frac{1-(1+r)^{-p}}{r}$$

Capital expenses include the additional cost of energy efficiency measures, energy converter, fuel system and fuel-storage costs. Operational expenses include all additional costs of operating the equipment, while the fuel expenses include the additional or reduced fuel cost. The lost opportunity cost is an estimated cost to the shipowner of reducing speed. The costs are relative to a ship with baseline energy efficiency measures, no speed reduction and a conventional VLSFO/MGO diesel engine. The discount rate *r* is set to 4%.

SCRAPPING RATES

The Pathway Model takes into account the scrapping of vessels before new vessels are added to match projected demand. Based on historical data and taking into account the range of new regulations (e.g. ballast water, sulphur limits) we assume that each year 3% of the oldest ships in a segment are scrapped, in terms of transport capacity.

INVESTMENT HORIZONS

A shipowner's investment calculation is usually shorter than in a societal perspective that would include the full lifetime of the vessels and measures. In the model, each vessel is randomly assigned a horizon (*p*) based on the distribution for its segment as shown in Table 12-7. The investment horizon used when evaluating measure for existing ships is half the length as when evaluating for newbuilds, assuming that newbuild investments are more long term than subsequent investments (see e.g. Stott 2013).

Table 12-7: Distribution of investment horizon for different segments for newbuilds (NB) and retrofits (RF); based on (DNV, 2012)

Segment	NB: p=4 years RF: p=2 years	NB: p=10 years RF: p=5 years	NB: p=20 years RF: p=10 years
Container and vehicle	20%	60%	20%
Cruise	10%	40%	50%
All other segments	30%	60%	10%

ENERGY EFFICIENCY MEASURES

The GHG Pathway Model does not evaluate the uptake of each single energy efficiency measure (e.g. waste-heat recovery, air-cavity lubrication) due to the interactions between the measures. We instead compile the energy efficiency (EE) measures into five internally consistent packages based on generation and maturity, as presented in Table 12-8. A measure needs to be on a TRL level 10 or 11 in order be considered mature for large scale uptake. The measures included in the different EE packages will depend on the applicability for the ship type in question.

Table 12-8: Energy efficiency (EE) packages used in the GHG Pathway Model (DNV, 2022b)

Energy efficiency package	Maturity	Measures included
Baseline EE	–2015	Average energy efficiency of a vessel built before 2015. Includes basic operational measures, as well as standard hull cleaning, propeller polishing, engine auto-tuning and optimisation of cargo handling systems.
Basic EE	2015–2020	Average energy efficiency of a vessel built after 2015 and until 2020. Includes hull form optimisation, basic machinery improvements, variable frequency drives, shaft motor/generator, and measures to improve hydrodynamic propulsion, such as devices before the propeller and high-efficiency propellers and rudders.
Enhanced EE	2020–2025	Energy efficiency measures expected to be mature between 2020 and 2025. Includes batteries, waste-heat recovery systems, bow shapes optimised for real sea states, variable engine speed and improved steam-plant.
Advanced EE	2025–2030	Energy efficiency measures expected to be mature between 2025 and 2030. Includes, among other measures, air lubrication, hard sails, solar panels, next-generation waste-heat recovery systems, and reduced-ballast design.
Cutting-edge EE	2030–	Measures expected to mature after 2030 are placed in the cutting-edge package, including digital twins and onboard wind turbines.

SPEED REDUCTION

The model applies four different levels of speed reduction: 0%, 10%, 20% and 30%. The speed reduction is relative to the design speed of the fleet in 2015. The resulting reductions in main-engine power for an individual vessel are estimated using the “Cubic Rule” method where the engine power increases with speed raised to the third power. The model assumes that the distance sailed per year is reduced by the same amount as the speed reduction, and without changing time spent at sea and in port. Speed reduction comes at a cost – a lost opportunity cost. As the transport capacity of the vessel is reduced, its earning capacity also declines. More vessels would have to be built and operated to cover for the lost capacity. In addition, the cargo owner has increased costs due to capital being tied up through longer sailing times (Longva & Sekkesæter, 2021).

FUEL TECHNOLOGIES

Fuel technology costs include the cost of energy converter and fuel-supply system in USD per kilowatt (kW) of installed power, and the cost of the fuel-storage system in USD per gigajoule (GJ) of energy storage capacity, which is a function of the vessel's design range.

Retrofitting to the specific fuel technology is assumed to cost an additional 50%. We have not considered opportunity costs related to loss of cargo-space due to additional volume required for fuel storage, nor lost income during installation.

FUEL PRICES

We have estimates realistic spans in production and distribution costs per fuel based on a systematic analysis of different fuel-supply chains and the most important cost drivers for candidate fuels (Brynolf et al., 2018; DNV, 2022; EC, 2017; Nelissen D. et al., 2020). The costs are based on bottom-up estimates of levelised cost of production and distribution for different fuels and have a long-term focus, e.g. the energy crisis and recent LNG price spikes, are not captured.

We recognise that there are large uncertainties in future prices of candidate fuels. The particular scenario applied in the fleet modelling, reflects a future where biomass is scarce, and high availability of renewable electricity for producing e-fuels and falls within the range identified in the literature review in APPENDIX 1. It should be noted that for the purpose of the BAU scenario the prices of candidate fuels have little impact as there are few policies in place that incentivise the use of these fuels.

Table 12-9 shows the projected fuel prices used in the modelling.

Table 12-9: Fuels used in the modelling with projected fuel prices to 2050

Fuel	Fuel prices (USD/GJ)			
	2022	2030	2040	2050
LSFO/MGO	14.5	14.3	15.5	15.4
HFO+scrubber	13.1	12.9	14.0	13.9
LNG	12.6	12.2	12.0	11.4
LPG	18.6	17.7	16.7	15.9
e-MGO	47.5	43.1	37.7	33.1
liquefied e-methane	43.4	40.2	35.0	30.5
e-methanol	40.8	37.1	32.9	29.3
bio-MGO	30.8	33.5	37.6	42.8
liquefied biomethane	28.4	29.0	30.1	32.1
biomethanol	29.1	30.2	32.3	35.4

Key: Biofuel (bio-); synthetic fuels (e-); gigajoules (GJ); heavy fuel oil (HFO); low sulphur fuel oil (LSFO); liquefied natural gas (LNG); liquefied petroleum gas (LPG); marine gas oil (MGO).

APPENDIX 3 : SELECTING SEABORNE TRANSPORT DEMAND PROJECTIONS

The Fourth IMO GHG Study (see Section 4.2.2 in that study) seaborne transport demand projections for non-energy products are based on long-term socio-economic projections using the Shared Socioeconomic Pathways (SSPs) developed by the IPCC, as well as the OECD long-term baseline projection. Global GDP is used in the logistic model and country GDP and country population in the gravity model. Transport demand projections for energy products (oil, coal, gas) are based on energy consumption projections from the SSPs and Representative Concentration Pathways (RCPs) integrated assessment scenarios developed by the IPCC.

For the non-energy transport demand, according to the GHG study, SSP5 has the highest economic growth followed by SSP1, SSP2, SSP4 and OECD. However, the study notes that SSP1 and SSP5 have very optimistic assumption on future economic developments. According to the study, gravity-model projections are less sensitive to economic growth and generally gives lower transport demand in 2050 than the corresponding logistics-model projections. To provide a plausible range for this study, SSP1 and SSP5 are not considered, and a gravity-based projection is used for the low growth scenario and a logistics-model projection is used for the high growth scenario.

For the energy products transport demand, it may be argued that the most stringent shipping decarbonisation pathways will coincide with the world following a RCP1.9 scenario while the BAU pathway is more consistent with a RCP4.5 or even higher concentration scenario. However, in order to reduce complexity and make the results comparable across decarbonisation pathways, the same high and low seaborne transport demand scenarios are applied for all business as usual and decarbonisation pathways. RCP2.6 is selected for both the high and low projections as this is reasonably consistent with all decarbonisation pathways.

Based on the above considerations, this study uses SSP2_RCP2.6_L for the high seaborne trade growth scenario, and OECD_RCP2.6_G for the low growth scenario. OECD_RCP2.6_G projects a 39% growth and SSP2_RCP26_L an 81% growth in seaborne trade from 2022 to 2050 (see Table 12-10). These two scenarios provide a reasonable range on expected future shipping activity.

The Fourth IMO GHG study projects seaborne transport demand from 2018 to 2050. As this study uses 2022 as the base year, we use the estimated seaborne trade level in 2022 from Clarkson (2023), and then apply the same annual growth rates per segment as in the Fourth IMO GHG study demand projections from 2022 to 2050. This means that the projected seaborne transport demand in 2050 will be lower than projected in the Fourth IMO GHG study, in particular for the high growth scenario, as the actual seaborne transport demand in 2022 was also lower than projected.

Table 12-10: Current (Clarksons Research, 2023) and projected seaborne transport demand in 2050 per cargo type for the high and low growth scenarios

Cargo type	**Current**	**Low growth OECD_RCP2.6_G**		**High growth SSP2_RCP2.6_L**	
	Transport work in 2022 [bill tonne-miles]	Growth 2022-2050 [%]	Transport work in 2050 [bill tonne-miles]	Growth 2022-2050 [%]	Transport work in 2050 [bill tonne-miles]
Bulk	28,457	55 %	44,069	115 %	61,258
Tank	14,425	-12 %	12,657	-7 %	13,443
Gas	2,423	15 %	2,789	145 %	5,926
Container	8,340	66 %	13,845	134 %	19,556
Other unitized	4,802	65 %	7,904	-18 %	3,949
Total	58,447	39 %	81,351	81 %	105,873

The demand in 2050 was calculated using percentage growth between 2022 and 2050 from the scenarios in the Fourth IMO GHG study. Note that the numbers include both international and domestic shipping.

APPENDIX 4 : ESTIMATING FUTURE ENERGY AVAILABILITY

This study uses a two-step approach for assessing the future availability of candidate fuels for shipping (Figure 12-1):

In Step 1, we assess the future availability of candidate fuels for the transportation sector[32] in 2030, 2040 and 2050. Different approaches have been applied, depending on the year in question:

- Short-term availability assessment (2030): Estimated based on a mapping of announced, planned, and existing candidate fuel production projects
- Long-term availability assessment (2040 and 2050); Estimated based on a literature review of energy system forecasting studies.

In Step 2, we do a high-level evaluation on how much candidate fuel can be made available for shipping in 2030, 2040 and 2050.

Figure 12-1 Methodology for estimating availability of candidate fuels for shipping

Step 1:

Assessment of future supply of candidate fuels in 2030, 2040, and 2050

Scope: fuel products relevant for the transportation sector

Year	Basis
2030	Announced, planned or existing projects
2040	Forecasting studies
2050	

→

Step 2:

High-level evaluation of candidate fuel availability for shipping

Scope: shipping sector

SHORT-TERM CANDIDATE FUEL AVAILABILITY (2030)

For the short-term availability estimate (2030), we base our estimate of fuel production capacity on existing, planned, and announced projects. To our knowledge, there exists no public comprehensive database containing data on all biofuel, blue fuel, and e-fuel production projects. As a result, we had to compile data from various sources. The sources include data-sets and reports, each drawing on a variety of media articles, press announcements, and other industry literature and studies. The result is a diverse database, giving quite comprehensive data on existing, planned, or announced fuel production projects globally, although we recognise that there may be projects that are not included in our overview.

When combining several sources of information, it is important to avoid overlap of data which could lead to double-counting. To avoid this, we have used one main-source of information per candidate fuel. Other sources have been added in order to capture specific projects or specific fuel production pathways not covered by the main source. For instance, since (IEA Bioenergy, 2022) does not cover biomethane production in Brazil, we added (ANP, 2023) as another source for this particular fuel production pathway.

Relevant sources applied for each candidate fuel is shown in Table 12-11.

[32] Subsectors include road transportation, marine shipping, aviation, and rail.

Table 12-11 Sources for production projects per candidate fuel

Fuel category	Candidate fuel	Main source	Other sources
Biofuels	bio-based liquid fuels[33]	(IEA Bioenergy, 2022)	(EIA, 2022b); (EIA, 2022c); (ANP, 2023)
	biomethanol	(IEA Bioenergy, 2022)	
	bioethanol	(IEA Bioenergy, 2022)	(EIA, 2022a); (ANP, 2023)
	biomethane[34]	(IEA Bioenergy, 2022)	(Argonne, 2021); (ANP, 2023)
	bio-hydrogen	(IEA Bioenergy, 2022)	
	bio-ammonia	(IEA Bioenergy, 2022)	
E-fuels	e-MGO	(IEA, 2022e)	
	e-methane	(IEA, 2022e)	
	e-methanol	(IEA, 2022e)	(IRENA, Methanol Institute, 2021); (Methanol Institute, 2023)
	e-ammonia	(IEA, 2022e)	(DNV, 2023)
	e-hydrogen[35]	(IEA, 2022e)	
Blue fuels	blue ammonia	(IEA, 2022e)	
	blue hydrogen	(IEA, 2022e)	

When compiling the different data-sources we identified some data-gaps, in particular, for biofuels where we found data-availability to generally be more fragmented than for e-fuels and blue fuels. Most importantly, we lack data on announced projects for production of biofuels made from food or feed crops (also known as conventional biofuels). There may also be projects that are not captured in any of the sources. An implication of this is that the production capacity pipeline may be underestimated.

It is also important to note the following regarding the compiled database used in this study:

We have only included projects producing or aiming to produce fuels at significantly lower well-to-wake GHG emissions than conventional fossil fuels. That said, GHG emissions could still occur during production due, for example, to production plants utilising grid electricity with significant carbon footprint. The capture of biogenic carbon or carbon from DAC for carbon-based e-fuels could also involve significant emissions. In this work, however, we assume that there are large incentives for operators of the different projects to produce fuels with the lowest GHG emissions possible, and over time the production emission will reduce.

The compiled database contains information on production capacity of candidate fuels. Unless plants are running at maximum capacity, the utilisation of the plants will be less than 100% and the actual availability of candidate fuels will be lower than the production capacity.

[33] Includes bio-crudes, bio-oil, FAME, and HVO.

[34] Production of upgraded biogas has been taken into consideration.

[35] We only include production of compressed (>200 bar) and liquefied hydrogen.

There will be potential energy losses associated, for example, with compressing or liquefying hydrogen, ammonia synthesis, to make it suitable for use on board ships. This is not captured in the production capacities given in the database which is a mix of various energy carriers like hydrogen, ammonia, and methanol.

The candidate fuel production projects in our database are at different points in their development phases. While some projects are only on the concept stage, and no final investment decision has been taken yet, others are under construction or operational. In order to address this, we have categorised each fuel production project into five different categories (in order of maturity):

- *Operational:* project is already in operation
- *Under construction:* project is under construction and will become operational after the construction period.
- *Post-FID:* Final investment decision (FID) taken for the project.
- *Pre-FID:* FID has not been taken and project is in the Front-end engineering and design (FEED) phase or due to enter that phase soon.
- *Concept*: feasibility study or conceptual design for the project is being assessed.

LONG-TERM CANDIDATE FUEL AVAILABILITY (2040 AND 2050)

The assessment of the long-term availability to 2040 and 2050 of candidate fuels to the transportation sector are based on a review of energy system forecasting studies (see Table 12-12). The following boundary conditions of our review were applied:

Transportation sector. Only the supply for use of candidate fuels in the transportation sector has been investigated. The transportation sector includes road-transportation, rail, aviation, and shipping. In 2021, it represented 27% of final energy consumption (DNV, 2022a).

Scenarios from the forecasting studies are based on widely different assumptions, especially with respect to decarbonisation requirements and ambitions. Because of this, we do a grouping of the scenarios we consider in the study:

Current policies: scenarios where no decarbonisation ambitions are imposed. Such scenarios can typically represent a “most likely” outcome given current adopted regulations and policies. These scenarios are not consistent with 1.5–2.0 C limitation on global warming compared to pre-industrial levels.

Decarbonisation ambitions: scenarios consistent with a limitation of global warming to a 1.5–2.0 C increase. There are still significant differences between the scenarios; while some decarbonise fully by 2050, others do not until decades lates. However, they are characterised by assumed stronger polices and ‘forcing’ renewable energy production increase in order to achieve the target, as opposed to the current policies scenarios. It should be noted that some of the studies found in this category, focus on what it takes in order to achieve decarbonisation, rather than what the realistic outcome is.

The scenarios considered are given in Table 12-12.

Table 12-12 Overview of forecasting studies and scenarios used in availability assessment, grouped into Decarbonisation ambitions and Current policies scenarios

Source	Scenario-name	Category
(BP, 2022)	Accelerated	Decarbonisation ambitions

Source	Scenario-name	Category
(Equinor, 2022)	Bridges	
(IEA, 2022c)	Announced pledges	
(Bloomberg, 2022)	Net zero scenario	
(IRENA, 2022)	1.5°C scenario	
(Shell, 2021)	Sky scenario 1.5°C	
(BP, 2022)	Net Zero	
(IEA, 2022c)	Net Zero Emissions by 2050	
(DNV, 2022a)	Pathway to Net Zero Emissions	
(Shell, 2021)	Waves	Current trajectories
(Shell, 2021)	Islands	
(DNV, 2022a)	Most likely	
(BP, 2022)	New momentum	
(Equinor, 2022)	Walls	
(ExxonMobil, 2022)	Outlook for energy	
(IEA, 2022c)	Stated policies	

From each scenario, we extracted the volume of biofuels, e-fuels, and blue fuels supplied to the transportation sector. In each case, the volume of biofuels includes those produced from both conventional and advanced feedstocks. Since each study provides varied level of detail regarding the type of fuel supplied to the transportation sector, in particular, the split between e-fuels and blue fuels, we had in some cases to estimate the split based on total production of blue hydrogen and electro-based hydrogen.

AVAILABILITY OF ADVANCED BIOFUELS

Due to the potential impact on ILUC and well-to-wake GHG emissions, we have divided biofuel production into advanced and conventional, based on feedstock applied for production. It is recognised that type of biomass and impact on in-direct land-usage change (ILUC) will be a key determinant of lifecycle GHG emissions (see APPENDIX 1 for a literature review of WtW GHG emissions from various biofuels), though the regulatory environment with respect to biomass source will differ between regions. For example, according to the U.S. Environmental Protection Agency (EPA), sugarcane ethanol meets the sustainability criteria for advanced biofuels with a threshold of at least 50% lifecycle GHG reductions (U.S. EPA , 2023). The EU Renewable Energy Directive (RED II), on the other hand, is more restrictive and considers only ethanol made from biomass sources such as straw and bagasse as advanced, and the threshold for being considered sustainable is at least 65% GHG reduction (EC, 2018). The proposed revision of the EU RED framework (European Commission, 2023) targets an advanced biofuel share of 25% in 2030 and increases the GHG reduction threshold to 70%, which will serve to boost advanced biofuel production and increase its share in the total biofuel mix.

In our assessment of candidate fuel availability, we have included all available data on production capacity for biofuels, both using food and feed crop feedstocks (herein referred to as conventional feedstocks) and non-food and feed crop feedstocks (herein referred to as advanced feedstocks), before assessing how much of this could come from advanced feedstocks. Another reason to not exclude certain biofuels with specific production pathways from our production capacity estimate, is to make sure that it is aligned with projected biofuel uptake for transportation (ref. to the long-term availability estimate for 2040 and 2050).

Table 12-13 gives the share of advanced liquid biofuels from different forecasting scenarios. Scenarios has been categorised by their respective decarbonisation requirements and ambitions (see Section 2 for more details), with the addition of FAO's Agricultural Outlook study within the Current trajectories category.

Table 12-13 Sources providing forecast on share of liquid biofuels produced from advanced feedstocks

Source	Scenario	Scenario category	Share of advanced feedstocks in biofuel production		
			2030**	2040	2050
(FAO, 2022)	-	Current trajectories	10%	-	-
(IEA, 2022c)	Stated policies		21%	34%*	46%
(IEA, 2022c)	Net Zero Emissions by 2050	Decarbonisation ambitions	41%	66%*	90%
(IEA, 2022c)	Announced pledges		34%	55%*	75%
Median – current trajectories			15.5%	34%	46%
Median – decarbonisation ambitions			37.5%	60.5%	73.5%

**based on linear interpolation between 2030 and 2050*

Besides the sources given in the above table, it is worth noting that:

- In 2021, liquid biofuels produced via non-food or feed feedstocks (also known as advanced biofuels) made up approximately 8% of total biofuel production (IEA, 2022d), or approximately 0.4 EJ. Meanwhile, the current production of biomethane and biogas is already pre-dominantly based on advanced feedstocks such as animal manure and municipal solid waste (IEA, 2020b).
- IEA notes that in recent years, the number of facilities producing advanced biofuels has increased sharply (IEA Bioenergy, 2021).
- BP reports that the vast majority of bioenergy in their three forecasting scenarios (Accelerated, Net Zero, and New Momentum), is sourced through residual sources (i.e. advanced feedstock sources) (BP, 2022).
- Shell gives a very limited share of advanced biofuel production in 2030, for their forecasting scenarios (Sky 1.5, Waves, and Islands). In the longer term towards 2050, the share of advanced biofuels rises towards ~70% (Sky 1.5) and ~50% (Waves), while remaining very limited in the Islands scenario (Shell, 2021).

APPENDIX 5 : LIST OF PORT AND INFRASTRUCTURE DEVELOPMENT PROJECTS

Table 12-14: List of port and bunkering projects

Project name	Initiative maker	Project type	Fuel type	Region	Project status
Shanghai – LA corridor	Industry or NGO	Green corridor	Unknown	North America, Asia	Planning
Pacific Northwest-Alaska Green Corridor	Public-private	Green corridor	Unknown	North America	Feasibility
Chilean Green Corridor Network	Public-private	Green corridor	Unknown	South America	Feasibility
Great Lakes – St. Lawrence Seaway System Green Shipping Corridor Network	Government	Green corridor	All or multiple options	North America	Feasibility
Antwerp – Montreal (North Atlantic Green Shipping Corridor)	Port	Green corridor	Unknown	North America, Europe	Initiation
Halifax – Hamburg corridor	Port	Green corridor	All or multiple options	North America, Europe	Initiation
Clean Tyne Corridor	Public-private	Green corridor	Unknown	Europe	Initiation
Dover-Calais and Dover-Dunkirk Ferry Corridor	Public-private	Green corridor	Electric	Europe	Initiation
Gothenburg – North Sea Port (Ghent)	Port	Green corridor	All or multiple options	Europe	Initiation
H_2 powered North Sea Crossing	Public-private	Green corridor	Hydrogen	Europe	Initiation
Gothenburg – Rotterdam corridor	Port	Green corridor	All or multiple options	Europe	Initiation
European Green Corridor Network	Industry or NGO	Green corridor	All or multiple options	Europe	Feasibility
Nordic Regional Corridors	Public-private	Green corridor	Unknown	Europe	Feasibility
Decatrip	Public-private	Green corridor	Unknown	Europe	Initiation

Project name	Initiative maker	Project type	Fuel type	Region	Project status
Green Corridors Spain	Government	Green corridor	Unknown	Europe	Feasibility
Rotterdam- Singapore Green and Digital Corridor	Public-private	Green corridor	All or multiple options	Europe, Asia	Feasibility
SILK Alliance	Industry or NGO	Green corridor	Unknown	Asia, Africa, Oceania	Planning
Australia – East Asia Iron Ore	Industry or NGO	Green corridor	Ammonia	Asia, Oceania	Feasibility
QUAD Shipping Taskforce /Green Shipping Network	Government	Green corridor	All or multiple options	North America, Asia, Oceania	Feasibility
Gulf of Mexico	Industry or NGO	Green corridor	Unknown	North America	Initiation
Los Angeles-Long Beach – Singapore Green and Digital Shipping Corridor	Public-private	Green corridor	Unknown	North America, Asia	Initiation
ROK-USA Green Corridor	Public-private	Green corridor	Unknown	North America, Asia	Feasibility
Rotterdam - West-coast Norway Green Corridor	Public-private	Green corridor	Methanol	Europe	Initiation
Busan-Seattle/Tacoma	Government	Green corridor	Unknown	North America, Asia	Feasibility
Green Suez Canal	Industry or NGO	Green corridor	Unknown	Africa, Asia	Initiation
P2XFloater: floating production unit for green ammonia at industrial scale	Industry or NGO	Bunkering infrastructure	Ammonia	Europe	Planning
Ammonia Fuel Bunkering Network for marine sector	Industry or NGO	Bunkering infrastructure	Ammonia	Europe	Planning
Port of Newcastle Hydrogen Hub Feasibility Study	Public-private	Bunkering infrastructure	Hydrogen	Oceania	Planning
Tiwi H_2	Industry or NGO	Bunkering infrastructure	Hydrogen	Oceania	Planning
Ammonia as a marine fuel in Singapore	Industry or NGO	Bunkering infrastructure	Ammonia	Asia	Planning

Project name	Initiative maker	Project type	Fuel type	Region	Project status
Singapore ammonia marine fuel supply chain study	Industry or NGO	Bunker vessel	Ammonia	Asia	Feasibility
Exploring Ammonia Fuel Bunkering in Singapore	Industry or NGO	Bunkering infrastructure	Ammonia	Asia	Feasibility
MoU ammonia and LPG bunkering in Singapore	Industry or NGO	Bunkering infrastructure	Ammonia	Asia	Feasibility
Hydrogen Highway Project	Public-private	Bunkering infrastructure	Hydrogen	Europe	Planning
Aurora	Industry or NGO	Bunkering infrastructure	Hydrogen	Europe	Planning
Power System As A Service	Industry or NGO	Bunkering infrastructure	All or multiple options	Europe	Planning
HyEnergy Project	Industry or NGO	Bunkering infrastructure	Hydrogen	Oceania	Planning
Green Ammonia Berlevåg	Industry or NGO	Bunkering infrastructure	Hydrogen	Europe	Planning
NYK ammonia-fuelled ammonia gas carrier and Ammonia Floating Storage and Regasification Barge	Industry or NGO	Bunkering infrastructure	Ammonia	Asia	Planning
Mabanaft looking to provide ammonia bunkering for Hapag-Lloyd	Industry or NGO	Bunkering infrastructure	Ammonia	North America, Europe	Planning
Port of Corpus Christi to become green hydrogen hub	Industry or NGO	Bunkering infrastructure	Hydrogen	North America	Planning
The Keel Laying of The First Ship In The World to Sail Entirely on Hydrogen, The Neo Orbis	Port	Bunkering infrastructure	Hydrogen	Europe	Planning
Hydrogen pipeline connecting IJmuiden and Amsterdam. (The Port of Amsterdam and Gasunie)	Port	Bunkering infrastructure	Hydrogen	Europe	Planning
Amsterdam to Get Solid-Hydrogen Fuel Test Vessel in 2023	Industry or NGO	Bunkering infrastructure	Hydrogen	Europe	Planning
MoU to develop large-scale hydrogen import facilities at the port of Amsterdam	Industry or NGO	Bunkering infrastructure	Hydrogen	Europe	Planning

Project name	Initiative maker	Project type	Fuel type	Region	Project status
OCI and Unibarge developing Europe’s first green methanol bunker barge	Industry or NGO	Bunker vessel	Methanol	Europe	Planning
OljOla & Stena JV Methanol BV	Industry or NGO	Bunker vessel	Methanol	Europe	Initiation
Methanol BV - Global Energy Trading	Industry or NGO	Bunker vessel	Methanol	Asia	Planning

APPENDIX 6 : TECHNOLOGY AND COMMERCIAL READINESS LEVELS 2022-2050

The tables in this appendix detail the technologies, measures, fuel production stages and fuel pathways assessed for technical and commercial readiness in Section 3. For each technology the tables provide:

- The technical and commercial readiness level as evaluated according to the scale of TRL and CRL set out in Figure 3-1
- The potential for the technology/measure to be applied to existing vessels (retrofit) according to:

Potential for existing vessels (retrofit)	
No	Technology inherent to ship design
Unlikely	Retrofit unlikely to be possible/practical short of major rebuild
Limited	Retrofit potential limited or compromised benefit; challenges and costs likely to be high
Good	Retrofit possible but may need time to become technically/commercially viable
Excellent	Retrofit possible with similar technical/commercial readiness to new build

- The key sources used in evaluating the readiness

The evaluations used the assessments of internal Ricardo and DNV experts and feedback from the expert consultation interviews as well as the published sources listed.

Table 12-15: Forecast of readiness of vessel design technologies

Technology	2022	2025	2030	2035	2040	2050	Potential for existing vessels	Sources
Vessel construction weight	11	11	11	11	11	11	No	(Ricardo, 2022)
Vessel hull dimensions optimised	11	11	11	11	11	11	No	(Ricardo, 2022)
Bulbous bow	11	11	11	11	11	11	Excellent	(Liu, Zhang, Sun, & Li, 2014), (Babicz, 2008)
Bow thruster tunnel optimisation	11	11	11	11	11	11	Limited	(Ricardo, 2022)
Hull coatings	10	11	11	11	11	11	Excellent	(Ricardo, 2022; Clayton, 2021)
Interceptors (trim control)	10	10	11	11	11	11	Excellent	(Ricardo, 2022; Wärtsilä, 2008)
Ducktail waterline extension	10	11	11	11	11	11	Excellent	(Wärtsilä, 2008; Ricardo, 2022)

Technology	2022	2025	2030	2035	2040	2050	Potential for existing vessels	Sources
Air lubrication	9	10	10	11	11	11	Excellent	(ABS, 2019; Silverstream Technologies, 2023)
Air lubrication	9	10	10	11	11	11	Excellent	(ABS, 2019; Silverstream Technologies, 2023)
Ballast/trim optimisation	11	11	11	11	11	11	Excellent	(Ricardo, 2022)
Wave power bow foil	8	9	10	11	11	11	Excellent	(Seatech Consortium, 2023) (Wavefoil, 2023)

Table 12-16: Forecast of readiness of propulsion assistance and efficiency technologies

Technology	2022	2025	2030	2035	2040	2050	Potential for existing vessels	Sources
Large Area Propellers	11	11	11	11	11	11	Excellent	(Ricardo, 2022; Knutsson & Larsson, 2011)
Contra-rotating propellers	11	11	11	11	11	11	Excellent	(Ricardo, 2022) (Jukola & Ronkainen, 2006)
Podded thrusters	11	11	11	11	11	11	Excellent	(Carlton, 2012; Eyres & Bruce, 2012)
Ducts	11	11	11	11	11	11	Excellent	(Ricardo, 2022; Bertram, Chapter 3 - Resistance and Propulsion, 2012)
Pre-swirl	11	11	11	11	11	11	Excellent	(Ricardo, 2022; Gougoulidis & Vasileiadis, 2015)
Post-swirl fins and rudder bulbs	11	11	11	11	11	11	Excellent	(Ricardo, 2022; ABS, 2011)
Waste heat recovery (advanced)	9	10	11	11	11	11	Excellent	(The Maritime Executive, 2021; Wee, 2022; IMO-GLOMEEP, 2023; CLIMEON, 2022; Vahvanen, 2020)

Table 12-17: Forecast of readiness and availability of vessel operation efficiency technologies

Technology	2022	2025	2030	2035	2040	2050	Potential for existing vessels	Sources
Speed reduction	11	11	11	11	11	11	Excellent	(Degiuli, Martic, Farkas, & Gospic, 2021; Lee, Lee, & Zhang, 2015; Mallidis, Iakovou, Dekker, & Vlachos, 2018)
Advanced autopilots	11	11	11	11	11	11	Excellent	(Ricardo, 2022)
Autonomous shipping	6	7	8	9	10	11	No	(Ricardo, 2022; YARA, 2022; Makkonen, Nordberg-Davies, Saarni, & Huikkola, 2022; Koscielecki, 2019)
Advanced power demand management	10	10	11	11	11	11	Excellent	(Ricardo, 2022)

Table 12-18: Forecast of readiness and availability of wind assistance technology

Technology	2022	2025	2030	2035	2040	2050	Potential for existing vessels	Sources
Flettner rotors	9	10	10	11	-	-	Excellent	(IEA, 2020a; Chou T. , Kosmas, Acciaro, & Renken, 2021; IMO, 2022a; ANEMOI Marine, 2023)
Towing kites	8	9	-	-	-	-	Excellent	(IEA, 2020a; Chou T. , Kosmas, Acciaro, & Renken, 2021; IMO, 2022a)
Sails-rigid/hard	8	9	10	-	-	-	Limited	(IEA, 2020a; Chou T. , Kosmas, Acciaro, & Renken, 2021; IMO, 2022a)
Sails – soft and hybrid	7	8	-	-	-	-	No	(Chou T. , Kosmas, Acciaro, & Renken, 2021; IMO, 2022a)
Suction wing	8	9	9	-	-	-	Excellent	(Chou T. , Kosmas, Acciaro, & Renken, 2021; IMO, 2022a)

Technology	2022	2025	2030	2035	2040	2050	Potential for existing vessels	Sources
Hull form wind assistance	3	-	-	-	-	-	No	(IMO, 2022a)

Table 12-19: Forecast of readiness and availability of shore power and electrical assistance

Technology	2022	2025	2030	2035	2040	2050	Potential for existing vessels	Sources
Shore power	10	10	11	11	11	11	Excellent	(GloMEEP, 2022; British Ports Association, 2020)
Solar panels	8	9	10	-	-	-	Excellent	(Prevljak, 2021; Ricardo, 2022; Eco Marine Power Co. Ltd., 2022)
Wind turbines	3	3	-	-	-	-	Excellent	(IMO, 2022a)

Table 12-20: Forecast of readiness and availability of biofuel production stages and overall pathways

Technology	2022	2025	2030	2035	2040	2050	Sources
Transesterification [biodiesel FAME]	11	11	11	11	11	11	(Concawe, Aramco, 2022; EMSA/ABS, CE-DELFT, & ARCSILEA, 2022)
Hydroprocessing [biodiesel HVO/HEFA]	10	11	11	11	11	11	(EMSA/ABS, CE-DELFT, & ARCSILEA, 2022; Norwegian Ministry of Climate and Environment, 2022; Oxford Research, 2021; Concawe, Aramco, 2022)
Fermentation + hydrolysis [Ethanol/Butanol]	11	11	11	11	11	11	(EMSA/ABS, CE-DELFT, & ARCSILEA, 2022; EMSA/ABS, CE-DELFT, & ARCSILEA, 2022)
Next generation algae biofeedstock	5	6	6	-	-	-	(Lloyd's Register (UMAS), 2023; EMSA/ABS, CE-DELFT, & ARCSILEA, 2022; Concawe, Aramco, 2022)
Anaerobic digestion [biomethane/biogas]	10	10	11	11	11	11	(Ricardo, 2022; Oxford Research, 2021; Norwegian Ministry of Climate and Environment, 2022)
Biogas upgrading [biomethane + CO_2]	11	11	11	11	11	11	(Ricardo Internal Review, 2022)

Technology	2022	2025	2030	2035	2040	2050	Sources
Gasification or pyrolysis of wood/waste	9	10	10	11	11	11	(Norwegian Ministry of Climate and Environment, 2022; EMSA/ABS, CE-DELFT, & ARCSILEA, 2022)
Methanol synthesis [methanol]	10	11	11	11	11	11	(Oxford Research, 2021; IRENA, Methanol Institute, 2021; CIMAC, 2020; Global Maritime Forum, 2022)
Biodiesel (overall pathway)	10	11	11	11	11	11	Ricardo experts, consulted experts
Biomethane (overall pathway)	9	10	11	11	11	11	(Lloyd's Register (UMAS), 2023; Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021)
Biomethanol (overall pathway)	9	10	10	11	11	11	(Lloyd's Register (UMAS), 2023; IRENA, Methanol Institute, 2021; Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021; Shell, 2020a; Lloyd's Register (UMAS), 2020)

Table 12-21: Forecast of readiness and availability of e-fuel production stages and overall pathways

Technology	2022	2025	2030	2035	2040	2050	Sources
Electrolysis [green/pink hydrogen]	9	11	11	11	11	11	(Ricardo, 2022; EMSA/ABS, CE-DELFT, & ARCSILEA, 2022; CIMAC, 2020; IEA, 2022b; IRENA, 2018)
Haber Bosch process [ammonia]	10	10	11	11	11	11	(Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022; Oxford Research, 2021; EMSA/ABS, CE-DELFT, & ARCSILEA, 2022; CIMAC, 2020)
Carbon capture – point source (biogenic)	9	9	10	11	11	11	(Global Maritime Forum, 2022)
Carbon capture – point source (fossil)	6	9	10	-	-	-	(DNV GL, 2020)
Carbon capture – direct air	7	9	9	10	11	11	(DNV GL, 2020; CIMAC, 2020; IEA, 2022a)
Sabatier process (methanation) [methane]	10	11	11	11	11	11	(CIMAC, 2020; Samsatli, 2018; ACS Energy, 2021)

Technology	2022	2025	2030	2035	2040	2050	Sources
Methanol synthesis [methanol]	10	11	11	11	11	11	(Oxford Research, 2021; IRENA, Methanol Institute, 2021)
Fischer Tropsch [synthetic diesel]	9	9	10	11	11	11	(Oxford Research, 2021; CIMAC, 2020; Concawe, Aramco, 2022; EMSA/ABS, CE-DELFT, & ARCSILEA, 2022; Samsatli, 2018)
Green hydrogen (overall pathway)	9	10	11	11	11	11	(Lloyd's Register (UMAS), 2023; Oxford Research, 2021; Norwegian Ministry of Climate and Environment, 2022; Wärtsilä, 2020b; IEA, 2021b; IRENA, 2018; Ammonia Energy Association, 2023)
Green ammonia (overall pathway)	8	9	10	11	11	11	(Lloyd's Register (UMAS), 2023; Oxford Research, 2021; Norwegian Ministry of Climate and Environment, 2022; EMSA/ABS, CE-DELFT, & ARCSILEA, 2022; DNV, 2022d; IRENA, AEA, 2022; Ammonia Energy Association, 2023; Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022; Kiwi AG, 2023; Yugo & Soler, 2019)
E-methane (overall pathway)	7	7	9	-	-	-	(Concawe, Aramco, 2022; EMSA/ABS, CE-DELFT, & ARCSILEA, 2022)
E-methanol (overall pthway)	8	9	10	11	11	11	(Lloyd's Register (UMAS), 2023; Norwegian Ministry of Climate and Environment, 2022; IRENA, Methanol Institute, 2021; Global Maritime Forum, 2022)
E-diesel (overall pathway)	9	9	10	11	11	11	(Concawe, Aramco, 2022; EMSA/ABS, CE-DELFT, & ARCSILEA, 2022)

Table 12-22: Forecast of readiness and availability of blue fuel production stages and overall pathways

Technology	2022	2025	2030	2035	2040	2050	Sources
SMR with carbon capture [Blue Hydrogen]	8	10	10	11	11	11	(Ricardo, 2022; CIMAC, 2020; IEA, 2021b)

Technology	2022	2025	2030	2035	2040	2050	Sources
ATR with Carbon Capture [Blue hydrogen]	8	10	11	11	11	11	(IEA, 2021b)
Pyrolysis of methane [Turquoise hydrogen]	7	8	9	-	-	-	(CIMAC, 2020; Concawe, Aramco, 2022)
Blue Hydrogen (overall pathway)	8	10	11	11	11	11	(Ricardo, 2022; Lloyd's Register (UMAS), 2023; Norwegian Ministry of Climate and Environment, 2022)
Blue ammonia (overall pathway)	8	10	10	11	11	11	(Lloyd's Register (UMAS), 2023; Norwegian Ministry of Climate and Environment, 2022; IRENA, AEA, 2022)

Table 12-23: Forecast of readiness and availability of electric propulsion technologies

Technology	2022	2025	2030	2035	2040	2050	Potential for existing vessels	Sources
Electric motor/drive	11	11	11	11	11	11	Unlikely	(DNV, 2022b; IEA, 2020a; Norwegian Ministry of Climate and Environment, 2022)
Batteries (hybrid drive/aux)	10	11	11	11	11	11	Limited	(DNV, 2022b; Ricardo, 2022; Ricardo, 2021; Shell, 2020a; Wärtsilä, 2020b)
Batteries (main propulsion)	9	10	10	-	-	-	Unlikely	(DNV, 2022b)

Table 12-24: Forecast of readiness and availability of ICE with candidate fuels

Technology	2022	2025	2030	2035	2040	2050	Potential for existing vessels	Sources
Biodiesel ICE	9	10	11	11	11	11	Excellent	(Oxford Research, 2021; Lloyd's Register (UMAS), 2023; EMSA/ABS, CE-DELFT, & ARCSILEA, 2022; Longva & Sekkesæter, 2021)

Technology	2022	2025	2030	2035	2040	2050	Potential for existing vessels	Sources
Methane ICE	10	11	11	11	11	11	Limited	(Lloyd's Register (UMAS), 2023; DNV, 2022b; Norwegian Ministry of Climate and Environment, 2022; Lloyd's Register (UMAS), 2020)
Methanol ICE (2-stroke)	9	10	11	11	11	11	Excellent	(DNV, 2022c; DNV, 2022b; Lloyd's Register (UMAS), 2023; Oxford Research, 2021; IRENA, Methanol Institute, 2021; Lloyd's Register (UMAS), 2020; IRENA, Methanol Institute, 2021; IRENA, 2021)
Methanol ICE (4-stroke)	9	10	11	11	11	11	Excellent	(DNV, 2022c; DNV, 2022b; Oxford Research, 2021; Norwegian Ministry of Climate and Environment, 2022; Lloyd's Register (UMAS), 2020; IRENA, 2021)
Hydrogen ICE (2-stroke)	4	5	7	-	-	-	Limited	(Ricardo, 2021; DNV, 2022b; Lloyd's Register (UMAS), 2023; DNV, 2021a; IEA, 2020a; Lloyd's Register (UMAS), 2020)
Hydrogen ICE (4-stroke)	7	9	10	11	11	11	Limited	(DNV, 2022c; DNV, 2022b; Lloyd's Register (UMAS), 2023; IEA, 2020a; Lloyd's Register (UMAS), 2020; MAN Energy Solutions, 2021a)
Ammonia ICE (2-stroke)	5	8	10	11	11	11	Good	(DNV, 2022c; DNV, 2022b; Lloyd's Register (UMAS), 2023; IEA, 2020a; Lloyd's Register (UMAS), 2020; Oxford Research,

Technology	2022	2025	2030	2035	2040	2050	Potential for existing vessels	Sources
								2021; DNV, 2021a; DNV, 2022d)
Ammonia ICE (4-stroke)	7	8	10	11	11	11	Good	(DNV, 2022c; DNV, 2022b; Norwegian Ministry of Climate and Environment, 2022; Lloyd's Register (UMAS), 2020)
Dimethyl ether (DME) ICE	6	8	-	-	-	-	Excellent	(Oxford Research, 2021; EMSA/ABS, CE-DELFT, & ARCSILEA, 2022)

Table 12-25: Forecast of readiness and availability of fuel cell powertrains

Technology	2022	2025	2030	2035	2040	2050	Potential for existing vessels	Sources
Hydrogen Fuel Cell	8	9	10	11	11	11	Unlikely	(DNV, 2022c; DNV, 2022b; DNV, 2021a; Lloyd's Register (UMAS), 2023; IEA, 2020a; Norwegian Ministry of Climate and Environment, 2022; Shell, 2020a; Wärtsilä, 2020b; IRENA, 2018)
Methane Fuel Cell	7	8	9	10	11	11	Unlikely	(Lloyd's Register (UMAS), 2023; Lloyd's Register (UMAS), 2020)
Methanol Fuel Cell	7	8	9	10	11	11	Unlikely	(DNV, 2022c; DNV, 2022b; DNV, 2021a; Oxford Research, 2021; Norwegian Ministry of Climate and Environment, 2022; Lloyd's Register (UMAS), 2020)
Ammonia Fuel Cell	5	7	8	9	-	-	Unlikely	(Ricardo, 2021; DNV, 2022c; Oxford Research, 2021; Norwegian Ministry of Climate and Environment, 2022; Lloyd's Register

Technology	2022	2025	2030	2035	2040	2050	Potential for existing vessels	Sources
								(UMAS), 2020; Cai & Rozario, 2022)
On-board ammonia reformer/cracker (ammonia)	5	7	9	10	-	-	Limited	(Ayvalı & Tsang, 2021)
On-board reformer (methane/methanol)	5	7	9	10	11	11	Limited	(DNV, 2022c; DNV, 2022b; Lloyd's Register (UMAS), 2020)
LOHC hydrogen storage	7	9	10	11	11	11	Unlikely	(H2 Industries, 2022; Hydrogenous Maritime, 2023; Biogradlija, 2023)

Table 12-26: Forecast of readiness and availability of on-board carbon capture

Technology	2022	2025	2030	2035	2040	2050	Potential for existing vessels	Sources
Carbon capture (exhaust)	7	7	9	9	-	-	Good	(DNV, 2022c; DNV, 2022b; Ricardo, 2021; ABS, 2022a; Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022b)
Carbon capture (fuel reformation)	6	7	8	10	-	-	Good	(Ricardo, 2021; DNV, 2022c; Lloyd's Register (UMAS), 2020; Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022)

APPENDIX 7 : COST OF CANDIDATE FUELS 2022-2050

Table 12-27 presents the range of projected costs required to produce the candidate fuels assessed in this study as reported in literature, and the sources from which these cost estimates were found.[36] Ranges are often wide, reflecting the large degree of uncertainty in these projections – sources note that assumptions on the price of renewable electricity and other feedstocks into fuel production needed to be made, and we include all assumptions in the reported range. This is contrary to Appendix 1.14, which assumes one cost scenario for the purposes of energy demand modelling. For the figures in Section 7.2 Price of candidate fuels compared to fossil fuels, we only present the average of this range to illustrate key trends.

For most fuels, these should be interpreted as costs of production and not the price at which the fuel would be sold on the market. As an exception, we report the market price of LNG since this is an input cost to the production of blue fuels. As such, the methodology to derive the cost estimates for blue fuels is also different, as denoted with an asterix (*) below: a higher cost of blue hydrogen production in 2022 as estimated by the IEA (IEA, 2022b) is assumed to fall linearly to 2030 as the temporary volatility in LNG price brought on by the Russia-Ukraine conflict dissipates. This affects the cost of blue ammonia production by the same margin.

[36] Note that if the literature also presented a range of costs, we took the midpoint of that range as the representative figure from that source.

Table 12-27: Forecast costs for candidate fuels, expressed as a range of estimates from literature

Fuel	Fuel prices (USD/GJ)			Sources
	2022	2030	2050	
Green hydrogen	40 - 58	23 - 31	18 - 26	(IRENA, 2018), (World Energy Council, 2021), (IEA, 2022b), (IRENA, 2021), (Energy Networks Association, 2020)
Blue hydrogen (*)	64 - 76	14 - 29	13 - 21	(IEEFA, 2022) , (Energy Networks Association, 2020), (Rystad Energy, 2022) , (Norwegian Ministry of Climate and Environment, 2022)**,** (IEA, 2022b)
Green ammonia	50 - 62	33 - 48	19 - 39	(EMSA/ABS, CE-DELFT, & ARCSILEA, 2022), (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021) , (IRENA, 2021), (IRENA, AEA, 2022), (Alfa Laval, Haldor, & Vestas, 2020)
Blue ammonia (*)	80 - 80	20 - 35	21 - 36	(EMSA/ABS, CE-DELFT, & ARCSILEA, 2022), (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021), (Lloyd's Register (UMAS), 2020), (Alfa Laval, Haldor, & Vestas, 2020)
Biomethanol	19 - 38	24 - 36	22 - 58	(Norwegian Ministry of Climate and Environment, 2022), (IRENA, 2022), (IRENA, Methanol Institute, 2021), (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021), (Lloyd's Register (UMAS), 2020), (IRENA, 2021), (Global Maritime Forum, 2022), (MAN Energy Solutions, 2021b)
E-methanol	30 - 65	37 - 51	26 - 35	(DNV, 2022c), (IRENA, 2022), (IRENA, Methanol Institute, 2021), (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021), (IRENA, 2021), (Global Maritime Forum, 2022), (MAN Energy Solutions, 2021b)
Biomethane	24 - 28	19 - 29	15 - 32	(DNV, 2022c) (Norwegian Ministry of Climate and Environment, 2022), (IRENA, 2022) , (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021), (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021), (IRENA, 2021)
Biodiesel	18 - 40	19 - 34	21 - 43	(DNV, 2022c) (IRENA, 2022) , (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021), (OECD, 2021), (Kyeongsu Kim et al., 2023)
E-methane	43 - 59	40 - 44	31 - 35	(Frontier Economics, 2018) , (DNV, 2022c)
VLSFO	11 - 13	11 - 14	11 - 11	(Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021), (EMSA/ABS, CE-DELFT, & ARCSILEA, 2022)
LNG	39 - 41	8 - 12	8 - 11	(Transport & Environment, 2022) , (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021), (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021), (Lloyd's Register (UMAS), 2020) (DNV, 2022c)

In Association with:

T: +44 (0) 1235 75 3000

E: enquiry@ricardo.com

W: ee.ricardo.com