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Agenda item 7

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REDUCTION OF GHG EMISSIONS FROM SHIPS

Report on the study on the readiness and availability of low- and zero-carbon ship technology and marine fuels

Note by the Secretariat

SUMMARY

Executive summary:	This document contains, in the annex, the summary report of the draft final "Study on the readiness and availability of low- and zero-carbon ship technology and marine fuels" undertaken by Ricardo and DNV for the IMO Future Fuel and Technology Project (FFT Project). The study was commissioned in response to the request by MEPC 77 with a view to supporting the revision process of the Initial IMO GHG Strategy.
Strategic direction, if applicable:	3
Output:	3.2
Action to be taken:	Paragraph 8
Related documents:	MEPC 80/8 and resolution MEPC.304(72)

Background

1 In September 2022, IMO launched the *Future Fuels and Technology* project (FFT Project) to support GHG emissions reduction from international shipping by providing technical analysis to the Organization in support of relevant policy discussions held in the Committee. This project is funded by the Voyage Together Trust Fund of the Repand implemented by the Secretariat.

2 MEPC 77 initiated the Revision of the Initial IMO GHG Strategy and MEPC 78, following consideration of varying views on the levels of ambition required and their achievability, requested the Secretariat to consider carrying out additional studies and organizing information session(s) and/or symposia, as appropriate, supporting the revision process of the Strategy.

Study on the availability and readiness of low- and zero-carbon ship technology and fuels

3 To that end, the FFT Project, with additional support provided through the IMO GHG TC Trust Fund[1], carried out a study providing 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 towards the revision of the Initial IMO GHG Strategy by providing a feasibility analysis on possible strengthened levels of ambition.

4 The main findings of the study conducted by Ricardo and DNV were presented[2] during the ISWG-GHG 14.

5 The annex to this document contains the summary report as the first deliverable of the for the FFT project.

6 The key findings of this study are:

.1 Achieving a more ambitious decarbonization 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.

.2 While candidate fuels are and will be more expensive than currently used fuels, this is not a barrier to their uptake for the shipping industry if the demand signal is clear.

.3 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 GHG Strategy setting revised levels of ambition in combination with the policies needed to drive the transition to the revised ambition.

.4 All three decarbonization scenarios (50%, 80% and 100% GHG reduction by 2050) considered in this study 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.

.5 Considering that the planned investments and announced projects on candidate fuel production towards 2030 are still conservative, achieving a possible 2030 target of 45% GHG reduction in the 100% reduction scenario could be challenging. Hence, a clear demand signal and more ambitious policies are needed very soon to come into effect by 2025 in order to meet the 2030 target of this scenario.

7 The full final report of this study will be available from early April 2023 and can be downloaded from https://futurefuels.imo.org. Delegations that wish to send in comments or have questions with regard to the study can contact Mr. Ji-Man Seo, project manager of the FFT project (JSeo@imo.org).

Action requested of the Committee

8 The Committee is invited to note the information contained in this document and its annex, notably in the context of its ongoing work on the revision of the IMO Initial GHG Strategy.

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1 In particular through a contribution by Japan, funded by the Nippon Foundation.

2 The "Update on the IMO FFT Project" was presented on 22 March 2023 during the ISWG-GHG 14. It is available on both IMODOCS (ISWG-GHG 14 → Virtual Portal) and https://futurefuels.imo.org/.

ANNEX

In Association with:

DNV

RICARDO

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

Summary Report

Report for: International Maritime Organization (IMO)
Future Fuels and Technology Project

Ref. Contract No. 2022-19, RFP2022-08

Ricardo ref. ED17328 – Summary | Issue: 2 | 31 March 2023

Customer:
International Maritime Organization (IMO) Future Fuels And Technology For Low- And Zero-Carbon Shipping Project (FFT Project)

Customer reference:
Contract No. 2022-19, RFP2022-08

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Ricardo reference:
ED17328 – Summary Issue 2

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Approved by:
Tim Scarbrough

Signed

Date:
31st March 2023

Ricardo is certified to ISO9001, ISO14001, ISO27001 and ISO45001.

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 in September 2022 the ***"Future Fuels and Technology for Low- and Zero-Carbon Shipping Project (FFT Project)"*** 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 finalized 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

EXECUTIVE SUMMARY

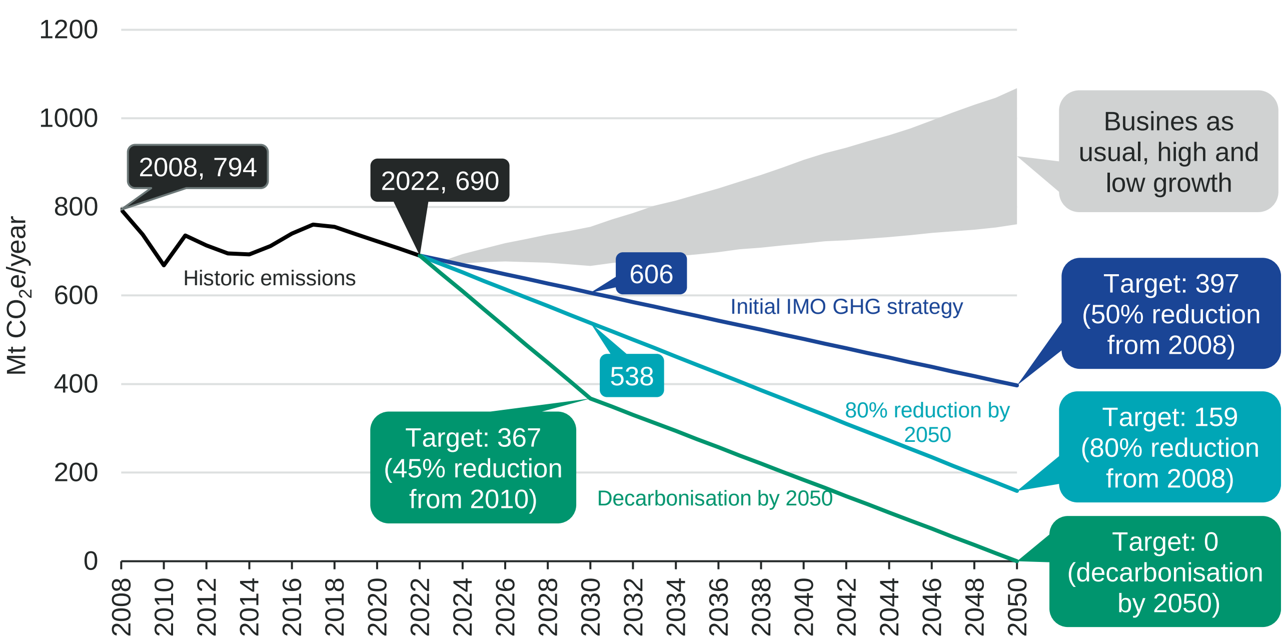
This study assesses the availability and readiness of low- and zero-carbon ship technology and marine fuels that can decarbonise international shipping, and the feasibility of achieving different decarbonisation scenarios.

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.

CONTENTS

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), 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.

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 organization of outreach activities to reinforce mutual understanding and cooperation between developed and developing countries and the global shipping industry.

1.2 AIM OF THE STUDY

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, in order to help inform Member States as they work towards the revision of the Initial IMO GHG Strategy.

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. 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 STRUCTURE OF THIS PAPER

This is the Summary Paper of a full technical report. The full detail of the supporting evidence is available in the full report. The full reports of the study will be available from early April 2023 and can be downloaded from https://futurefuels.imo.org.

After this introduction chapter, the rest of this paper is set out as follows:

- Part A, '*What are possible pathways to decarbonise?*', defines the decarbonisation scenarios considered in this paper (section 2) and estimates their energy demands (section 3).
- Part B, '*How could we meet these pathways?*', sets out the readiness of technologies and fuels (section 4) as well as the readiness of landside infrastructure of bunkering, ports and shipyards (section 5) needed, the potential availability of fuels (section 6), and costs of the fuels (section 7).
- Part C, '*Is it feasible to meet these decarbonisation scenarios?*', compares the energy demands from Part A with the fuel availability in Part B to assess the feasibility of meeting decarbonisation scenarios. It also suggests possible mitigating actions to help achieve the decarbonisation scenarios and the conclusions.

1.4 SCOPE AND KEY DEFINITIONS

1.4.1 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 method of international shipping** from the Fourth IMO GHG Study.
2. The emission estimates in the Fourth IMO GHG Study are tank-to-wake (TtW) emissions, and the Initial IMO GHG Strategy does not make any explicit reference to TtW or well-to-wake (WtW) emissions. This study does not prejudge the discussions around whether the Revised IMO GHG Strategy should cover WtW or TtW GHG emissions. Rather, we aim to show possible decarbonisation fuel pathways to evaluate the feasibility of strengthened GHG emission reduction targets.

   For the purpose of this study, and the need to select one approach, **GHG emissions are calculated according to a TtW scope where carbon dioxide (CO_2) emissions from combustion of biogenic carbon or carbon from direct air capture are considered zero.**
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 CO_2, methane (CH_4) and nitrous oxide (N_2O) as GHG emissions**. 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. The GWP values are unitless values indicating the equivalent global warming potential of a unit of GHG 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.

1.4.2 Key definitions

The following key 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 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.

Term	Definition
Business as usual (BAU) energy efficiency measures	A selection of technologies or measures 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.[1] 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.
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, 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, liquified petroleum gas (LPG) and liquified natural gas (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. [1] 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.

[1] https://www.ipcc.ch/sr15/chapter/glossary/

1.5 FUELS CONSIDERED AS CANDIDATES TO DECARBONISE THE SECTOR

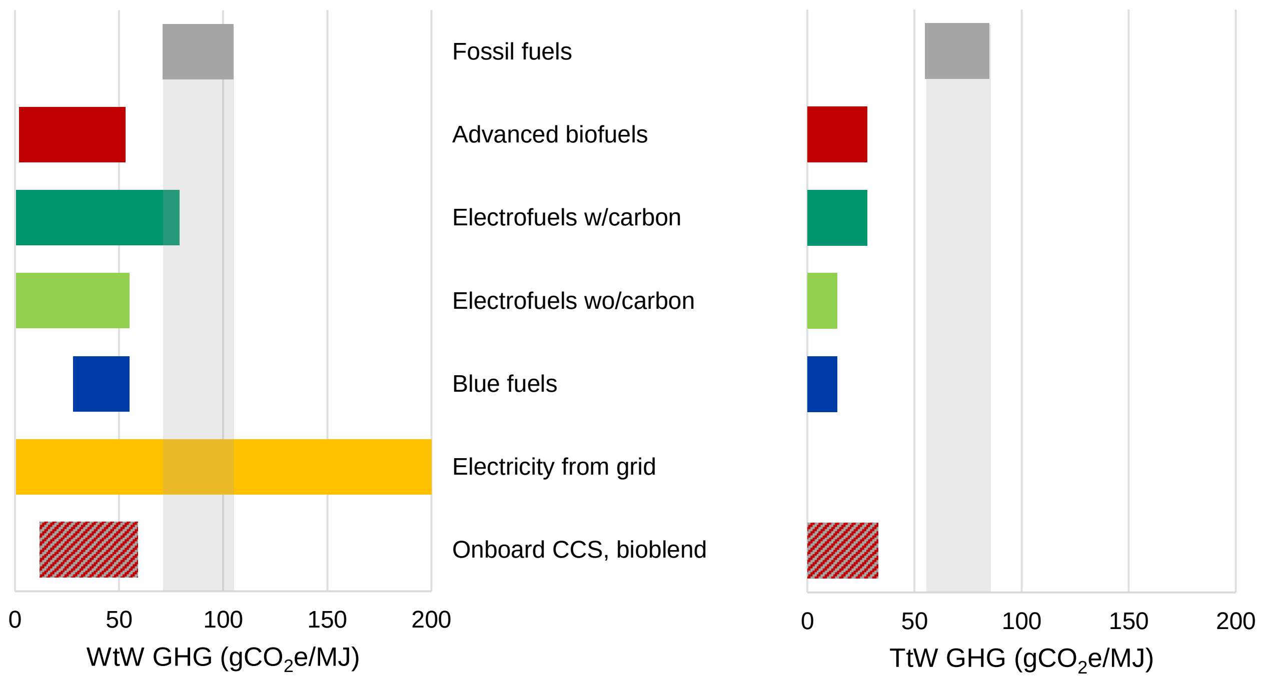
To avoid any connotations from other terms and definitions, **this study uses the term 'candidate fuels' to denote fuel paths (including fossil fuels used in conjunction with onboard carbon capture and storage) that have close to zero TtW GHG emissions and can contribute to achieving the GHG reduction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

The fuels considered as candidates for decarbonising international shipping include:

- **Biofuels** made from advanced biomass (e.g. waste, algae) feedstocks (biomethanol, biomethane, biodiesel)[2]
- **E-fuels** or renewable fuels of non-biological origin based on hydrogen produced by electrolysis primarily using renewable or nuclear electricity (without carbon: e-hydrogen, e-ammonia; or with carbon from direct air capture or biogenic sources: e-methanol, e-methane, e-diesel)
- **Blue fuels** based on hydrogen made from fossil energy sources with landside carbon capture and storage with a >90% capture rate (blue hydrogen, blue ammonia)
- **Electricity** from the grid, produced from a mix of fossil and renewable sources, and delivered as shore power[3]
- **Fossil fuels blended with advanced biofuels paired with onboard carbon capture (e-fuels could also be used)**. Onboard carbon capture rates are expected to be >70%.[4]

All the candidate fuels can reduce TtW GHG emissions to zero or close to zero. 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 large well-to-tank (WtT) and TtW GHG emissions. This study has made a high-level assessment, based on available literature, of the WtW and TtW emissions of the candidate fuels (Figure 1-1). For the purpose of this study, candidate fuels are assumed to have zero TtW GHG emissions.

Figure 1-1: Well-to-wake (left) and tank-to-wake (right) GHG emissions per candidate fuel category, based on a literature review



[2] Conventional biofuels have not been considered as candidate fuels due to concerns of wider environmental impacts such as land use.

[3] Although electricity from the grid potentially has high WtW GHG emissions, it is included as a candidate fuel as it also has the potential to reach zero WtW GHG emissions.

[4] The CO_2 captured onboard is assumed to be temporarily stored onboard before removal to landside infrastructure for permanent storage.

PART A: WHAT ARE POSSIBLE PATHWAYS TO DECARBONISE?

Part A defines decarbonisation scenarios (section 2) and estimates candidate fuel demand (section 3).

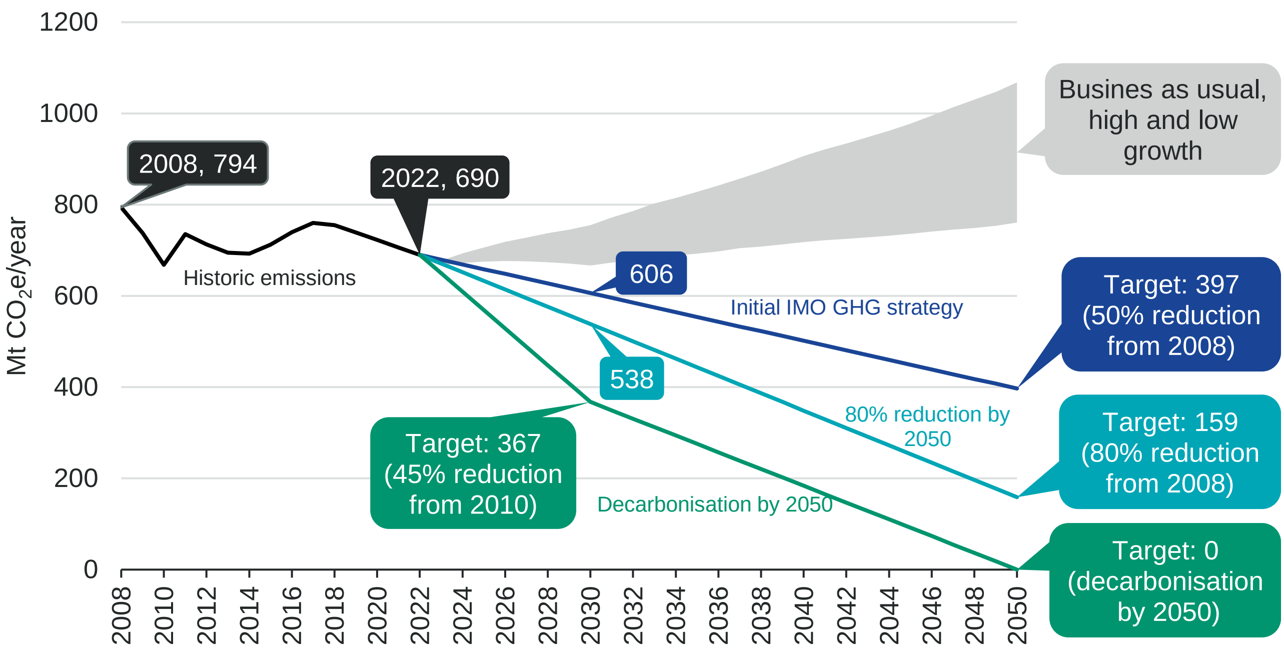
2. THREE DECARBONISATION SCENARIOS AS OPTIONS TO BOUND THE POTENTIAL REVISED IMO GHG STRATEGY

Three decarbonisation scenarios are defined outlining conceivable pathways for the maritime sector in the context of the current business as usual, the current level of ambition of the Initial Strategy as well as two more ambitious scenarios. These provide for possible considerations for the forthcoming Revised IMO GHG Strategy:

- The **Initial IMO Strategy** showing a trajectory matching the (minimum) ambition of the Initial IMO GHG strategy, i.e. reducing total annual GHG emissions by (at least) 50% by 2050 compared to 2008.
- A scenario of **80% reduction by 2050** of annual GHG emissions compared to 2008. This scenario approximately aligns with the maritime trajectories in 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 the sector 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.

The scenarios are shown in Figure 2-1 with their 2030 and 2050 targets.[5]

Figure 2-1 Three decarbonisation scenarios with targets compared to business as usual GHG emissions



Notes: Historical data from 2008 to 2018 were taken from the 4th and 3rd IMO GHG studies, and 2019 to 2022 emissions were interpolated. The business as usual scenario is detailed in Section 3. 2040 targets for these scenarios are linearly interpolated between the 2030 and 2050 targets.

[5] For the **decarbonisation by 2050** scenario, the 2030 target is based on the IPCC (2018) which uses 2010 as a reference to define the 1.5°C aligned trajectory; given 2050 is by definition zero in this scenario, 2040 is interpolated.

3. DEMAND FOR CANDIDATE FUELS TO MEET THESE DECARBONISATION SCENARIOS WILL BE SIGNIFICANT, EVEN WITH ADOPTING ENERGY EFFICIENCY MEASURES

Key findings:

- Seaborne transport demand is 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 BAU scenario, 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.
- The remaining energy demand for candidate fuels is between 8.2 and 11.5 EJ in 2050 under the low and high growth scenarios respectively, for decarbonisation by 2050 using the additional energy efficiency measures.

3.1 BUSINESS AS USUAL ENERGY DEMAND BY 2050 IS EXPECTED TO BE 23-75% HIGHER THAN 2022

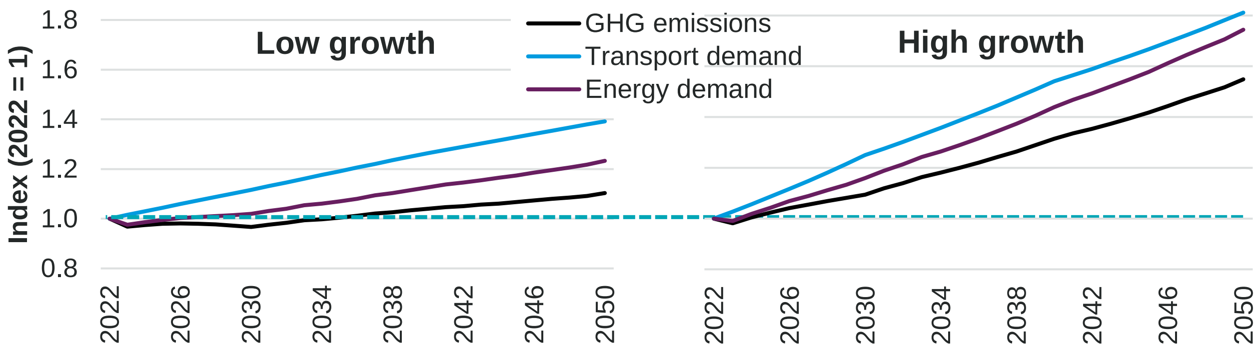
A business as usual (BAU) scenario has been defined as continuing the trajectory in shipping emissions based on assumed compliance with energy efficiency policies that have already been adopted (EEDI, EEXI, CII and SEEMP). Similarly to other sectors, the expected growth of the maritime sector over the coming decades increases the scale of the decarbonisation challenge. The **demand for seaborne transport is estimated to by between 39% and 81% by 2050** under the BAU scenario (labelled as low and high growth scenarios respectively). These low (OECD_RCP2.6_G) and high (SSP2_RCP2.6_L) seaborne trade growth rates have been selected from the 4th IMO GHG Study.

Based on the assumed growth in the BAU scenario, the sector will, without further policy intervention, **demand between 23% and 75% more energy in 2050 compared to 2022** to deliver the demand for seaborne transport. The 2022 energy demand is estimated to be 9.0 EJ, rising to between 11.1 and 15.8 EJ in 2050. This projection accounts for the effects of the policies already adopted on energy efficiency which act to slightly counter the upwards trend in energy consumption driven by growth in seaborne transport demand.

Without additional policies to address GHG emissions from the sector, this increase in energy demand is estimated to lead to a growth in emissions. The estimated **growth in emissions** is from 690 Mt CO_2e in 2022 to between 761 Mt and 1068 Mt CO_2e in 2050, representing increases **from 2022 of 10% to 55%** respectively for the low and high growth scenarios. Compared to 2008 emissions, this represents changes of -4% to +35%.

The relative BAU trends in the demand for seaborne transport, the energy demand and GHG emissions as estimated from 2022 to 2050 are summarised in Figure 3-1.

Figure 3-1: Business as usual increases from 2022 to 2050 of GHG emissions are projected to be lower relative to energy demand, which in turn is projected to be lower relative to seaborne transport demand



In more detail, the projected energy demand of the BAU scenario is shown in Figure 3-1, overlaid with text on the projected associated GHG emissions. When estimating these trends, which are within the bounds of the scope and assumptions described in Section 1.2, we have made the following additional observations:

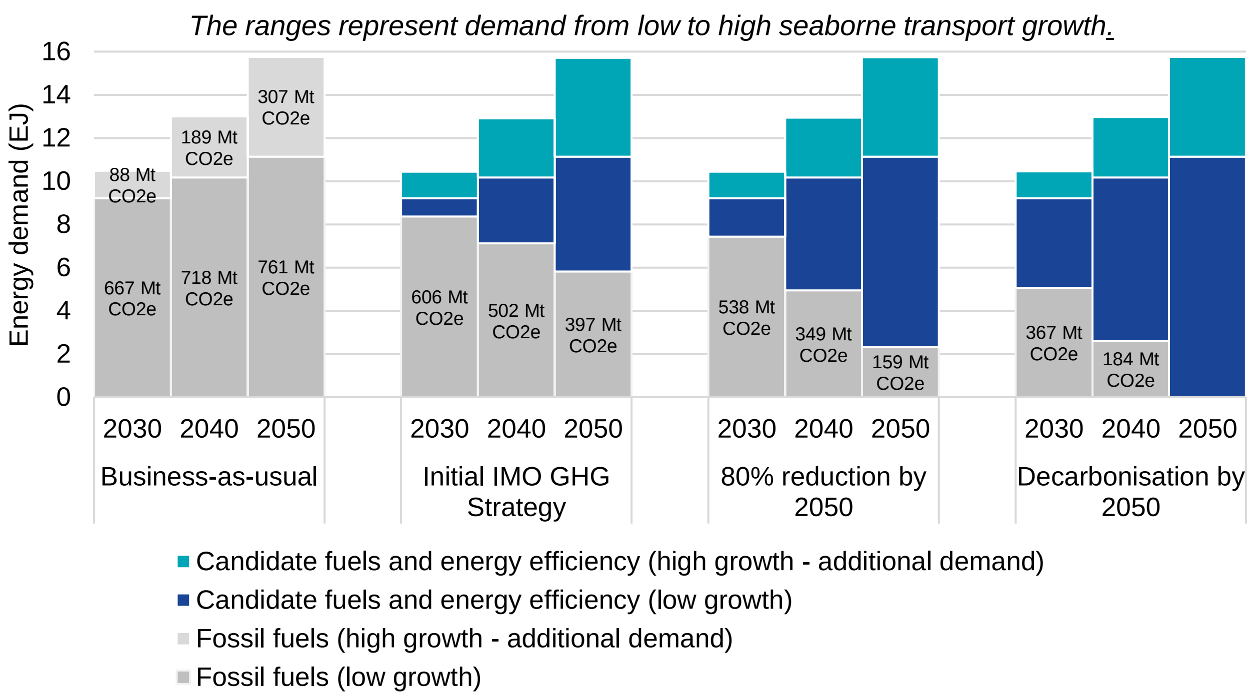
- **The uptake of LNG is expected to continue**, reaching 49-54% of energy use in 2050, with the high growth scenario resulting in a higher share of LNG in the fuel mix than the low growth scenario. This increases the share of CH_4 in the total GHG emissions almost five-fold to 4.7-5.3 % in 2050, although the total GHG intensity of the fossil fuels reduces.
- **Bio- 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 the policies not becoming more stringent under business as usual after 2030, and as new and more energy efficient ships replace the existing ships the need for bio- and e-fuels reduces.

The fleet turnover, which is partially a function of the growth rate, also determines the rate that new build technologies/fuels could permeate the fleet (i.e. not considering retrofits). An analysis of the energy demand split by the period of when vessels are commissioned demonstrates this. In 2030, between 20% and 28% of the energy demand is estimated to be from vessels commissioned since 2025, for the low and high growth scenarios respectively. This is estimated to rise in 2040 to between 56% and 69% for the low and high growth scenarios respectively. Retrofitting new technologies can accelerate the uptake of both energy efficiency measure and alternative fuel systems.

3.2 TO MEET THE DECARBONISATION BY 2050 SCENARIO, CANDIDATE FUEL DEMAND IN 2030 COULD BE HALF OF THE 2022 FOSSIL FUEL DEMAND

The constraint imposed by the GHG emission targets of the decarbonisation scenarios provides a maximum boundary for the use of conventional fossil fuels (without CCS). Therefore, subject to the potential additional deployment of energy efficiency and reduction technologies, this provides an estimate of the minimum energy demand that would need to be supplied by the provision of candidate fuels and/or saved through the deployment of additional energy efficiency measures (including speed reduction). This has been estimated and is shown in Figure 3-2. It shows that the *decarbonisation by 2050* scenario would need, in *2030*, between 4.1 EJ and 5.4 EJ of energy to be either supplied by candidate fuels or saved through additional energy efficiency measures, with this range rising to 7.6-10.4 EJ in 2040 and to 11.1-15.8 EJ in 2050. For comparison, the energy demand in 2022 – supplied almost exclusively with fossil fuels – was ~9.0 EJ.

Figure 3-2: Ranges of demand under business as usual for fossil fuels and, in the three decarbonisation scenarios, for candidate fuels and/or to be met with savings from energy efficiency



3.3 ADDITIONAL ENERGY EFFICIENCY MEASURES COULD REDUCE ENERGY DEMAND BY 27% IN 2050

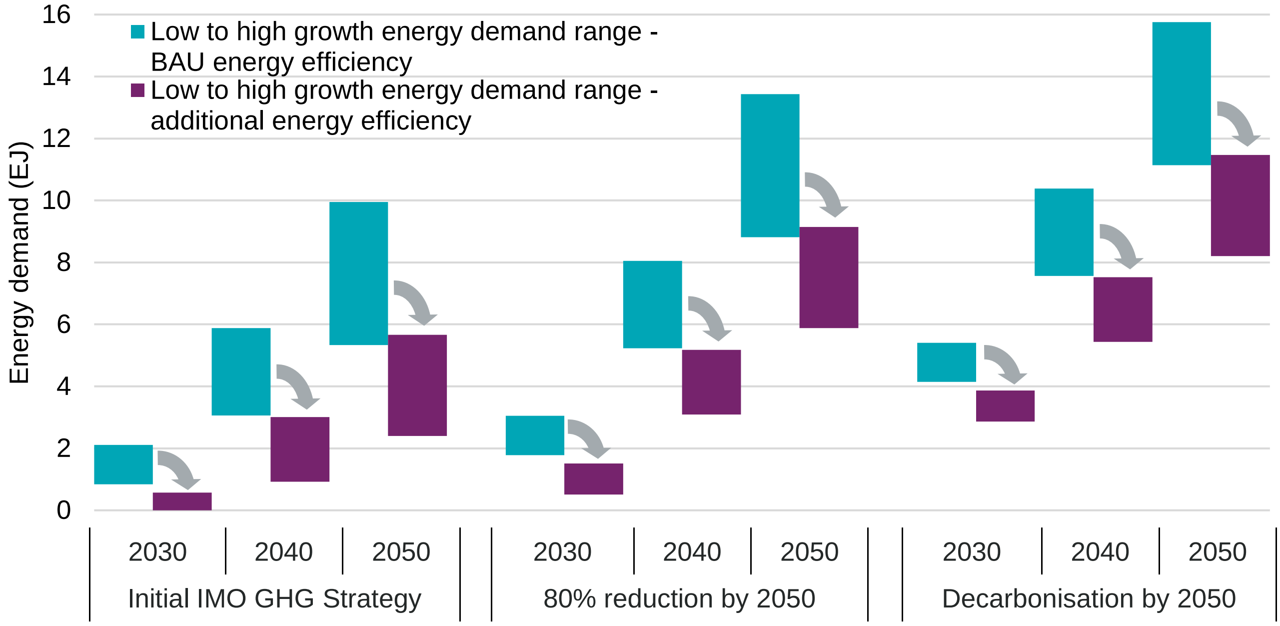
The energy demand projections in Section 3.2 do not assume any greater uptake of energy efficiency measures beyond what is assumed in the BAU scenario. The greater the deployment of energy efficiency measures (up to a maximum feasible uptake), the lower the demand will be for supplying candidate fuels. We have estimated what the impact could be on energy demand if there was a:

- maximum uptake of available energy efficiency measures on board vessels
- 30% reduction in speeds of all vessels, relative to a 2015 design speed average. We acknowledge this as a maximum, as although speed reductions up to 50% may be possible, they would require complex changes to supply chains.
- maximum feasible uptake of shore power replacing a proportion of at-berth energy demand. We have assumed a potential of 5% of total fuel consumption in 2050 for conversion to shore power.

The implementation of these additional energy efficiency measures would be beyond BAU and would require additional policies to achieve them, though the use of more expensive fuels would be expected to drive and maintain elevated levels of uptake of energy efficiency measures. Figure 3-3 estimates, as plum-coloured bars, how much lower energy demand would be if additional energy efficiency measures were taken up. For example, in 2050 this is estimated to lead to reductions of about 27% in the energy demand across the three decarbonisation scenarios. In the *decarbonisation by 2050* scenario 8.2-11.5 EJ of candidate fuels would be required in 2050.

Figure 3-3: Ranges of minimum energy (EJ per year) demand from candidate fuels reduced by deployment of additional energy efficiency measures, in 2030, 2040 and 2050 for low to high growth

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.



The energy and GHG emissions for the reference year 2022[6] have been calculated using DNV's MASTER model which uses global AIS data combined with ship-specific data. DNV's Pathway Model has been used to estimate the uptake of energy efficiency technologies and fuels to 2050. This is used to estimate the total energy demand and the demand to be provided by candidate fuels to achieve a certain decarbonisation target. The range of forecasts of energy demand in 2050 in this study have been compared with other literature and were found to lie broadly within the ranges of reports by IEA, IRENA, DNV, Ricardo, UMAS and the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping.

[6] As 2022 is used as a reference year, the BAU projections differ from the 4th IMO GHG study which used 2018 as a reference year.

PART B: HOW COULD WE MEET THESE PATHWAYS?

Part B covers the readiness of technologies and fuels (section 4), the readiness of landside infrastructure of bunkering, ports and shipyards (section 5), the potential availability of candidate fuels (section 6) and the costs of candidate fuels (section 7).

4. THE TECHNOLOGIES AND FUELS NEEDED TO MEET THE DEMAND WILL BE COMMERCIALLY READY IN TIME

Achieving the decarbonisation scenarios requires both the use of candidate fuels and the application of additional energy efficiency technologies to reduce energy demand. The feasibility of the scenarios therefore depends on those candidate fuel production methods and the vessel efficiency and powertrain technologies being technically ready and sufficiently mature for commercial use.

This study evaluated the current and forecast readiness of individual technologies and assessed them against a technology and commercial readiness scale using an extensive literature review of over a hundred sources, experts within Ricardo and DNV, and validated through targeted consultation with industry 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**.[7] 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.

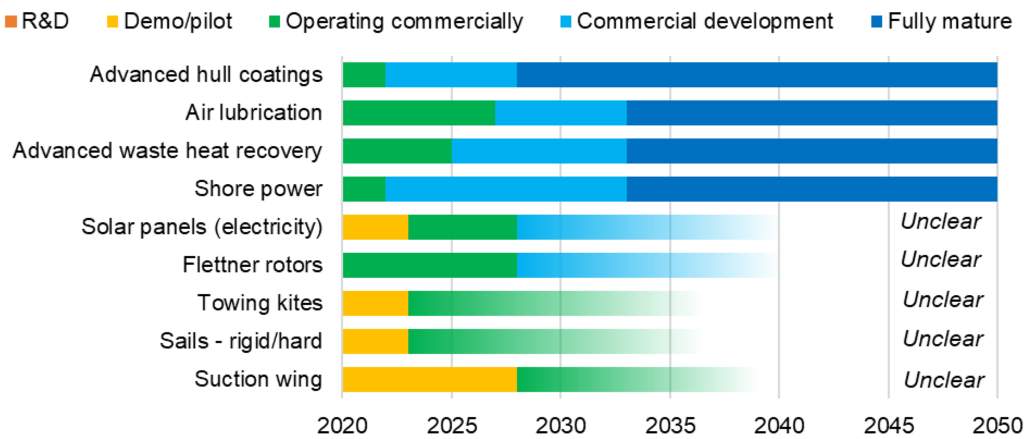
[7] Similar arguments have been made or implied in previous submissions (e.g. ISWG-GHG 13/3/3): that projections of future commercialisation based on current technology development often underestimate what is possible if increased demand is specified.

4.1 READINESS OF ENERGY EFFICIENCY AND REDUCTION TECHNOLOGIES

The shipping industry has developed and applied energy efficiency technologies for many years, driven by the desire to reduce fuel costs, and more recently by regulatory measures (e.g. EEDI, EEXI, CII). Several **vessel design technologies** are already mature and applied to many new vessels, including weight reduction, optimising hull dimensions, bulbous bow, bow thruster tunnel optimisation, ballast and trim optimisation. There remains potential for wider roll-out of these technologies and hence greater fleet fuel savings in the future.

A range of vessel energy efficiency and reduction technologies are not yet mature, and the forecast readiness of a selection of these is shown in Figure 4-1.

Figure 4-1: Forecast of readiness and availability of selected energy efficiency and reduction technologies



The current and forecast readiness of these **vessel-based** technologies in Figure 4-1 are:

- Friction-reducing **advanced hull coatings** are already applied in commercial operation and are expected to reach full maturity before 2030. **Air lubrication** also serves to reduce hull friction. Although used on some vessels commercially today, some limitations have meant it has not yet become established. Commercial development is expected to improve its effectiveness and competitiveness by late 2020s, reaching full maturity by 2035.
- **Advanced waste heat recovery** systems recover useful energy from low-grade waste engine (or high-temperature fuel cell) heat. Although relatively recently developed for maritime use, they are starting to be used in commercial operation, and are forecast to be fully mature in a decade.
- **Shore power** is transitioning from commercial operation to commercial development for larger vessels, with international standards in place. However, its high capital costs have been difficult to justify without firm demand, with unclear financial benefit to vessel operators or ports. Favourable policies are starting to be adopted and so it could be widely used (i.e. full maturity) within a decade.
- **Solar panels**, a fully mature technology on land, have been demonstrated on-board and are expected to develop commercially later this decade. However, their use is expected to be limited by practical constraints, so the extent of their possible commercialisation is unclear.
- **Flettner rotors** which are now in use providing wind assistance on several vessels operating commercially, with commercial development expected to accelerate into the 2030s. **Towing kites** and **rigid sails** have achieved pilot demonstrations, and commercial operation is expected by 2025. However, not all wind assistance[8] technologies are suited to all vessel types, so until their practicality and effectiveness has been more widely demonstrated their commercialisation paths are unclear.

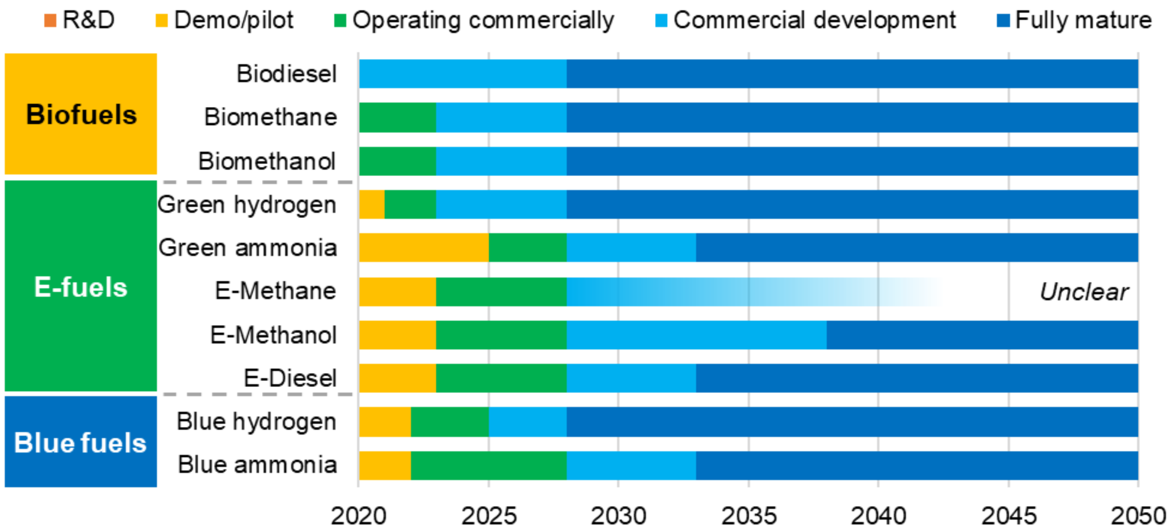
The study has also forecast the readiness of technologies that increase the **operational voyage efficiency** of vessels. **Slow steaming** of vessels during voyages is already a mature measure. **Advanced autopilots** also assist in voyage optimisation with more recent developments ready and expected to be fully mature in the next 5 years; these include just-in-time arrivals for optimising fuel use. **Autonomous shipping** is currently at a research and development stage for which adequate regulations are still needed and is yet to be proven in all operational and weather conditions. Fully autonomous internationally trading vessels are not expected to be ready for commercial development for at least 10 years and full maturity may not be reached until 2050.

[8] Wind propulsion assistance technologies are considered as energy reduction technologies to reduce demand on using fuel for propulsion.

4.2 READINESS OF CANDIDATE FUEL PRODUCTION PATHWAYS

There are a range of production methods (or pathways) for manufacturing candidate fuels. The readiness of the *technologies used in the key production stages* of the fuels has been evaluated, such that Figure 4-2 summarises the forecast readiness of the fuel *production pathways*.

Figure 4-2: Forecast of readiness and availability of fuel production pathways



The biofuel pathways are in commercial development today and forecast to be fully mature before 2030. Biodiesel is already widely used in road transport and more recently in small quantities for shipping, blended with conventional fuel. **Biomethane** and **biomethanol** are also already in use today. To commercially develop requires a scale-up of production plants and sourcing of waste feedstocks; this may be partially driven by use in other sectors although this could bring competition for these fuels and/or their feedstocks.

The e-fuel production pathways are mostly transitioning from demonstration stage to commercial operation today, forecast to reach full maturity in the 2030s. There are no technical barriers for **green hydrogen and ammonia** production, though ammonia production plants are currently at the pilot stage. There is investment in both the plants and the renewable energy to commercialise their production over the next 5-10 years, and increasing the rate of commercialisation through greater investment would be possible with increased certainty on the level of ambition. Current and planned pilot plants for carbon-containing candidate e-fuels (**e-methane, e-methanol and e-diesel**) usually use CO_2 from biogenic sources, but scaling up production is likely to need direct air capture, expected to be ready for commercial operation around 2030 and hence able to support full commercialisation of e-fuel production. Although pilot e-methane plants exist there is less evidence of development reaching maturity than for e-methanol and e-diesel, perhaps due to established biomethane supply rather than technical barriers. The commercial development of e-diesel through to full maturity forecast for the early 2030s may be driven by demand from the road sector, which may also compete for supply.

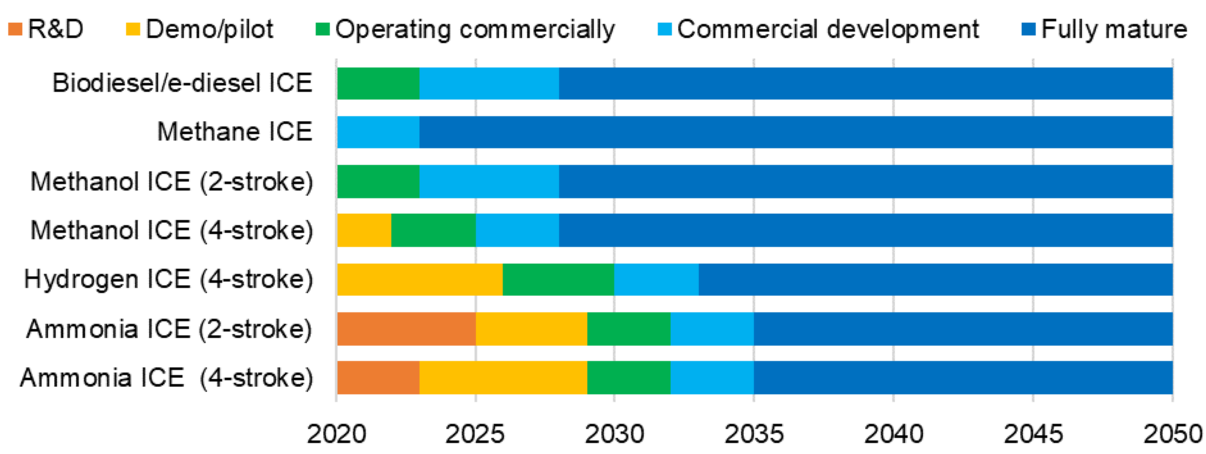
For blue fuels, the blue hydrogen and ammonia production pathways are forecast to reach full maturity before 2030 and mid-2030s respectively. Current CCS technologies have proved challenging and costly for large scale steam methane reforming plants for **blue hydrogen** production, but development of autothermal reforming hydrogen production is expected to enable commercial development of CCS with higher carbon capture rates from the middle of this decade. Further commercialisation to full maturity depends on the economics rather than technology, although retrofit of CCS to existing steam methane reforming plants is likely to be limited. Current ammonia plants already capture around a third of the total CO_2 (used in other industries); reaching higher capture rates for **blue ammonia** will need the same technologies as for blue hydrogen. CCS also relies on a route to permanent storage of the captured CO_2.

4.3 READINESS OF CANDIDATE FUEL PROPULSION TECHNOLOGIES

Ships using conventional fuels have internal combustion engines (ICE) to generate propulsion or electrical power; similar engines are possible for the candidate fuels. Fuel cells are an emerging technology for the maritime industry, offering efficiency and other benefits. The readiness of both groups of technologies for use with the candidate fuels has been evaluated in Figure 4-3 (engines) and Figure 4-4 (fuel cells).

The potential for retrofitting existing vessels has also been considered. Retrofitting a vessel with a fuel cell powertrain is more complex than converting an engine to using an alternative fuel, on top of the need to change fuel storage and supply systems. However, building new vessels with possible future conversions in mind – such as using an electric propulsion system (already established technology) – could make a switch from engines to fuel cells a more practical proposition.

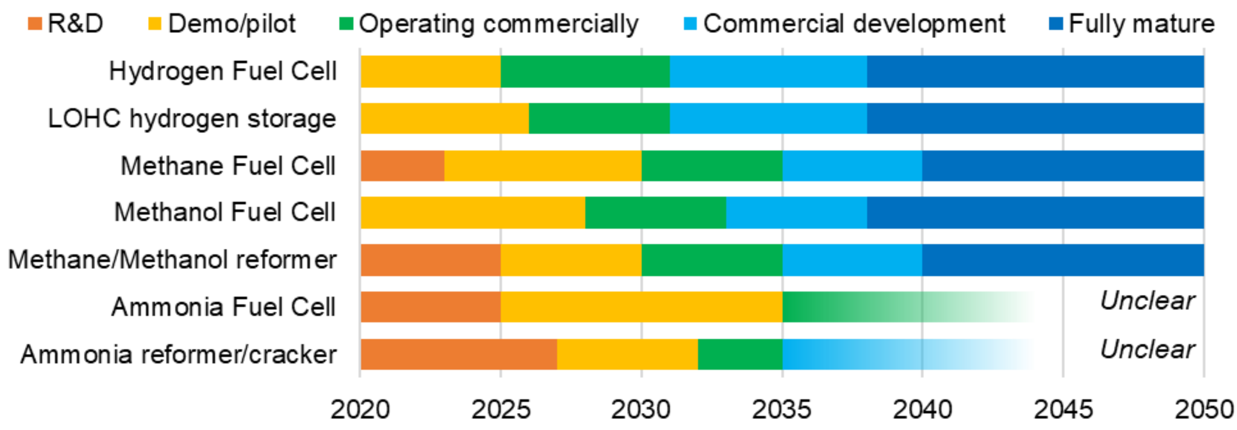
Figure 4-3: Forecast of readiness and availability of candidate fuel marine combustion engine technologies



In summary, **fuel combustion engine technologies with candidate fuels are forecast to reach commercial operation by 2030 or sooner**:

- **Marine engines** are already using biodiesel blended with conventional fuels**. Engines able to use pure biodiesel are forecast to reach full maturity in the late 2020s.** This is because there are few technical barriers to higher or pure biodiesel blends, nor e-diesel; bio and e-diesel are backward-compatible with existing diesel engines with minimal modification. Bio- and e-diesel can also be the ‘pilot' fuel to initiate/stabilise combustion of other candidate fuels.
- **Marine engines running on methane are fully mature (as LNG); biomethane and e-methane could be directly substituted without technical restrictions.**
- **Methanol engines are already operating commercially today, with increasing commercial development particularly for 2-stroke engines, and forecast to reach full maturity before 2030**. Retrofit of existing vessels to use methanol has been demonstrated and is likely to be a more practical option for oil-fuelled vessels than conversion to a gas fuel.
- **Hydrogen 4-stroke engines are currently reaching demonstration level and are expected to be operating commercially later this decade.** The development of regulations for on-board use of hydrogen may however be a limiting factor in the near-term. Storage requirements are likely to limit hydrogen use to shorter voyage applications and so no interest has been found for larger 2-stroke engines. Retrofitting is possible although the storage and handling of hydrogen adds complexity.
- **Ammonia engines are today at the research and development stage, and are progressing rapidly, forecast to reach pilot demonstration by 2025 and commercial operation before 2030**. Commercialisation is expected to be rapid since the technology change from existing engines is small, and ammonia offers better energy storage density (by volume) than hydrogen. Retrofit is expected to be challenging for oil-fuelled vessels, but more feasible for LNG-fuelled vessels.

Figure 4-4: Forecast of readiness and availability of marine fuel cell technologies



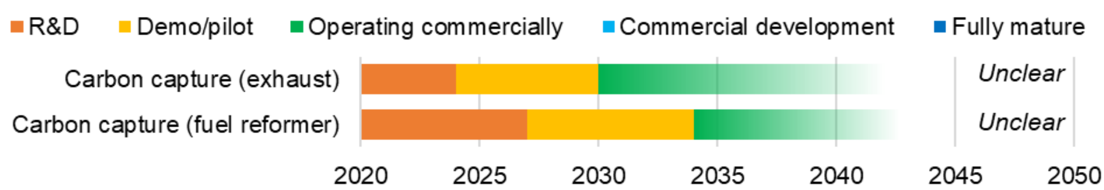
Fuel cell technologies may take until the late-2030s to reach full commercial maturity:

- **Hydrogen fuel cells are already being piloted and commercial operations are expected in the late 2020s, at least for smaller vessels**. The key challenges are scaling up the power output, ensuring reliability for sustained operation, fuel storage/handling and regulatory maturity.
- **Liquid organic hydrogen carrier (LOHC) technology** provides higher density hydrogen storage. Though more recently developed, it is also forecast to commercialise over similar timescales as hydrogen fuel cells, i.e. forecast to be used in commercial operations later this decade.
- **Methane and methanol fuel cells are forecast to begin commercial operation around 2030 and take a decade to fully mature.** Methanol and methane can either be used directly in some fuel cells or reformed on board to produce hydrogen first. Development of both technologies is forecast to be similar. Vessels using methane/methanol for propulsion with engines may provide an opportunity to accelerate commercialisation of methane/methanol fuel cells through use for auxiliary power.
- **The first vessels to pilot using ammonia directly in fuel cells are expected in the late 2020s. Onboard cracking of ammonia into hydrogen is forecast to commercialise earlier however**. Cracking into hydrogen allows a wider choice of fuel cell types but adds complexity. The full commercialisation of ammonia fuel cell technologies for propulsion is unclear because it depends on how its efficiency, cost, and robustness compares with ammonia engines.

4.4 READINESS OF ON-BOARD CARBON CAPTURE TECHNOLOGIES

Carbon capture technology offers the potential to reduce tank-to-wake CO_2 emissions. On-board carbon capture systems can be 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); their readiness is forecast in Figure 4-5.

Figure 4-5: Readiness of on-board carbon capture technologies



Carbon capture technologies applied to exhaust gas are operating commercially today in land-based systems but are still at the research and development stage for on-board use. Demonstrations are expected later this decade, and first commercial operation (at the capture rates required) in the 2030s. Development of similar technology for fuel reformers is forecast to be slower. In both cases, there are energy (fuel use) penalties, practical and space challenges of installing capture equipment onboard as well as the necessary CO_2 storage onboard, and a need for handling and storage at ports to receive and permanently store the CO_2. This means that the barriers to uptake once on-board carbon capture is demonstrated will no longer be technical readiness, but rather dependent on other factors including policy requirements/incentives, and so a forecast of commercialisation is unclear.

5. MARITIME INFRASTRUCTURE TO PROVIDE CANDIDATE FUELS AND VESSEL TECHNOLOGIES CAN SCALE-UP

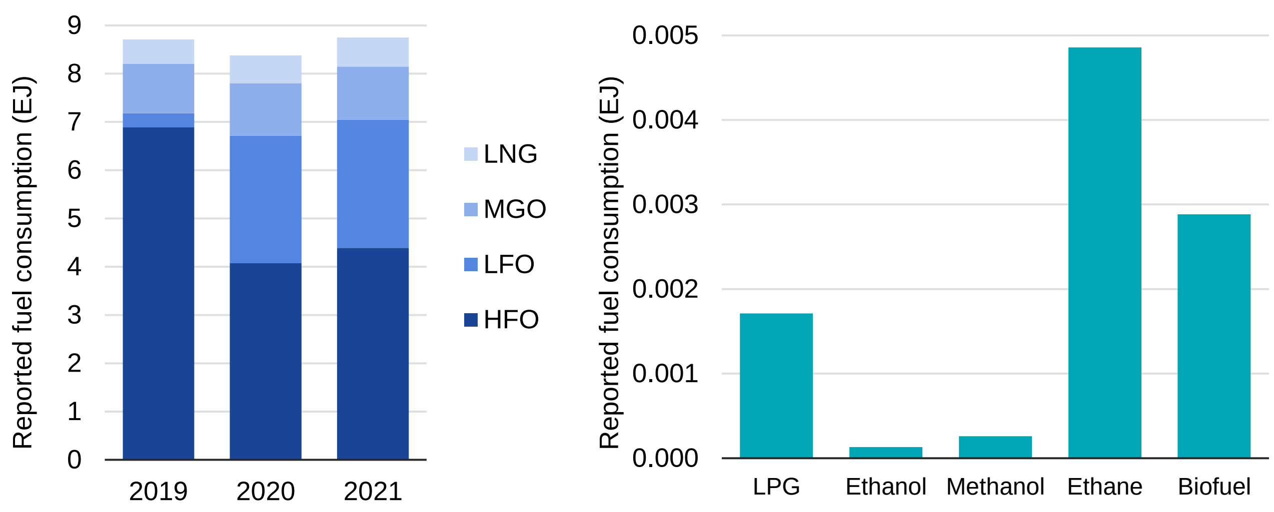
5.1 EXISTING PORT AND BUNKERING INFRASTRUCTURE CAN BE USED FOR SOME CANDIDATE FUELS, AND WILL NEED TO BE DEVELOPED FOR OTHERS

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.

Today, 99.9% of the fuel consumption of ships >5000GT is of conventional fuels (~93%) or LNG (~7%) (Figure 5-1). The LNG component is rising in absolute and proportional terms; it has an expanded bunkering network with a particularly high density of locations in Europe and an increasing number of refuelling facilities in Asia. The remaining 0.1% of fuel consumed in 2021 by >5,000GT vessels comprised ~49% ethane, ~30% biofuels (a growing proportion), ~17% LPG and the remainder methanol/ethanol. It's assumed these small quantities have been mainly delivered via small scale terminals with truck-to-ship transfers.

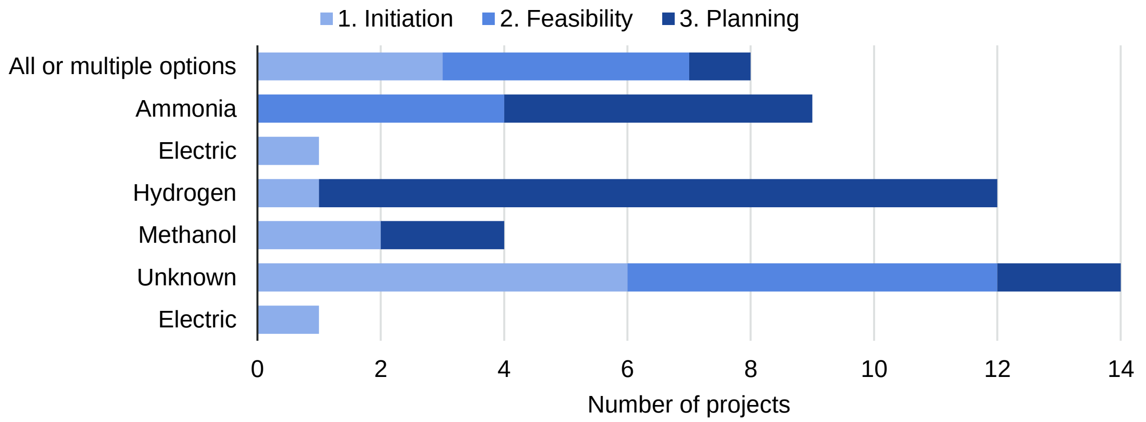
Figure 5-1: Reported fuel consumption for conventional fuels and LNG in 2019 to 2021 (left) and for minority fuels in 2021 (right)



Nearly half of bunkering takes place today at major bunkering hubs located along international trade lanes using ship-to-ship transfer: the top ten hubs supplied 44% of total fuel sold, with Singapore contributing over half of this 44%. This focus on refuelling in limited locations is strategic, because today the vessels have tank capacities large enough to allow them to refuel at the lowest prices, taking on board enough fuel for several voyages. **In the future, a shift may be needed away from refuelling being dominated by a small number of major bunkering hubs as some candidate fuels have lower energy density, reducing the range for the vessels.**

There are already several methanol and hydrogen vessels on order. This orderbook will drive demand for bunker facilities. However, this is not the only driver for demand, as, the total of 48 port and bunkering infrastructure projects identified by this study as pushing the provision for candidate fuels (Figure 5-2) includes a large number additionally related to ammonia as well as unspecified fuel types (often, these are green shipping corridor projects).

Figure 5-2: 48 port and bunkering projects were identified, categorised by fuel type and status of development



The push for **green shipping corridors** between ports/regions to overcome current barriers to deployment of candidate fuels is leading to several announcements for developing infrastructure and associated bunkering vessels at ports. Green shipping corridors is a concept aiming to facilitate adoption and bunkering infrastructure development of alternative fuels. The 'Global Shipping Challenge' at COP27 highlights the growing list of green shipping corridors that were initiated with the Clydebank Declaration at COP26.

We evaluated how well aligned the current distribution and storage and the bunkering infrastructure are for each group of candidate fuels. In summary, **bio- and e-diesel, and bio- and e-methane will be able to use existing bunkering infrastructure, while ammonia, hydrogen and methanol will need new bunkering infrastructure to be built**. Infrastructure will need to be tailored to each fuel's characteristics, with these ranges of characteristics posing a new complexity on infrastructure development. Table 5-1 is a high-level screening of the readiness for each candidate fuel.

Table 5-1 Screening of readiness of 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 global network of terminals, used for global methanol trading/transport	Demonstration bunkering operations have been successful, ship-to-ship bunkering proven. 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.

5.2 SHIPYARDS CAN SCALE UP TO MATCH CANDIDATE FUEL ROLL-OUT

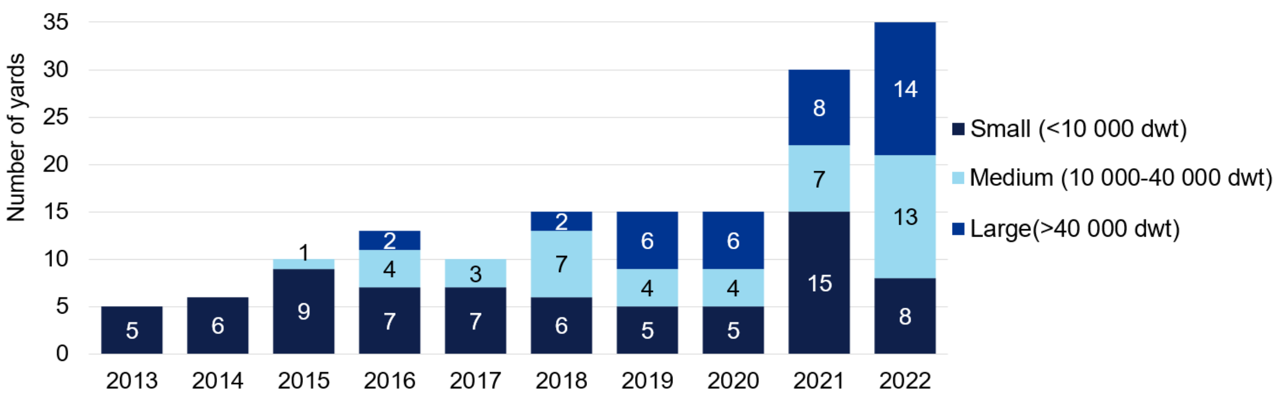
Key findings:

- 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.

The shipbuilding industry has excess newbuild capacity, as current production levels are just less than half the peak of 130 million GT in 2011. 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.

Compared to the total number of newbuild vessels >1,000 GT delivered in 2022 of around 1500, around 8.0% of these were using alternative fuels of LNG, LPG or methanol. This proportion has increased from 1.7% in 2020, and 4.2% in 2021. **The 2023 orderbook suggests this increasing trend of building alternative fuelled vessels continues**. There has not only been an increase in the number of alternative fuelled vessels delivered in the period 2013 to 2022, but that **there has also been an increase in the number of yards delivering larger alternative fuelled vessels** (Figure 5-3).

Figure 5-3: Number of shipyards that have delivered small, medium and large vessels running on alternative fuels above 1000 GT per year from 2013 to 2022



Source: IHSMarkit (2023)

As an example of the industry's ability to scale up, the development of exhaust gas cleaning systems (EGCS) was driven by the revised MARPOL Annex VI which capped marine fuel sulphur content at 0.5% from 2020, unless the ship had an EGCS. After the IMO reviewed and confirmed the regulation in 2016, the uptake of EGCS accelerated: around 4,000 ships were retrofitted with EGCS from 2017 to 2020. This example implies that **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**. Hence industry capacity 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 alternative fuels such as ammonia or methanol is more complex. Recently, more than 200 vessels have been built with various 'fuel-ready' notations, indicating that these have been prepared to a certain degree for retrofitting at a later point in their life. This is expected to reduce the complexity of retrofitting, potentially increasing the number of yards that can do such retrofits.

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

6. POTENTIAL AVAILABILITY OF CANDIDATE FUELS

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.

To estimate the availability of candidate fuels in 2030, we developed three availability scenarios based on compiled data from various databases and reports on existing, planned, and announced fuel production projects. The scenarios are:

- A **confirmed projects (low)** scenario where the final investment decision has been made
- All **announced projects (mid)** scenario
- An extrapolated **additional projects (high)** scenario, based on historical growth rates of similar technologies, assuming additional projects are announced until 2024 which could be commissioned and in operation by 2030.

The difference between *all announced projects* and those with *confirmed* final investment decisions suggests that clarity on future demand, e.g. through the Revised IMO GHG Strategy, may help reduce this uncertainty in availability. Indeed, further *additional projects* are considered possible if a firm demand is agreed and if policies requiring or incentivising the scaling-up of production are agreed.

Our estimates of candidate fuel availability further ahead, to 2040 and 2050, are based on reviews of multiple global energy system forecasting studies. We clustered studies into those that are forecasts of business as usual (i.e. assume current policies), and those that adopt decarbonisation ambitions (i.e. assume additional policies are implemented to help achieve those ambitions).

- Our **BAU trajectories (low)** scenario is based on the median of the availability in the BAU trajectories forecasts, and
- The **Decarbonisation trajectories (mid and high)** scenarios are based on the median and high range of the availability in the decarbonisation trajectories forecasts.

The above scenarios are summarised in the table below.

Scenario	2030	2040 and 2050
Method	*Based on fuel production and CO_2 storage projects*	*Based on global energy system forecasts*
Low	Confirmed projects	Median of BAU trajectories
Mid	All announced projects	Median of decarbonisation trajectories
High	Extrapolated additional projects	High end of decarbonisation trajectories

To support the scenarios, several assumptions have been made as follows.

The estimates of near-term availability (2030) as well as the longer-term forecasts (2040, 2050) are of fuel availability to the transportation sector. For methanol and ammonia, traded today as commodities, it was impossible to tie individual projects to intended end use, and we assumed a 20% share for transportation in the low scenario and 80% in the mid and high scenarios. Of fuels for transportation, a proportion is to maritime transport. Indeed, 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 demand are not determined. Based on our review of multiple forecasting studies, we assess the maritime sector could increase its share of the total transportation fuel consumption, excluding electricity, from its current 10% share, and could rise to 37% by 2050.

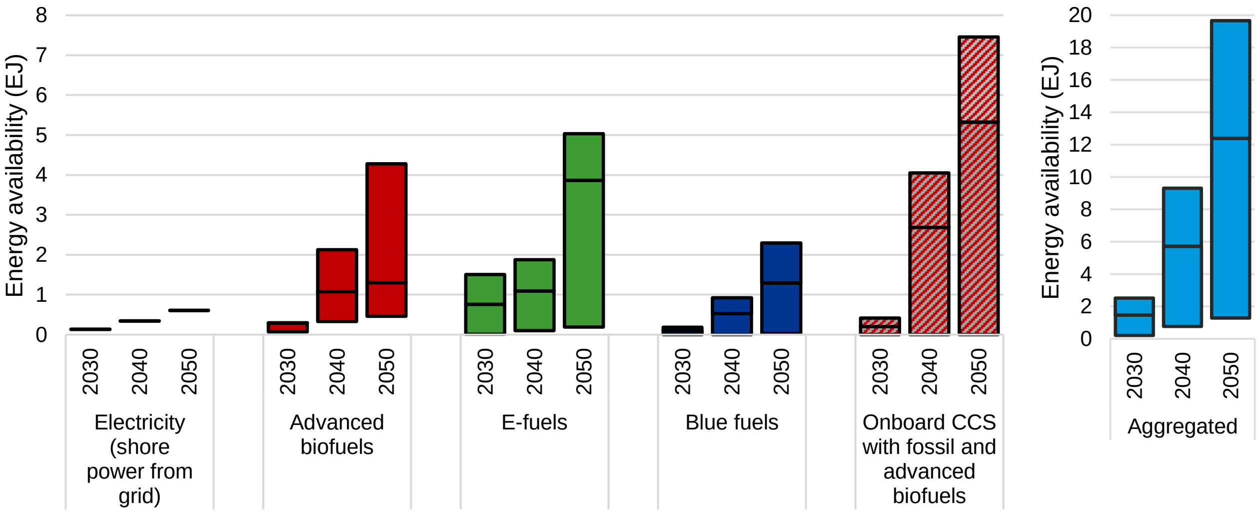
We have included all available data on production capacity for advanced biofuels; conventional biofuels using food and feed crop feedstocks have been excluded. The type of biomass and impact on indirect land-use change (ILUC) will be a key determinant of lifecycle GHG emissions.

The potential ceiling for deployment of onboard carbon capture was assessed based on a review of the global capacity for permanently storing CO_2, and how much the shipping sector could access of this storage capacity. The assessment in 2030 is based on announced projects, and an estimate of the potential for additional projects based the current growth rate. For 2040 and 2050, the assessment is based on the median and high range of the global energy system forecasts that have projected volumes of CO_2 stored. We expect that there will be infrastructure around storage sites, but shipping would need its own specialised infrastructure for receiving the CO_2 from ships and transporting it to storage sites or reception facilities. Considering shipping is a hard-to-abate sector, we assume that shipping could access up to 5% of the global CO_2 storage capacity.

Based on the above scenarios and assumptions, the span of estimated availability of candidate fuels for shipping in 2030, 2040, and 2050 is shown in Figure 6-1. Currently announced projects for production of e-fuels are already close to the median production volume of the energy system forecasts for 2040. 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 is forecast to grow after 2030 with increased storage capacity.

The results indicate a span in aggregated candidate fuel availability for shipping from 0.2–2.5 EJ in 2030, 0.8–9.3 in 2040, and 1.3–19.7 EJ in 2050. It is important to note however that the high availability scenarios do 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, both on the planning and the commission phase. As the forecasts are based on matching the demand with availability, they do not represent the maximum growth possible in fuel production. To reach the high range availability in 2050 an average annual growth rate of 6-12% would be required from currently announced projects in 2030, which is well below the historical sustained growth rates seen for solar and wind power generation.

Figure 6-1: 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

7. THE PRICES OF CANDIDATE FUELS ARE NOT A BARRIER TO THEIR UPTAKE IF DEMAND IS KNOWN AND PLANNED FOR

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.

The previous chapter suggests that readiness of technologies, infrastructure and shipyard readiness are unlikely to be a barrier to their adoption. This section considers cost barriers related to the candidate fuels.

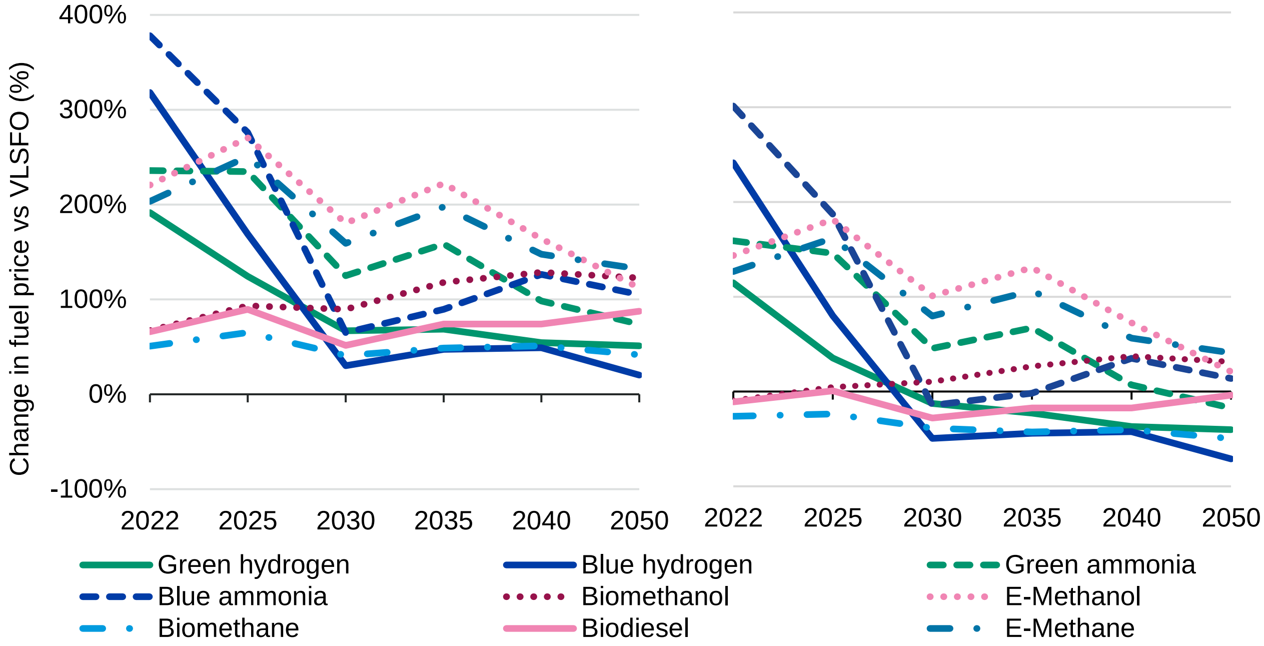
Several of the candidate fuels (bio- and e-diesel, bio- and e-methane) are considered ‘drop-in’ fuels which can be used in existing machinery and will not lead to additional vessel capital costs compared to the fuels they displace. The additional capital costs of vessels using ammonia or methanol (+11% to +16% relative to conventional fuels, dependent on the ship type), are not expected to be markedly different to the relative increased costs of LNG vessels. Given LNG vessels already make up 10-20% of the global order book, it is reasonable to assume that, for many segments of the market, **the increased capital costs of vessels using these candidate fuels will not be a significant barrier to adoption**. And as the current orderbook includes several methanol fuelled vessels, the **upfront costs of some alternatively fuelled vessels can already be managed today**, provided the right incentives and fuel supply are in place. It can nevertheless still be expected that there may be some highly price-sensitive vessel categories or geographies.

The high capital costs of onboard carbon capture systems are anticipated to be a barrier to adoption. Onboard carbon capture systems are considered in this paper for pairing with drop-in replacements for VLSFO. Early estimates range from 25% to 70% increases in vessel capital costs, depending on the capture rate and the type of vessel. These increases in capital costs are significantly higher than those for the candidate fuels discussed above, so represent a greater barrier to adoption.

Instead, provided the fuel is available, the price of the fuel itself could be the main barrier to uptake of candidate fuels, as fuel can account for 50-60% of vessel total annualised costs (though this varies by vessel type). The prices of alternative fuels are expected to be higher than conventional fuels. Nevertheless, the high variations over the last decade of conventional bunker prices have been accommodated by the industry by necessity. These fluctuations have undoubtedly caused knock-on impacts and disruption, affecting pass-through costs and profitability, particularly when prices have risen considerably over short periods. But based on this historic accommodation of price volatility, and supported by views of experts consulted**, 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 the fuel prices could change**. Uncertain and/or immediate price shocks are problematic, whereas known and planned-for price changes can be less problematically accommodated by the market.

Assessing the future prices of conventional fuel and of candidate fuels is highly uncertain. However, our meta-analysis of others’ price forecasts, and taking into account the fuel cost saving from increased energy efficiency measures, suggests that many of the candidate fuel prices (on an energy content basis) are forecast to lower to within a doubling of the forecast VLSFO by 2050, which could be considered to be within the fuel price volatility already often accommodated by the industry (Figure 7-1, left). Furthermore, should policies be agreed that would act to put a price on environmental externalities (e.g., through a price on carbon) – for example faced today by participants of the European Union Emissions Trading System – would bring down the forecast prices of the candidate fuels to within ±50% of the forecast price of VLSFO in 2050 (Figure 7-1, right).

Figure 7-1: Forecast of fuel costs relative to VLSFO after accounting for the impact of additional energy efficiency measures, without a €100/t carbon price (left), and with a €100/t carbon price (right).



These findings point to the need to provide a clear demand signal of the market through the clear specification of the ambition level for decarbonisation, how this will be met through policy measures, and concretely what the scope of the policy measures will be regarding how fuels and their GHG emissions (TtW/WtW, and which GHGs) will be accounted. Experts consulted highlighted their wish to know the planned (policy-driven) changes a long time in advance to allow for factoring in fuel price changes, including adopting efficiency measures to mitigate the effect of fuel price increases.

PART C: IS IT FEASIBLE TO MEET THESE DECARBONISATION SCENARIOS?

Part C evaluates the feasibility of meeting the decarbonisation pathway based on the technology, candidate fuel and infrastructure availability and readiness (Section 8), suggests possible mitigating actions to help achieve the pathways (Section 9), before ending with concluding remarks (Section 10).

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

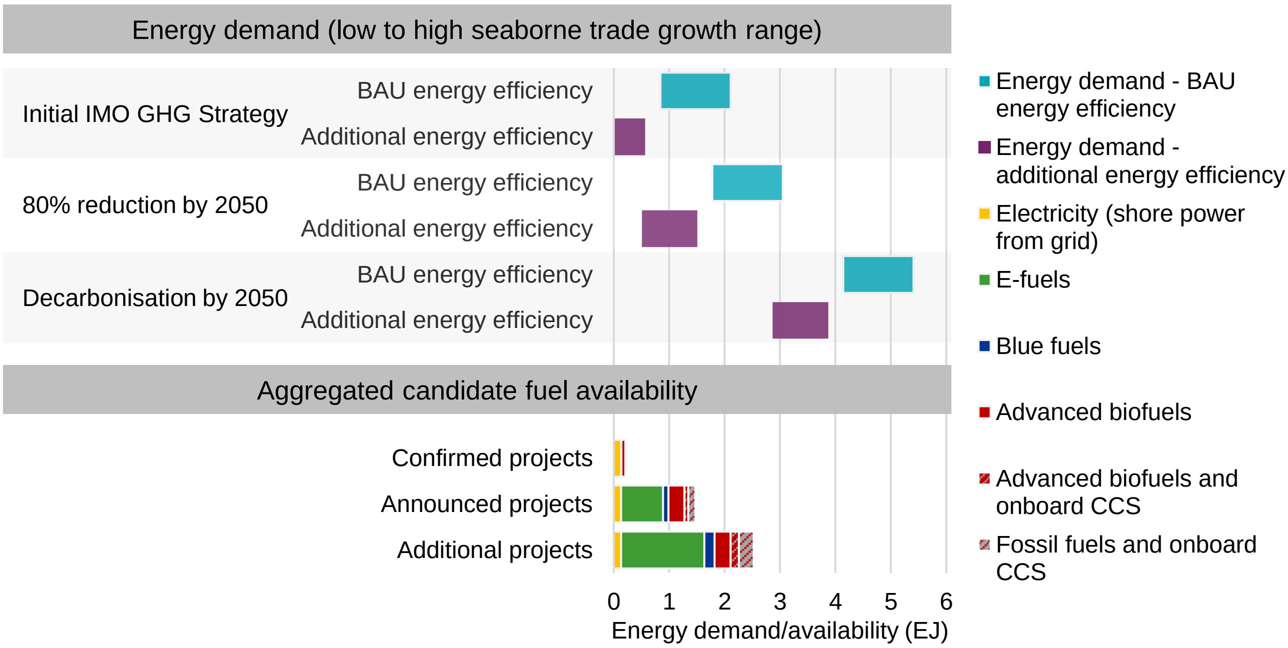
- The feasibility of these decarbonisation scenarios, and particularly the most ambitious pathways, requires an early clarification of further policy targets and measures to help unlock investment in candidate fuels and their associated infrastructure.
- From a basket of candidate mid-term GHG reduction 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. FEASIBILITY OF MEETING DECARBONISATION SCENARIOS

8.1 FEASIBILITY OF MEETING DECARBONISATION SCENARIOS IN 2030

Figure 8-1 compares the demand for candidate fuels for each of the decarbonisation scenarios and under the high and low growth scenarios, against the availability of candidate fuels under different availability scenarios by 2030. This shows the potential gap by 2030 between demand and availability for each decarbonisation scenario.

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: The required quantity 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. Candidate fuel availability shows the aggregated availability per fuel and should not be construed as a likely fuel mix.

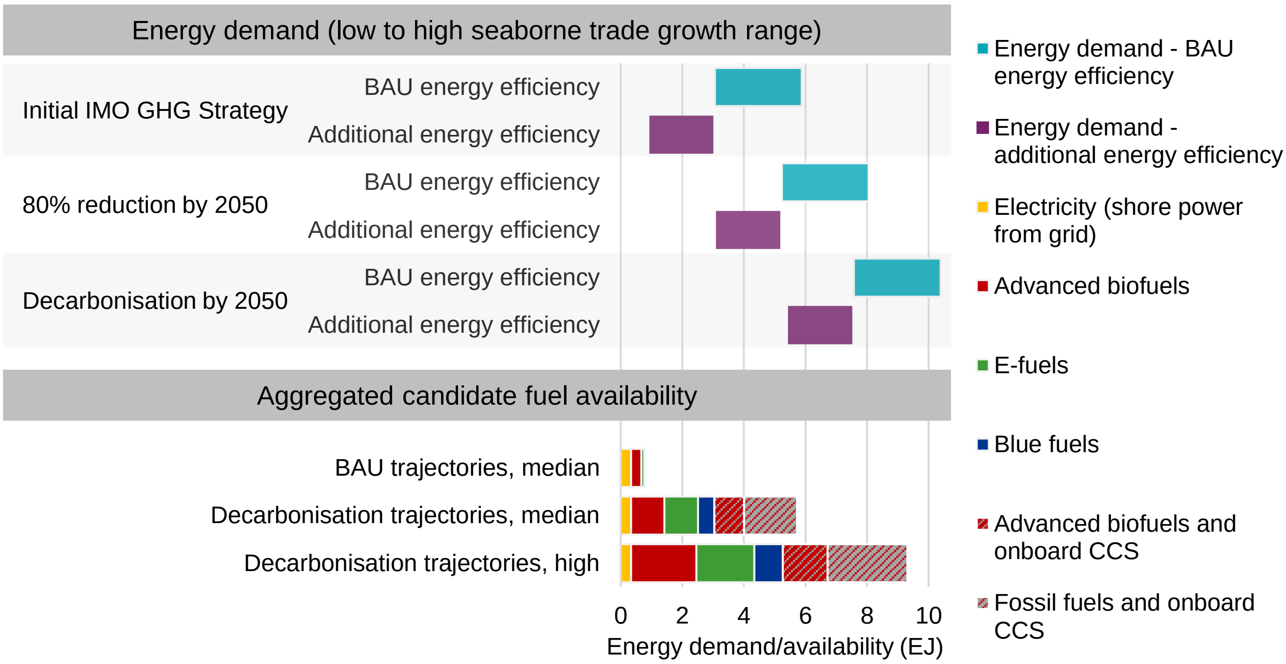
The following conclusions can be drawn for each decarbonisation scenario by 2030:

- **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 BAU 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.

8.2 FEASIBILITY OF MEETING DECARBONISATION SCENARIOS IN 2040

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.

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: The required quantity 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. Candidate fuel availability shows the aggregated availability per fuel and should not be construed as a likely fuel mix.

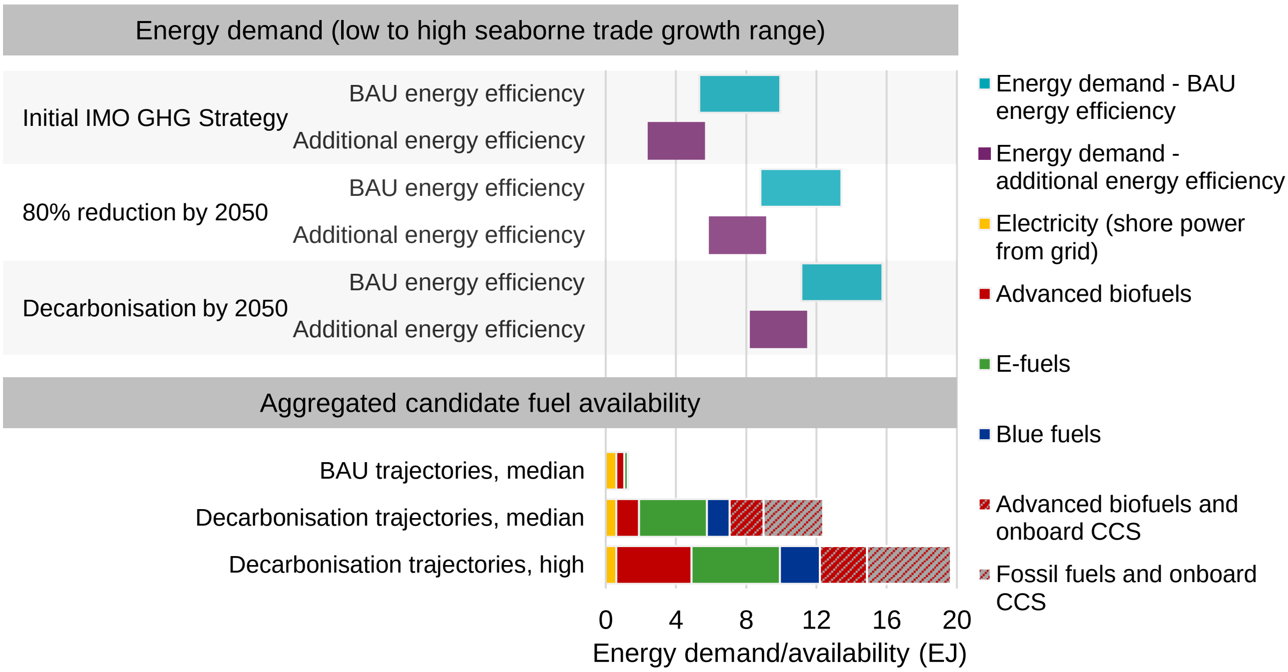
The following conclusions can be drawn for each decarbonisation scenario by 2040:

- **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*.

8.3 FEASIBILITY OF MEETING DECARBONISATION SCENARIOS IN 2050

Figure 8-3 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 2050. This shows the potential gap by 2050 between demand and availability for each decarbonisation scenario.

Figure 8-3: Top: energy demand for candidate fuels in 2050, without and with additional energy efficiency savings; Below: candidate fuel availability scenarios by 2050



Notes: The required quantity 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. Candidate fuel availability shows the aggregated availability per fuel and should not be construed as a likely fuel mix.

The following conclusions can be drawn for each decarbonisation scenario by 2050:

- **Initial IMO GHG Strategy: Feasible with increased policy ambition**. A combination of energy efficiency measures and energy availability 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 additional energy efficiency measures under low growth. Under a high growth scenario, either the full potential of additional energy efficiency measures or a higher availability 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.

8.4 SUMMARY OF FEASIBILITY ANALYSIS

The feasibility analysis by 2030, 2040 and 2050 is summarised in Table 8-1. **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 8-1: 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 <u>if policies to deliver an increased level of ambition are implemented in the short term</u>. 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[9] 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

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

APPENDIX: ABBREVIATIONS, AND INDEXES OF FIGURES AND TABLES

List of abbreviations

Abbreviation	Definition
BAU	Business as usual
CCS	Carbon capture and storage
CII	Carbon intensity indicator
CH_4	Methane
CO_2 / CO_{2e}	Carbon dioxide / Carbon dioxide equivalent
EEDI	Energy efficiency design index
EEXI	Energy efficiency existing ship index
EGCS	Exhaust gas cleaning systems
EJ	Exajoule
GHG	Greenhouse gas
GJ	Gigajoule
GT	Gross tonnage
GWP	Global warming potential
HFO	Heavy fuel oil
ICE	Internal combustion engine
IMO	International Maritime Organization
LCA	Life cycle analysis
LFO	Light fuel oil
LOHC	Liquid organic hydrogen carrier
LPG	Liquefied petroleum gas
LNG	Liquefied natural gas
MGO	Marine gas oil
MJ	Megajoule
Mt	Megatonnes
N_2O	Nitrous oxide
SEEMP	Ship energy efficiency management plan
TtW	Tank-to-wake
VLSFO	Very low sulphur fuel oil
WtT	Well-to-tank
WtW	Well-to-wake

Index of figures

Index of tables

In Association with:

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