Future Maritime Fuels in the USA – the options and their potential pathways

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Preface

This report has been written by a team of experts from UMAS for Ocean Conservancy. This report looks at the current state-of-the-art in maritime fuels with the purpose of understanding their potential specifically in the US maritime context. The views expressed are those of the authors, not necessarily of the client.

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About UMAS

UMAS undertakes research using models of the shipping system, shipping big data (including satellite automatic identification system data), and qualitative and social science analysis of the policy and commercial structure of the shipping system. Research and consultancy is centred on understanding patterns of energy demand in shipping and how this knowledge can be applied to help shipping transition to a low-carbon future. UMAS is world-leading on two key areas: using big data to understand trends and drivers of shipping energy demand or emissions; and using models to explore what-ifs for future markets and policies. For more details visit www.u-mas.co.uk.

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List of abbreviations

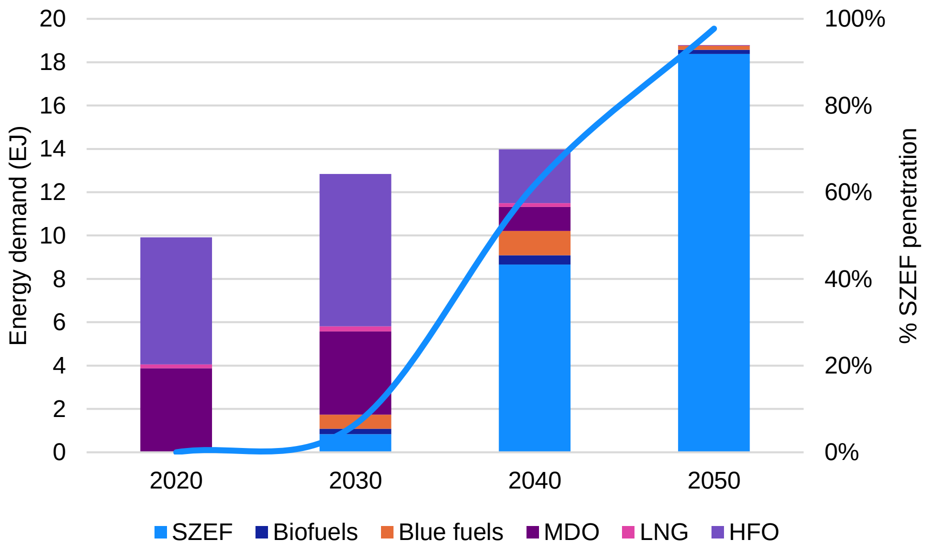
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalent
COP 26	Glasgow Climate Change Conference
DAC	direct air capture
DF	dual fuel
DME	dimethyl ether
DOE	Department of Energy
ECA	emission control area
EGR	exhaust gas recirculation
EPA	Environmental Protection Agency
EU	European Union
FAME	fatty-acid methyl ester
FC	fuel cell
FT	Fischer-Tropsch
GHG	greenhouse gas
GWP	global warming potential
HFO	heavy fuel oil
HT PEMFC	high-temperature proton exchange membrane fuel cell
HVO	hydro-treated renewable diesel
ICE	internal combustion engine
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MDO	marine diesel oil
MEPC	Marine Environment Protection Committee
MGO	marine gas oil
NO_x	nitrogen oxide(s)
PEMFC	proton exchange membrane fuel cell
PM	particulate matter
SCR	selective catalytic reduction
SMR	steam methane reformation
SOFC	solid oxide fuel Cell
SO_x	sulphur oxide(s)
SZEF	scalable zero emission fuels
TCO	total cost of ownership
UK	United Kingdom
US	United States

Executive summary

The shipping industry is at the start of a radical technology change and energy transition. The fossil fuels that supply the energy for moving passengers and freight by sea globally, as well as in the United States of America (US), will need to be substituted with new energy sources, supply chains for the production of that energy, propulsion technologies and ships.

The pace of this transition globally, along with transitions across all sectors of the economy, will need to be unprecedented, if we are to achieve the goals of the Paris Agreement. This report shows that the US is particularly well positioned to be a leader in that transition – and be at the vanguard to aligning its fleet and energy system to scalable zero emission fuels (SZEF) this decade:

- The US government has already taken a prominent political position, at the highest level, on the imperative for international shipping to reach zero greenhouse gas (GHG) emissions by 2050. Achieving this globally in just 28 years is only possible with major action and investment taken now by the US and other countries in a similar position.
- It is estimated that by 2030 the global average take-up of SZEFs needs to be 5% as a share of shipping's energy demand, but developed economies - as early adopters - will need to take a much higher share in the same timescale. The Getting to Zero Coalition's transition strategy proposes that such countries could decarbonise up to 30% of their domestic shipping emissions by 2030.



Source: Adapted from [101]

Figure 1 Global fuel transition mix towards decarbonisation in 2050

- As well as overarching GHG target leadership, the US government has taken up leadership on some of the key initiatives for progressing the use of SZEFs, such as Mission Innovation, as founding signatory of the Clydebank Declaration which aims to establish international corridors for early use of SZEFs, as well as leadership of the First Movers Coalition.
- The US domestically has several natural advantages, in the form of technology expertise and existing energy infrastructure that make it well suited to early use of the leading candidate SZEFs.
- The scale of coastal and domestic shipping in the US means that, although some existing fossil fuel use will be substituted by battery electrification, significant portions of shipping's energy demand will need to be met by SZEFs. National emission reductions will therefore be limited by the ability for the US shipping sector to access SZEFs.

- The US has a number of domestic routes on both the east and west coasts that lend themselves to early adoption of SZEFs, and these routes have been identified as some of the best routes globally for early adoption of SZEFs.
- The US has key trade routes that drive its economic prosperity, all of which are vulnerable to disruption by climate regulations if the operators on these routes do not proactively approach this fuel transition. The US can reduce trade and economic risk through early adoption action on SZEFs.
- Policy solutions will ultimately be needed at the International Maritime Organization (IMO), but the agreement of multilateral policy is only likely once solutions can be demonstrated at the domestic/national scale. The US as a key member state of the IMO, can improve the standing of this United Nations agency, and accelerate adoption of multilateral policy, by being progressive in its national leadership on SZEFs.

With these arguments creating the clear justification for US action on future maritime fuels, this report provides detailed analysis of the candidate SZEFs, their comparative suitability, and the pathways through which they could be both produced in the US and used in US shipping, in order to efficiently substitute out the existing fossil fuels. The report also explores the policy solutions that can incentivise their use. Some of the key findings include:

- There are many fuels that have the potential to be zero GHG emission. However, the upstream emissions related to different production pathways for the same fuels can make a big difference to their lifecycle GHG emissions. This can produce opportunities to phase in production of new fuels with progressively reducing lifecycle GHG emissions over time, but it also carries risks that unless energy production is incentivised to move to zero GHG, the GHG reduction potential of the fuel will not be realised.
- Of the candidate SZEVs, there are two key pathways for their production, one using natural gas (blue), and one using renewable electricity and electrolysis (green). Blue production pathways can serve a purpose in the short to medium term to help create lower cost supply and develop a market, as well as to help scale up production, but they will ultimately become less competitive to green production pathways.
- Given the ultimate need for green production pathways, the scale-up and reduction in the price of additional renewable electricity supply and electrolysis capacity (for the production of green hydrogen) is essential to efficiently transition away from fossil fuel use. Creating demand for hydrogen is therefore key, as is integrating shipping's demand for hydrogen into wider economic, state and national strategies.
- This report estimates that biofuels have only a small role to play in the transition because they suffer from scalability challenges as well as expectations of strong demand from other sectors.
- The transition to SZEFs needs to happen in parallel with increases in energy efficiency. This can both reduce the production volumes of SZEFs needed, and the cost of their use in shipping, as well as helping to secure GHG reductions from this sector in the 2020s while fuel-related GHG emissions may still be high.

The industry has several potential fuel options with specific implications that need to be evaluated carefully, because not all SZEFs are born equally.

Hydrogen and ammonia are both very versatile fuels capable of powering many applications by the use of fuel cells or internal combustion engines (ICE). The shipping sector sees hydrogen and ammonia as a way to shift away from fossil fuels to a zero-carbon future. In particularly, ammonia is an effective carrier of hydrogen and is deemed to be a long-term decarbonisation solution for ocean-going shipping (a sector that contributes 80% of the total carbon dioxide (CO_2) from global shipping).

Large-scale hydrogen and ammonia marine engines are expected to be commercially available by the mid-2020s, while large-scale fuel cell arrangements will be ready by 2023. Yet due to the inexperience of using hydrogen and ammonia technologies in the shipping sector, there are few rules and guidelines to control safety risks associated with the flammability and toxicity. Maritime risk-management expert DNV is establishing guidelines for the safe handling of hydrogen and ammonia as a shipping fuel, while amendments to the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels are required to establish international regulations for use of the fuels.

First generation (conventional) biofuels do not offer any reduction in overall CO_2 emissions. This is due to their high impact on land use, whereby highly carbon extracting forestry and grasslands are exchanged for low carbon extracting crops, thus negating the reductions that biofuels offer downstream.

Advanced biofuels, however, enable a significant reduction in lifecycle CO_2 emissions, but production routes and supply chains are yet to be established in a scale that can enable any meaningful decarbonisation in the shipping sector.

By the time that advanced biofuel supply routes are established, the sheer demand for fuel from other sectors will outprice the maritime sector to choose other scalable alternatives. And thus, the cost of production for biofuels can be very different to the prices that will be set by the market.

The current annual production capacity for methanol is 110Mt and has grown to more than present-day demand, so it is recognised that, in terms of supply, methanol may be able to satisfy a short- to medium-term demand as a maritime fuel. However, methanol production today is natural gas intensive and resultant overall GHG emissions is around 5% higher than that of heavy fuel oil (HFO). It is therefore crucial for cleaner supply chains to develop with the expansion of direct air capture (DAC) or carbon capture and storage (CCS) technology. Otherwise, in terms of lifecycle GHG emissions, methanol uptake would be a step in the wrong direction.

It is important to distinguish between different production pathways for hydrogen and ammonia.

The “colour” of a hydrogen pathway defines its feedstock. Grey is produced from natural gas via steam methane reformation (SMR); brown is produced by the gasification of coal; blue – is also produced using natural gas via the SMR process, but CO_2 emissions are captured using CCS; and green hydrogen is produced using renewable electricity.

Grey/brown hydrogen production methods account for 95% of all hydrogen produced today. Overall, the CO_2 emissions released solely from the production of worldwide grey hydrogen are equivalent to around a third of emissions released from EU member states: 830MtCO_2 annually.

Fugitive methane emissions released from upstream and mid-stream processes associated with grey and blue hydrogen will likely counteract any progress made by the reduction of CO_2 emissions from downstream emissions. Levels of methane leakage are currently uncertain but are a significant cause for concern because the global warming potential (GWP) of methane is 81 times that of CO_2 over a 20-year period. This suggests that, in the short term, curbing methane emissions is one of the most effective ways to combat global temperature rise.

The US has the potential to produce low-cost green hydrogen and launch a green hydrogen economy. Despite being situated in a unique position with low-cost renewable power from wind, solar and hydropower, currently, only 12% of the overall energy production in the US is derived from renewable sources. The ambition to produce 30GW of offshore wind power by 2030 is a step closer to decarbonisation of the power sector: which could contribute to the early establishment of green fuels in the shipping sector.

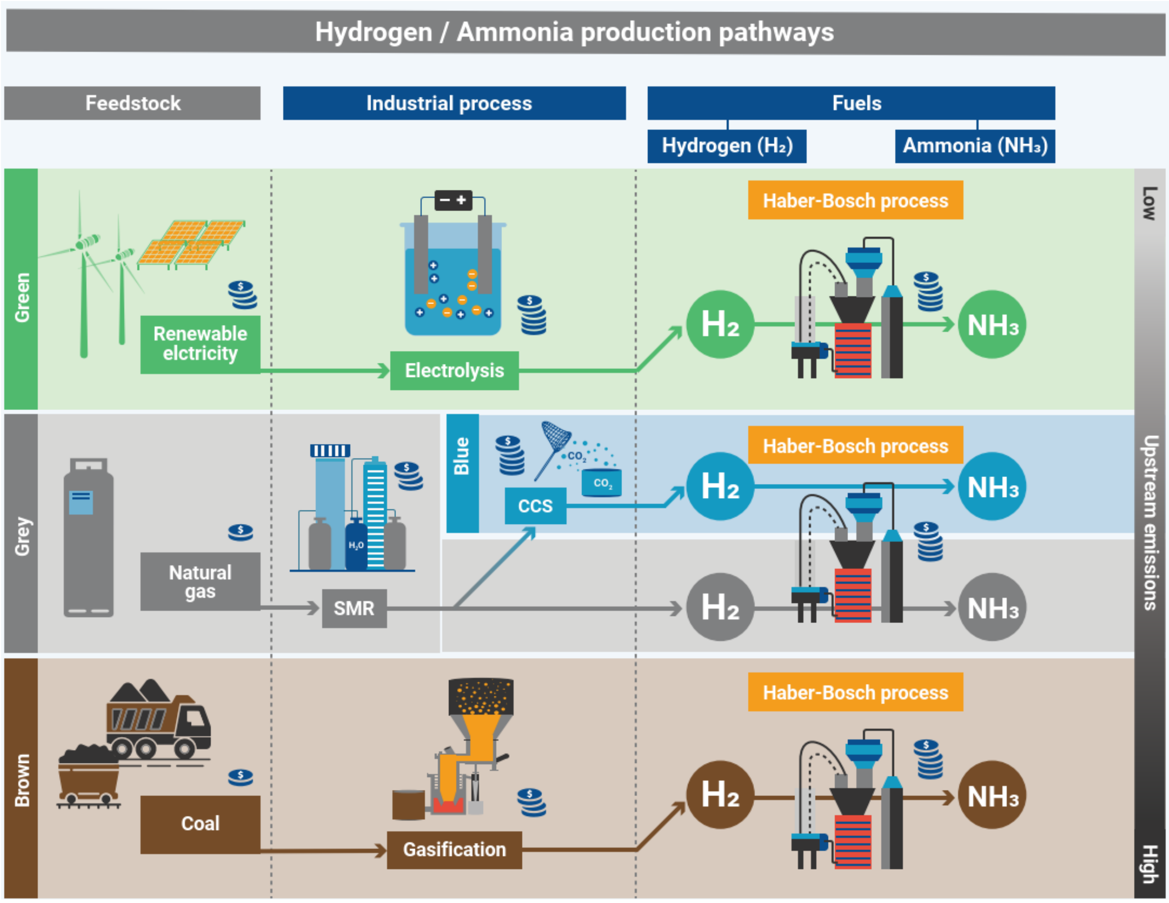


Figure 2 Hydrogen and ammonia production routes

A potential zero emissions pathway

As a means of achieving zero emission shipping goals by 2050, a progressive stance must be taken to establish green fuel supply chains in the immediate future so that when the transition unfolds these fuels scale up to lead the trajectory to zero emissions by 2050.

Recent work conducted by UMAS shows that around 10% of shipping's total fuel consumption takes place on routes that have ideal conditions for transitioning to SZEFs during the 2020s. These first mover routes are all domestic, regional or only require small groupings of countries that can incentivise the use of hydrogen by plurilateral action (groups of like-minded countries acting together) and show that the decarbonisation of shipping, as well as other neighbouring industries (e.g. the energy, cement and steel industries) is commercially viable.

To harness the short- to medium-term hydrogen demands, it may be necessary to draw upon current production methods and convert grey hydrogen and ammonia facilities into blue. This will be possible through the development of CCS, while significantly limiting methane leakage upstream and methane slip on board. Yet CCS is currently not at the level of development that can enable a rapid transition of facilities to blue hydrogen. Huge investments are therefore necessary, but there is potential that this will delay the investment in green hydrogen production facilities. And invariably, blue hydrogen will lose its competitive advantage over green in the mid-transition, which makes investment in CCS and reducing methane leakage questionable.

Methanol and biofuels are seen as a 'bridging' mechanism. From a technological standpoint these fuels are further developed than hydrogen and ammonia, but they are unable to deliver adequate emission reductions to be classed as a long-term solution.

Changes in maritime fuel are driving developments in propulsion technologies which need to provide flexibility.

The long design life expectancy of ships (around 25–30 years) and consequent long-term financial implications means that decarbonisation will not be rapid. But the ability to convert a ship to operate zero-carbon fuels will play a pivotal role in the transition to 2050 and decisions made for new-builds today will have long-lasting consequences. Hence, ship owners will have to make critical investment decisions to carefully balance the finances and ensure their assets do not become stranded.

The modern 2-stroke engine can burn almost anything. With modifications to the injection and fuelling supply systems and the addition of extra fuel tanks, a ship can be transitioned relatively easily to a dual fuel (DF) engine operating on a conventional fuel along with a zero-carbon fuel. Fuel cells are immature compared with DF engines. And with the very limited bunkering of hydrogen-based fuels, fuel cell applications in ships are currently limited to niche routes via demonstration or pilot projects, and/or projects that have been developed in parallel with wider energy networks.

Proton exchange membrane fuel cells (PEMFC) costs will likely be halved by 2050; however, it is unlikely that the total cost of ownership for a fuel cell will reach as low as a DF engine. Yet more efficient fuel cells (e.g. solid oxide fuel cells) will likely disrupt the debate in the long term once the world is dominated by zero emission fuels and being the only real way to obtain true zero emissions.

Several levers are available for the US to expedite the transition to SZEFs.

A wave of support for climate progressive action suggests the US government is embarking on a new paradigm. Re-joining the Paris Climate Agreement and setting out a USD 2 trillion clean energy investment to fully decarbonise the power sector by 2035 has cemented the ambitions towards climate change.

To proceed with the US goal of zero emissions by 2050, the US Department of Energy must rethink its hydrogen program plan. It was released in November 2020 and, with the inauguration of the new administration in January 2021, there is potential to reflect on the progressive new stances on climate change and align with a rethought long-term hydrogen plan that envisages green hydrogen as a fundamental element. This could look similar to the European Union (EU) Hydrogen Strategy, which predominantly aims to accelerate “renewable hydrogen” (green) but recognises the role of blue hydrogen initially and envisions a gradual trajectory to carbon neutrality by 2050.

In order to utilise blue hydrogen in the pursuit of deep decarbonisation, there is a substantial need to upscale CCS, but it is also crucial to understand the issues of methane leakage and apply a regulatory framework throughout the supply chain. The Trump administration removed methane as a regulatory pollutant in 2020, but the US congress repealed the rule in June 2021, thus making a step in the right direction. The US Environmental Protection Agency (EPA) planned to propose the “nation’s strongest rules against methane emissions” within the Clean Air Act 2021.

Taking into account local shipping segments favourable for decarbonisation, localised regulations, regional fuel availability, and other factors such as innovation clusters, proactive local actors and communities, there are four key geographic regions (i.e. the west coast, the Gulf, the Great Lakes, and the east coast) identified as being the most promising for the early adoption of SZEFs.

1 Introduction

1.1 Shipping's decarbonisation requires radical change and the introduction of new fuels

Maritime shipping is a growing contributor to anthropogenic climate change, with total emissions of around 1 gigatonne of carbon dioxide equivalent ($GtCO_2eq$) emitted in 2018 (2.89% of global emissions), which could increase to 130% of 2008 emissions by 2050 at a business-as-usual (BAU) scenario [1]. Following the adoption of the Paris Agreement and the stark warnings for temperature alignment coming from the Intergovernmental Panel on Climate Change (IPCC) [2], which imply the need for rapid decarbonisation, the industry is under increasing pressure to cut its carbon emissions. With such an aim in mind, in 2018 the International Maritime Organization (IMO) adopted an initial strategy to cut greenhouse gas (GHG) emissions from international shipping by at least 50% by 2050 compared with the 2008 levels (hereinafter referred to as IMO 2050) [3]. This target applies only to international shipping's operational emissions and does not include upstream emissions. As can be seen in Figure 1.1, for shipping to reach this decarbonisation trajectory the industry will have to significantly cut its emissions from the current BAU case. IMO 2050 is not aligned with the global temperature goal of 1.5ºC as set by the IPCC and the current Biden administration in the United States of America (US) has urged the IMO to increase its ambition to a 100% reduction by 2050 [4].

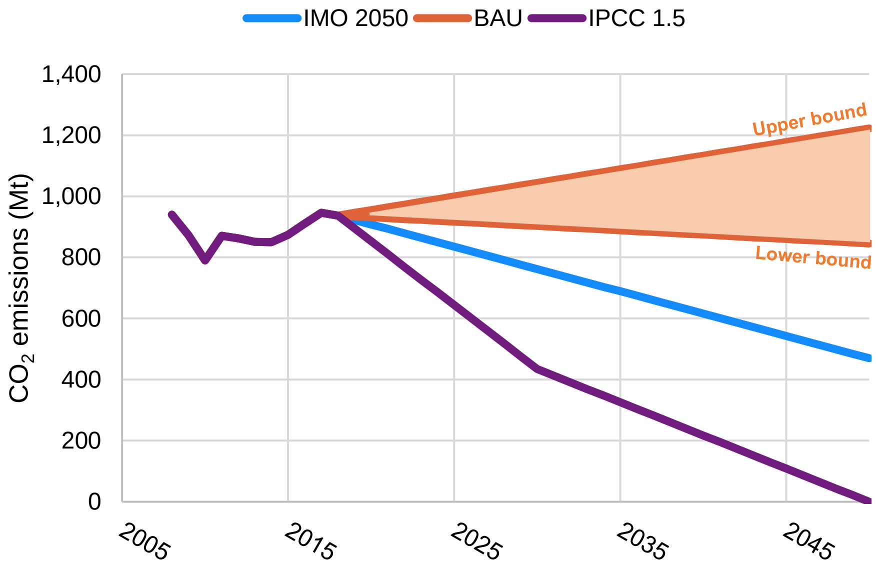


Figure 1.1 Global CO_2 emissions trajectories for potential future scenarios

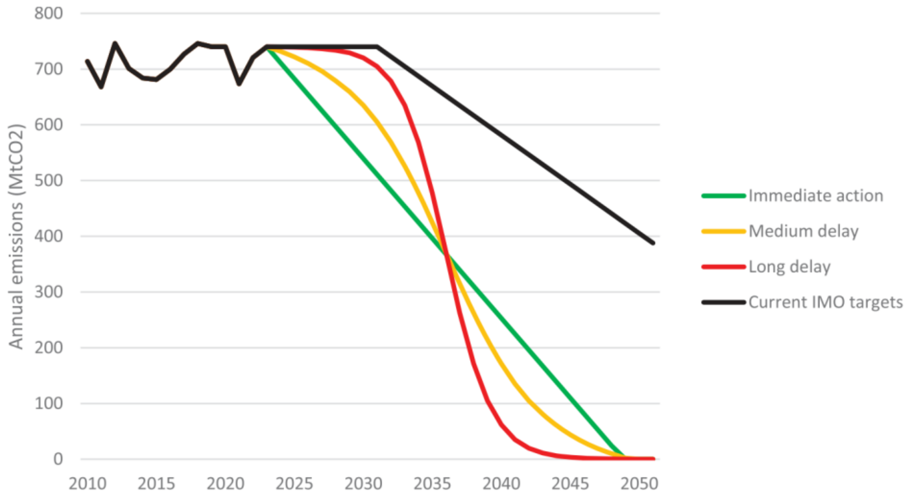
Such a rapid decarbonisation pathway will require the shipping industry to make a significant transition away from current ways of operating. Research by Lloyd's register and UMAS showed that, while it remains important to maximise efficiency, this cannot sufficiently lower GHG emissions from shipping to meet the ambitions of IMO 2050 [5]. In order for shipping to reach such goals, scalable zero emission fuels (SZEFs) will have to become an increasingly dominant part of the shipping energy fuel mix, replacing current fossil bunker fuels such as heavy fuel oil (HFO) and distillate fuels [5]. SZEFs contribute no GHG emissions throughout their whole lifecycle (both upstream in production and downstream when in use) and have no foreseeable supply constraints or barriers to production scalability.

There are several promising alternative marine fuels to be considered, each with its own merits and challenges. Questions relating to the feasibility of developing shoreside infrastructure, fuel costs, lifecycle GHG emissions, and current and future availability are causing ship owners, investors, fuels suppliers and the wider industry to delay making those investments. However, such delays would result in GHG emissions remaining at or increasing over current rates of increase, which would result in the need for an even more rapid decarbonisation pathway to achieve the 1.5ºC Paris-aligned temperature goals.

This problem is outlined in the recent IPCC assessment report (AR6), which showed that a global maximum limit of 500GtCO_2 emissions are allowed in order to have a good chance of not exceeding the 1.5ºC threshold by 2100 [6]. To put this into perspective, 500GtCO_2 is around 15 years of industrial emissions at current rates [7], which strongly indicates why hesitancy must be avoided.

If there were to be a stagnation period with failed action on GHG emissions the average global temperature would increase rapidly. This would demand an even quicker decarbonisation pathway, in which zero emissions must be achieved before 2050. This relationship is illustrated in Figure 1.2 using three decarbonisation trajectories: emissions that start to fall imminently (green – immediate action); emission that only start to fall by 2025 (yellow – medium delay); and emissions that start to fall in 2030 (red – long delay). Inactivity entails more rapid decarbonisation trajectories, and prolonged hesitancy until 2030 at current levels of emissions leaves only a decade to achieve zero emissions to avoid temperatures above 1.5ºC from pre-industrial levels by 2100. However, if emissions begin to fall in 2022 a less aggressive decarbonisation pathway is possible, avoiding an overwhelming feat that would result in a costly and disruptive transition [8].

For the shipping industry, the cornerstone of decarbonisation lies in fuel choice, which determines emissions on board ships as well as those associated with fuel production.



Source: Reference [8]

Figure 1.2 Annual emission trajectories in line with a global 1.5ºC carbon budget

1.2 Study objective

This report discusses the options available for the US maritime industry with regards to fuels that align with the emission reduction ambition set by the IPCC and the current US administration. Through a review of relevant studies and sources, the report will discuss:

- Maritime fuel options for the shipping industry, specifically SZEFs
- Different production routes for these fuels and implications in terms of emissions, costs and technology maturity
- The possible transition pathway away from the current fossil fuel status quo
- The role and implications of international and domestic emissions
- Policies and mechanisms that could incentivise and facilitate the transition.

2 US shipping – emissions and fuel demand

Maritime shipping in the US can be divided into domestic shipping (i.e. shipping connecting ports within US maritime waters) and international shipping (i.e. shipping responsible for international trade). The UMAS Fuel Use Statistics and Emissions (FUSE) model combines vessel technical specifications and automatic information system data to estimate fuel consumption and emissions for the global fleet. The model has been used for several applications, including the Third and Fourth IMO GHG studies [1], [9]. Figure 2.1 shows the total GHG emissions for US-flagged vessels for 2018, which amount to around 26MtCO_2 or 2.4% of global shipping emissions. Of these emissions 71% relate to domestic trade (presumably by vessels in the Jones Act fleet, as discussed in more detail in Section 3.1 of a related study [10]), while the remainder are from international voyages [10]. The US fleet's 2018 GHG emissions represent 0.5% of total domestic US GHG emissions [11].

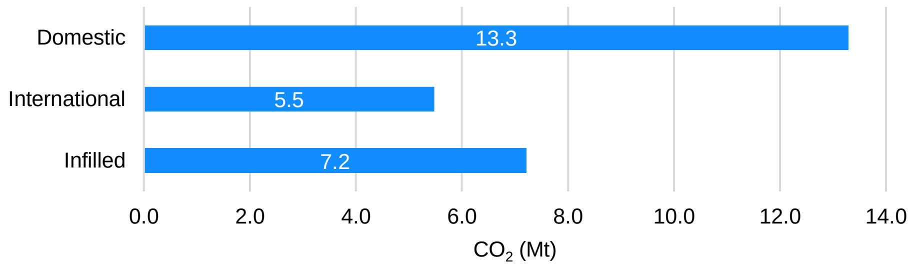


Figure note: Due to the nature of AIS data, not all vessels are captured because of poor coverage in some geographical areas, incomplete datasets or smaller vessels not having AIS fitted or switched on for a long enough period. In order to account for emissions from vessels missing from the AIS database, but whose technical specifications are found in the vessel database, an algorithm used in the Fourth IMO GHG Study [1] is applied. The purpose of the algorithm is to infill the missing emissions based on the average behaviour of a vessel of corresponding type and size. As a result, infilled data cannot be assigned to international or domestic trade specifically and is reported separately.
Source: Reference [10]

Figure 2.1 US-flagged fleet international and domestic emissions in 2018

As with many fleets worldwide, the current on-board machinery used in US-flagged vessels does not accommodate zero-carbon fuels, meaning the fuel mix is dominated by fossil fuels, mainly HFO, marine diesel oil (MDO) and limited amounts of liquefied natural gas (LNG), as shown in Table 2.1 and Figure 2.2. MDO dominates the US fuel mix, unlike the global fuel mix, where HFO is predominant.

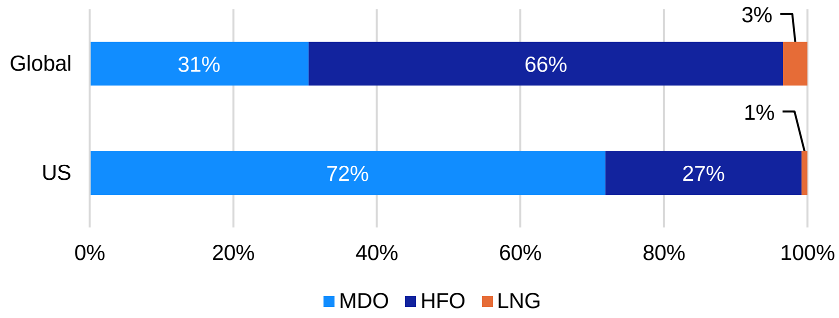
Table 2.1 Energy demand (TJ) US-flagged fleet, by fuel type, in 2018

	MDO	HFO	LNG	Methanol	Total
Total US fleet (TJ)	178	68	2	0	248
Total US fleet (%)	72	27	1	0	–
Total global fleet (%)	31	66	3	0	–

Source: Reference [10]

The difference between the global and US fuel mixes is that the US-flagged fleet is predominantly ships that operate within US waters and therefore are subject to emission regulations in the emission control area (ECA) in the US [12]. This makes MDO an obvious choice to reduce the level of sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM).

A small amount of LNG is being used as a fuel for container ships: this can be attributed to vessels operating between Florida and Puerto Rico [13], which are equipped with dual fuel (DF) engines due to their operation through ecologically sensitive areas on a closed-loop route making bunkering easy. While this may be seen as a solution to reduce CO_2 emissions, LNG has been extensively shown to be ineffective for several reasons, including methane slip (i.e. fugitive emissions) [14], [15], and use of LNG presents a serious risk of stranded assets[1] if investment in bunkering infrastructure is pursued [16], [17]. The notion of LNG playing a role as a temporary or transitionary fuel is flawed, given the subsequent technology lock-in that would make it very challenging to achieve zero carbon emissions.



Source: Reference [10]

Figure 2.2 Comparison of fuel mix for global and US-flagged fleet in 2018

[1] Stranded assets in shipping can be defined as a vessel or infrastructure that has suffered from premature devaluation or is considered a liability.

3 Alternative marine fuels – overview

Hydrogen (H_2), ammonia (NH_3), methanol and biofuels are considered to be the most promising alternative fuels to HFO and MDO [18]–[20]. Table 3.1 compares the performance of all alternative marine fuels against a non-exhaustive list of criteria that are considered to be the most influential in the marine fuel debate[2]:

- Volumetric energy density – amount of energy within a cubic metre of fuel
- On-board technological maturity – level of development of on-board propulsion and containment
- Supply chain maturity – level of development of upstream production and distribution networks
- Well-to-tank emissions (upstream) – emissions from fuel production and distribution
- Tank-to-wake (downstream) – operational emissions from on-board machinery
- Capital costs – associated costs of fuel containment and on-board machinery
- Fuel cost – projected fuel cost of production in the mid-transition[3]
- Fuel safety – status of regulations in handling the fuel[4]
- Availability as a shipping fuel – current global bunkering and production capacity
- Alignment with decarbonisation by 2050.

Table 3.1 Red/Amber/Green matrix for maritime fuel characteristics

Characteristic	**HFO**	**Green H_2**	**Blue H_2**	**Green NH_3**	**Blue NH_3**	**1st gen. biofuels**	**Advanced biofuels**	**Green methanol**	**Blue methanol**	**LNG**	**LPG**
Volumetric energy density	Dark green	Orange	Orange	Cream	Cream	Light green	Light green	Cream	Cream	Cream	Cream
On-board technological maturity	Dark green	Cream	Cream	Cream	Cream	Dark green	Dark green	Dark green	Dark green	Light green	Dark green
Supply chain maturity	Dark green	Orange	Orange	Orange	Orange	Orange	Red	Orange	Orange	Light green	Cream
Well-to-tank emissions	Orange	Dark green	Cream	Dark green	Cream	Orange	Dark green	Light green	Cream	Orange	Orange
Tank-to-wake emissions	Red	Dark green	Dark green	Dark green	Dark green	Cream	Cream	Light green	Light green	Orange	Cream
Capital costs	Dark green	Orange	Orange	Cream	Cream	Light green	Light green	Light green	Light green	Orange	Cream
Fuel cost	Light green	Cream	Cream	Cream	Cream	Cream	Orange	Cream	Cream	Light green	Light green
Fuel safety	Dark green	Cream	Cream	Cream	Cream	Dark green	Dark green	Light green	Light green	Cream	Cream
Availability as a shipping fuel	Dark green	Orange	Orange	Orange	Orange	Orange	Red	Orange	Orange	Light green	Cream
Alignment with decarbonisation by 2050	Red	Dark green	Cream	Dark green	Cream	Red	Light green	Dark green	Cream	Orange	Orange

Worst				Best
Red	Orange	Cream	Light green	Dark green

Chapters 4–6 assess the suitability of each fuel as a marine fuel and outline key characteristics that are prominent in the marine fuel debate, including production routes, upstream and downstream emissions, current and future fuel cost, availability and suitability as alternative fuels to the shipping sector. The Appendix to this report provides a summary of the key advantages and challenges of each of the fuels.

[2] Fossil fuels are included for comparative reasons and are not considered long-term decarbonisation marine fuels.

[3] Fossil fuel price estimates include cost of production and possible future carbon taxes.

[4] Regulations refer to the International Code of Safety for Ships using Gases (the IMO IGF code), which controls how ships can be powered by gases or other low-flashpoint fuels.

4 Hydrogen and ammonia

Chapter summary

Hydrogen and ammonia are both very versatile fuels capable of powering many applications using fuel cells or internal combustion engines (ICEs). **The shipping sector sees hydrogen and ammonia as important players in the shift towards SZEF.** With many governments lobbying for more ambitious targets than the IMO, the industry is relying on hydrogen and ammonia to play a pivotal role in achieving such ambitions.

Other hard-to-abate transport sectors are looking at hydrogen and ammonia as a long-term solution to zero emissions targets. Synergies can be established among the energy, heavy transport, industry and building heating sectors to develop supply chain networks, safety guidelines and regulations to enable scaling and reduction in the cost of hydrogen-based fuels.

Large-scale hydrogen and ammonia marine engines are expected to be commercially available by the mid-2020s, while large-scale fuel cell arrangements will be ready by 2023. Due to the immaturity of hydrogen and ammonia technologies in the shipping sector, there are currently few rules and guidelines to control safety risks associated with the flammability and toxicity. The maritime risk-management expert DNV is establishing guidelines for the safe handling of hydrogen and ammonia as fuels for shipping, but amendments to the IMO IGF code will be needed to establish international regulations for use of the fuels.

Ammonia is an effective carrier of hydrogen and is deemed to be a long-term decarbonisation solution for deep sea shipping, which contributes 80% of the total CO_2 from global maritime transport.

Headway can be made in the short term by incorporating carbon capture and storage (CCS) technology in existing hydrogen and ammonia production plants to ensure that supplies needed to fulfil imminent demand have reduced GHG emissions. **Green production pathways must be established as soon as possible.**

Recent ambitious goals set by the current US administration set the target to convert the US power sector to 100% renewable by 2035, which has been followed by several states setting out preliminary legislation to implement the 100% renewable and carbon-free targets. **With this in view, in the US, it is likely that by 2050 green hydrogen will be equal to or cheaper than blue and grey hydrogen, at less than USD 2/kg.**

In the transport sector, which is responsible for 35% of all emissions [21], hydrogen and ammonia have the potential to play a transformative role in the route to decarbonisation. Both fuels boast versatility for use in fuel cells and ICEs, making them an attractive option for the hard-to-abate transport sector. Battery technologies are enabling the electrification of road transportation with relatively ease and will dominate that sector, but for heavy-duty vehicles, particular trucks, ships and commercial planes, hydrogen and ammonia have the potential to be a competitive energy source [22]. Within the shipping sector, leading engine manufacturers expect hydrogen and ammonia engines to be commercially available in the mid-2020s.

In the energy sector, hydrogen can be converted directly from electricity and back again, making it an effective medium for backup power – ideal for the times of reduced supply that are inherent in renewable wind and solar energy production. Hydrogen and ammonia storage would also reduce the demand for the precious metals required for battery storage, where ethical debates surrounding the raw materials supply chain may continue to burden the technology [23]. Additionally, the combustible nature of hydrogen and the ability to mix it with natural gas means that hydrogen has been identified as the necessary component in achieving carbon-neutral heating for buildings [21].

Although this report considers hydrogen and ammonia as SZEFs for shipping sector, it is important to highlight the interest across multiple sectors to understand the potential scale of the hydrogen economy in the US and worldwide. Nevertheless, there are areas of concern that must be considered, and which may hamper the uptake of hydrogen, as discussed below.

4.1 Hydrogen production routes

Section summary

Grey and brown hydrogen production methods account for 95% of all hydrogen produced today. **Overall, the CO_2 emissions released solely from the production of worldwide grey hydrogen are equivalent to around a third of emissions released from EU member states: 830MtCO_2 annually**.

Fugitive methane/natural gas emissions released from upstream and mid-stream processes associated with grey and blue hydrogen will likely counteract any progress made by reducing CO_2 emissions downstream. Levels of methane leakage are currently uncertain but are a significant cause for concern because the global warming potential (GWP) of methane is 81 times that of CO_2 over a 20-year period. This suggests that, in the short term, curbing methane emissions is one of the most effective ways to combat global temperature rise.

The US produces 10Mt of hydrogen per year (global annual production is 70Mt), most of which is used for producing around 14 Mt of ammonia annually. **With such large outputs of these SZEFs, the US has the potential to utilise existing supply chains and production facilities while shifting to green production using renewable energy and electrolysis.**

Most climate experts agree that green hydrogen is essential for decarbonisation, but blue hydrogen may play a role in building market potential if methane emissions become strictly regulated and if CCS is scaled up to allow for a green transition in the medium term. **Only green hydrogen can get the world to the Paris-aligned emission reduction targets.**

The US has the potential to produce green hydrogen and to launch a green hydrogen economy. However, despite being in a unique position to generate low-cost renewable power from wind, solar and hydropower, only 12% of the overall energy production in the US is currently derived from renewable sources. The ambition to produce 30GW of offshore wind power by 2030 is a step closer to decarbonisation of the power sector; this could contribute to accelerate the uptake of SZEFs in shipping.

Seven of the world's largest hydrogen producers have united to drive a 50-fold scale-up in six years, with an aim to reduce green hydrogen to below USD 2/kg – half its current cost of production – by 2050.

Evidence suggests the US may chose blue hydrogen and hydrogen-derived fuels in the short term but phase these out to achieve long-term goals by 2050. **It is essential that blue hydrogen is phased out in favour of green hydrogen if SZEFs are to become the obvious choice for shipping.**

This section discusses the production pathways of grey, brown, blue and green hydrogen, including descriptions of relevant processes that constitute each pathway (Figure 4.1).

At present, fossil fuels are used to produce 95% of hydrogen worldwide [24]; namely, natural gas, which is used to produce grey hydrogen via steam methane reformation (SMR); or coal, producing brown hydrogen through coal gasification. Blue hydrogen is produced in the same way as grey hydrogen but uses CCS technology, which has the potential of reducing carbon emission substantially.

Green hydrogen uses renewable electricity to split water into its constituents (hydrogen and oxygen) through electrolysis. The hydrogen is captured, while the oxygen can be used for industrial processes or released into the atmosphere. Green hydrogen can be directly used as a fuel or can be used as a feedstock to form other fuels such as green ammonia, green methanol and synthetic fuels.

It is not sufficient to produce green fuels using zero-carbon sources: it is essential that the fuels are completely green by ensuring the storage, transportation and conversion into other hydrogen-derived fuels is all powered by renewable electricity.

Steam methane reformation
SMR is a mature technology that accounts for 95% of all hydrogen produced in the US [25]. High-temperature steam is reacted with natural gas/methane and a catalyst to produce hydrogen and carbon monoxide. The hydrogen extracted is denoted as grey hydrogen.
Coal gasification
Coal gasification is a much less common method of producing hydrogen and is more carbon-intensive, releasing over twice the amount of CO_2 emissions than the SMR process [26]. It involves combusting/heating coal to form a synthesised gas (syngas) that is composed primarily of hydrogen and carbon monoxide. The extracted hydrogen is known as brown hydrogen.
Carbon capture and storage
The CCS process captures CO_2 released during the process of burning fossil fuels. CO_2 can be captured from various industrial processes and stored in underground geological formations. In the production of blue hydrogen and blue hydrogen-derived fuels, CO_2 is captured from the SMR process. Power stations equipped with CCS technology have the potential to capture up to 90% of the CO_2 [27], and future plants could be designed to capture 99% at relatively low increases in capital cost compared with current technology [28]. However, the total CO_2 captured would fall to 60–85% of emissions [26] unless measures are put in place to capture the fugitive CO_2 emissions associated with the extraction of natural gas.
Electrolysis
Electrolysis is a process by which substances are broken down into their elemental components by applying an electric current. To produce hydrogen, water (H_2O) is subjected to an electric current to release gaseous hydrogen (H_2) and oxygen (O_2) due to the opposing electrical charges of electrodes.

The production of ammonia starts with hydrogen production followed by the Haber-Bosch process that adds nitrogen to the hydrogen molecules forming a more stable hydrogen carrier that is easier to contain and transport.

Haber-Bosch process
The Haber-Bosch is a well-established method of combining hydrogen with nitrogen that is extracted from air. The process is performed under high temperatures and pressures and in the presence of a catalyst. The mixture is cooled so the ammonia liquefies and can then be extracted.

4.2 Climate implications of grey, blue and green hydrogen

Currently, grey and brown hydrogen production methods are most common and account for 95% of all hydrogen produced globally [25], producing GHG emissions amounting to 830MtCO_2 annually. The US currently produces 10Mt hydrogen per year, around 15% of worldwide hydrogen [25][29]. Thus it is reasonable to attribute approximately 15% of global CO_2 emissions from hydrogen production to the US.

There is also great concern about the levels of fugitive methane (methane slip) that are released during the extraction and SMR processes in both grey and blue hydrogen production. The exact levels of escaped methane are uncertain, but it is crucial to understand the overall global warming effect of hydrogen derived from natural gas. The GWP of methane is 81 times more potent at warming the atmosphere than CO_2 within a 20-year timeframe [6].

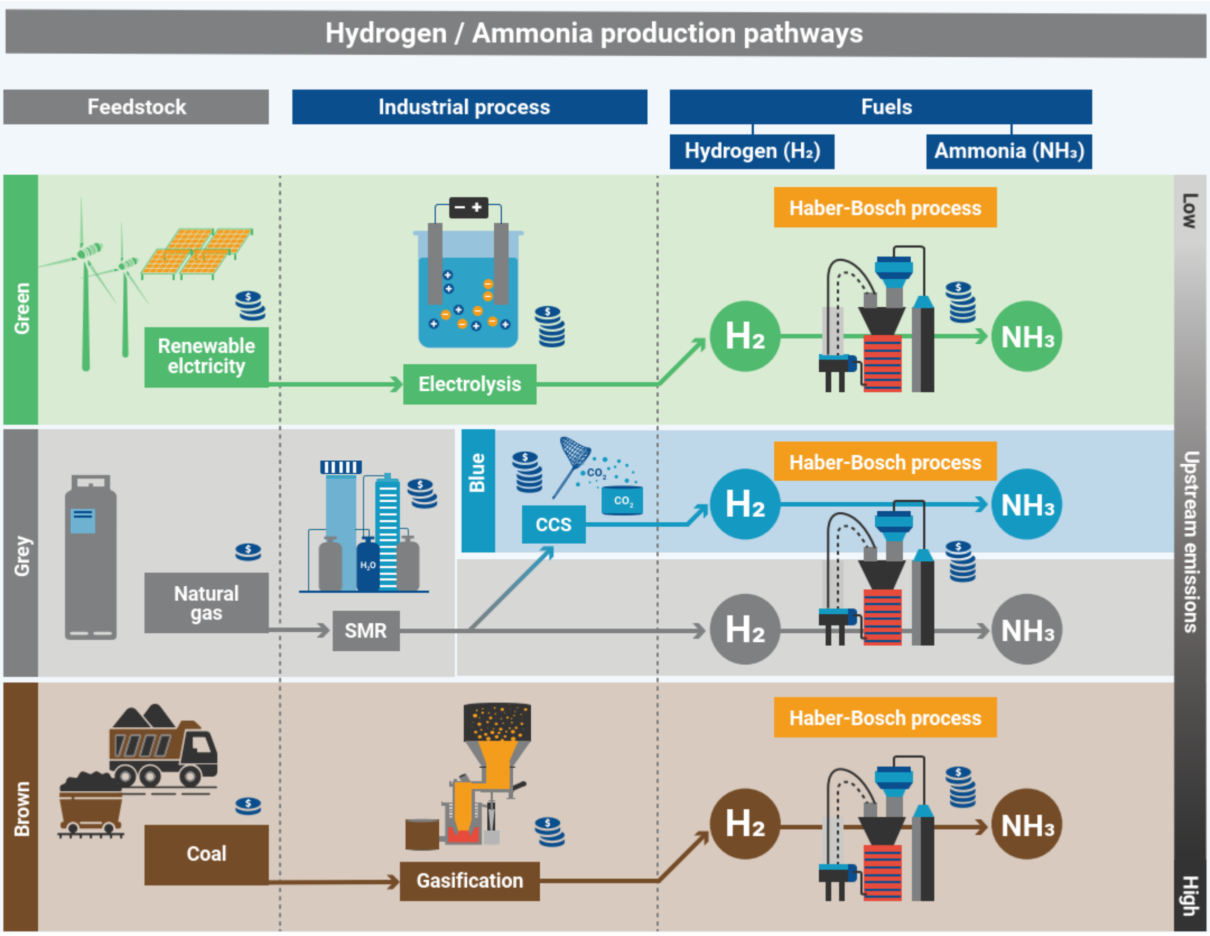


Figure 4.1 Hydrogen and ammonia production routes

Global warming potential

GWP is defined by the heat absorbed by a GHG in the atmosphere relative to the heat absorbed by CO_2. The GWP value also factors in how long the gas stays in the atmosphere and equates the GWP of the gas over a 100-year period. Thus, for a given GHG, the larger the GWP, the more it warms the atmosphere. Table 4.1 below shows the GWP of the GHGs that are prevalent in the production and combustion of marine fuels.

Table 4.1 Global warming potential for common GHG gases

Greenhouse gas	GWP (100-year time frame)	GWP (20-year time frame)
Carbon dioxide (CO_2)	1.0	1.0
Methane/natural gas (CH_4)	27.9	81.2
Nitrous oxide (N_2O)	273.0	273.0

Source: Reference [6]

The issue is further accentuated when carbon capture is considered. Additional energy is required to perform carbon capture, which typically comes from natural gas instead of renewable energy [30]. That means there are higher levels of methane slip from blue hydrogen production than from grey. Consequently, blue hydrogen may not in fact be as “clean” as was once thought. With current estimated levels of methane slip (3.5%) and CCS powered by natural gas, overall GHG emissions from blue hydrogen production are only 9–12% lower than for grey hydrogen[5]. If methane slip is reduced to 1.5% and a renewable energy source is used to power the CCS, it is possible to achieve a potential GHG reduction of 53% lower than for grey hydrogen [30].

Green hydrogen, on the other hand, is zero carbon with transportation being the only part of the process that may introduce some emissions.

4.3 On-board emissions

Hydrogen is considered to be an ideal SZEF in terms of operational emissions [31] and versatility because it is suitable to work as a drop-in fuel[6] in ICEs, gas turbines and fuel cells. Industry leaders, MAN Energy Solutions and Wärtsilä, are currently developing 2-stroke and 4-stroke hydrogen-based DF engines which are planned to be commercially available by 2023. Toyota and Corvus Energy are commencing the development and production of large-scale maritime fuel cells and aiming to be commercially available from 2023 [32]. A comparison of fuel cells and DF engines for shipping is presented in Section 8.2.

The level of operational emissions is dependent on the propulsion technology used and whether a pilot fuel[7] is present in the combustion process: fuel cells only emit water vapour by design; while ICEs fuelled by hydrogen and ammonia emit NO_x and potentially unburnt fuel, which can be extremely harmful to human health (increasing the risk of respiratory infections, heart disease and lung cancer) [33]. The amount of NO_x emitted is dependent on the fuel–air mixture: Rich mixtures emit higher rates of NO_x compared with leaner mixtures [34]; but leaner mixtures are less efficient. Both mixture ratios require emission reduction technologies such as exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) [35].

The reduction of NO_x is extremely important for all sectors, and thus a critical feature for limiting global warming to 1.5ºC, due to the substantial GWP of NO_x, which is nearly 300 times that of CO_2.

4.4 Fuel costs

The cost of hydrogen is heavily connected to the feedstock price, which accounts for between 45% and 75% of the total production costs [36]. This section discusses factors that affect the cost of grey, blue and green hydrogen and the cost implications of ammonia production. Cost data was obtaining mainly from the International Energy Authority (IEA) report "Future of Hydrogen" published in 2019 [36], with additional (more recent) sources as indicated.

Grey hydrogen

The cost of natural gas creates a wide price range for grey hydrogen ranging from USD 0.70 to USD 2.20/kg [37]–[40]. North America, Russia and the Middle East all report low hydrogen costs due to their access to large natural gas reserves, with 2018 figures indicating grey hydrogen costs in the US of around USD 1/kg [36]. Conversely, importers of natural gas such as Japan, Korea, China and India have higher feedstock costs [36] making a compelling argument for renewable electricity production to produce green hydrogen and reduce dependence on LNG imports.

Blue hydrogen

Blue hydrogen requires the use of CCS to produce a net-zero fuel source. Development of infrastructure has started in numerous US states including 14 CCS facilities and storage hubs in development, with

[5] Values consider the extraction, production, storage, CCS energy resource.

[6] A drop-in fuel refers to a fuel that can completely substitute diesel, meaning it is does not require any adaptation to the engine or fuel system.

[7] A fuel that initiates combustion; usually diesel derived.

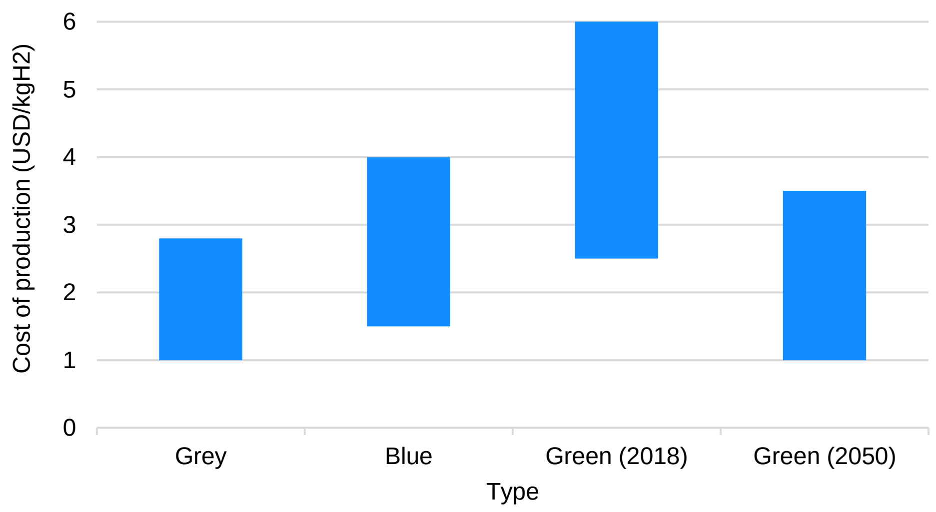
many states suggesting CCS as essential for achieving their net-zero ambitions [41], making the US a likely prime mover for blue hydrogen [42].

The capital expenditure and operating costs are around double that of grey hydrogen production, hence the cost of US blue hydrogen is around USD 1.50/kg. This cost remains at the lower end of the global range (USD 1.45–2.50/kg [36]) and CCS is expected to become cheaper as the market grows and technology develops [43].

Green hydrogen

Green hydrogen is highly dependent on the cost of the renewable electricity and is generally more expensive because of the capital cost of electrolysers, which remain high due to their immaturity at a commercial scale. Therefore the cost of green hydrogen (USD 2.50–6.00/kg [44]) as shown in Figure 4.2 is comparatively high. However, when coupled with the declining price of renewable electricity and the development of cheaper and larger electrolysers, green hydrogen is expected to see substantial cost reductions and could fall more than 50% by 2050 [44].

The growing capacity and potential for renewable energy in the US is vast. Recent ambitious goals include a target to convert the power sector to 100% renewable by 2035, followed by several states setting out preliminary legislation to implement the 100% renewable and carbon-free targets [45]. With this in view, in the US, it is likely that by 2050 green hydrogen will be equal to or cheaper than blue and grey hydrogen, costing less than USD 2/kg [37].



Source: Adapted from [44]

Figure 4.2 Projected cost of green hydrogen in 2050

Ammonia

Ammonia is produced from synthesised hydrogen, so the cost implications discussed above also apply to ammonia depending on the feedstock. Additional costs of production are associated with the Haber-Bosch process and the costs of air separation units (that capture nitrogen from the air). Although this production step increases the production cost, storage of hydrogen at cryogenic temperatures (–235ºC) or high pressure is more energy intensive: thus, when considering the overall cost of shoreside production and storage, the costs of ammonia and hydrogen are comparable [46].

4.5 Availability and suitability as a shipping fuel

4.5.1 Current and future availability

A global socioeconomic push to decarbonise economies will naturally increase the demand for hydrogen and ammonia. With the transport, heavy industry and energy sectors seeing hydrogen as a key solution to decarbonisation, a hydrogen economy may soon be established. It is apparent that the shipping sector backs hydrogen as a SZEF: as of March 2021 the Global Maritime Forum examined 106 projects looking at zero emission fuels in the maritime sector, of which nearly three-quarters were focusing on hydrogen or ammonia [47].

Only one of the hydrogen projects examined was based in North America, although the number of US-based hydrogen projects is expected to change soon, given the new administration in the US and the aggressive new climate change stance [48]. Furthermore, as of 2021, the US produces 10Mt of hydrogen per year (global annual production is 70Mt), which is mainly used in oil refineries and for ammonia production [49]. This puts the US at a significant advantage to kick-start shipping decarbonisation through the use of hydrogen and hydrogen-derived fuels.

It is expected that the global supply of hydrogen and its current expansion will be enough for the shipping sector in both the short and long term. In the short term, the pre-existing natural gas production route can be combined with the expansion of CCS technology. In the medium to long term, with the relative ease of scaling renewable electricity production and electrolysis, a clear SZEF pathway is emerging with few limitations compared with many other alternative fuels [50].

The case for ammonia is somewhat different. Current demands for blue ammonia could be sufficiently met by the production of grey hydrogen, although the production facilities would need to be assessed for their CCS potential. However, if demand for ammonia rapidly increases by the 2040s, as larger ships transition to SZEFs, additional production facilities will be necessary [51]. The availability of green ammonia in the short to medium term (i.e. up to 2030s) is expected to be met by current capacity, but as the demand for marine ammonia increases beyond the 2030s, additional renewable electricity would be necessary to meet demand [51].

4.5.2 Suitability for marine technologies

Compared with MDO and various distilled fuels, hydrogen and ammonia have a lower energy density per unit volume, implying that ships using these fuels would have a decreased range or lower cargo-carrying capacity (owing to the need to carry larger amounts of fuel). This is less of an issue for shortsea shipping because refuelling and loading stops can be made more frequently, if combined with local infrastructure developments. For deep sea shipping, the storage capacity issue becomes more prevalent which is where dual fuel (DF) ICEs can relieve some of the uncertainties, given that they can operate with both conventional and non-conventional fuels. As global bunkering networks develop, fossil fuel bunkering can be eased off making way for SZEFs.

DF ICEs have appeared in the market, with MAN Energy Solutions and Wärtsilä introducing engines that can be run on diesel and alternative fuels: liquefied petroleum gas (LPG), LNG, methanol or ethane [52]. Currently, hydrogen and ammonia DF ICEs are not commercially available; however, there are developments of 2-stroke ammonia ICEs and 4-stroke hydrogen ICEs (for both propulsion and acting as auxiliary generators) that will be commercially available by 2024 and 2023, respectively. With typical commercial ships taking around three years to build, these engines will likely be seen by the late 2020s and early 2030s for new-build ships. Retrofit hydrogen and ammonia engines could potentially surface before this, but that will depend on the development of storage and fuel supply systems.

UMAS's industrial outreach with stakeholders, using questionnaires, found that feasibility studies are also underway for 4-stroke ammonia engines. This is a complicated matter due to the slow burn rate of ammonia compared with hydrogen: the characteristic higher revolutions per minute of a 4-stroke ICE means less time is available for the combustion of ammonia, causing lower energy output and the possibility of fugitive uncombusted fuel (which is toxic). It is likely that 4-stroke ammonia engines, like a hydrogen 4-stroke engine, will require a pilot fuel to fuel ratio of up to 30%. Consequently, although still a significant reduction in carbon emissions compared with a diesel engine, a 4-stroke ICE will be unable to reach the same GHG reductions as hydrogen and ammonia 2-stroke engines.

Fugitive ammonia in an ICE is a highly toxic and colourless gas that dissolves rapidly in water, leading to eutrophication and long-term toxic effects on marine organisms [53]. When in contact with human skin or inhaled, its corrosivity can cause burning or cellular destruction [54]. Nevertheless, ammonia is less dense than air, meaning the gas dissipates into the air where low levels of ammonia are naturally present. Moreover, being the main ingredient in fertiliser, an extensive network of storage and transportation already exists. This means well-established safety measures have been honed through years of experience, thus reducing the risk of leakage of the toxic fuel [55]. Nevertheless, it is necessary to develop robust guidelines for the safe handling of ammonia on board ships, especially if the fuel is used in passenger ships.

Hydrogen and ammonia can be used within fuel cells, specifically proton exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs). Such technologies are at the forefront of research and development activities, with numerous pilot and research projects incorporating the technology in smaller ships (i.e. tugboats, support vessels and ferries) [47], [56]. Fuel cells may become more widespread as hydrogen bunkering scales up and the technology matures, making it more viable for marine transport. Until then, hydrogen fuel cells will gradually be taken up and seen within niche activities such as ferry crossings with robust hydrogen infrastructure [42].

4.6 The development of blue and green hydrogen in the US

Demand continues to grow for hydrogen, which is now established as a major business and commodity around the world [36]. Along with the future markets within the transport sector that hydrogen can power, conventional uses are still in high demand. Hydrogen use in oil refineries to remove sulphur from crude oil-derived fuel is the main consumer, although demand may decline as it is suggested the peak is nigh for fossil fuels [57]. Ammonia demand is set to grow 13% by 2025 [58] owing to the rising demand for agrochemicals for food crops in Asia, with the potential for demand to significantly increase as ammonia becomes more popular as a fuel [59]; and methanol will continue to be one of four major synthesised chemicals with growth set for the transport sector, particularly in China.

Direct electrification can contribute to reducing emissions for most of the power sector and a portion of transportation, but for hard-to-abate[8] sectors, which account for approximately 15% of CO_2 emissions in the US [60], decarbonisation can only be achieved through the use of SZEFs.

Most climate experts agree that green hydrogen is an essential SZEF for decarbonisation, but blue hydrogen may play a role in building market potential if methane emissions become strictly regulated and if CCS is scaled up to allow for a green transitional in the medium term [61]. Only green hydrogen can get the world to the Paris-aligned emission reduction targets [60]. The decision will come down to the cheapest form of hydrogen feedstock, and with that in mind the current US administration has promised to produce hydrogen from renewable energy when it is cheaper to do so than from natural gas [65].

Despite the US being situated in a unique position whereby low-cost renewable power from wind, solar and hydropower has the potential to produce low-cost green hydrogen and launch a green hydrogen economy [42] currently only 12% of overall energy production in the US is derived from renewable

[8] The shipping industry and other heavy-duty transport, the aviation sector and heavy industry are all known as hard-to-abate sectors because they possess many challenges that mean transitioning to electrification creates difficulties.

sources [62]. Consequently, the US lags behind the European Union (EU), China and Japan in terms of green hydrogen infrastructure and research investments.

The Department of Energy (DOE) in the US has invested between USD 100 million and USD 280 million annually over the last decade [42], predominantly into the research and development of hydrogen technology [63] [42]. It currently has no green hydrogen strategy in its hydrogen programme plan. Whereas the EU member states and the Chinese Government – in accordance with industry – are now investing USD 2 billion per year [39] and have corresponding green hydrogen plans. Furthermore, the EU alone pledges to invest USD 430 billion by 2030 to achieve its Green Deal, with similar large investments being made by the governments of Chile, Japan, Saudi Arabia and Australia [64]. Together with the fact that, in the US, 14 commercial-scale CCS projects have come online or will be operational in the coming years [41], and with many US gas producers trialling natural gas-derived hydrogen in existing hydrogen infrastructure [65], it is evident that blue hydrogen will lead the US hydrogen economy in the short term.

As of 2021, there were only two facilities globally that produce blue hydrogen commercially [30]: one operated by Shell in Canada and another operated by Air Products in Texas, USA [41]. If commercial-scale blue hydrogen were to expand to meet proposed demand in the coming decades, the way in which it is executed must change. The United Nation Environmental Programme concluded that methane emissions from all sources must be reduced by at least 40–45% by 2030 to limit global temperature rise to 1.5ºC [66].

If all the above were to happen, there would be a compelling case for the use of blue hydrogen the US, especially with the low natural gas price, which would align with the 50% IMO reduction by 2050. However, if the US is to achieve its goal of zero emissions by 2050 and to lead such a global effort, zero emission fuels must be implemented nationwide, reciprocated by government investments, and backed by industry.

For green hydrogen to become cost competitive production costs will need to be reduced substantially: if the costs of renewable electricity and electrolysers decline sufficiently, green hydrogen costs will fall below blue hydrogen and this is expected to occur between 2030 and 2050 [37]. This is particularly important in the US: the pledge by the new administration to achieve 50–52% reduction in domestic GHG emissions compared with the 2005 level requires significant investment into renewable energy capacity. The target (set in 2021) launched to produce 30 GW of offshore wind power by 2030 is a step closer to decarbonisation of the power sector [67], and this will inevitably contribute to the early establishment of green fuels in the shipping sector.

The acceleration of scaling up and subsequent cost reductions of green hydrogen have been taken up by seven of the world's largest hydrogen producers[9]. They have united to drive a 50-fold scale-up by 2026, with the aim of reducing green hydrogen costs to half its current cost, to below USD 2/kg [68]. This initiative, along with other large-scale developments across the globe, is key to achieving the complete phase out of fossil fuels in the international maritime industry by 2050. The target was announced after the new administration in the US announced that it will lead and work with the IMO, to "ensure that the shipping industry emits zero emissions by 2050"; a target which is far more ambitious than the current initial strategy outlined by the IMO [69]. When assessing a variety of pathways to 100% reduction in emissions by 2050, it is seen as critical for green fuels to make up 5% of the global fuel mix by 2030 [70]. Therefore, it is crucial for policies, initiatives and regulations (see Chapter 9) to adopt this target in order to increase renewable energy capacity and the uptake of green hydrogen-derived fuels in the shipping sector.

The evidence suggests that, for the time being, the US will align on a blue pathway, but to achieve long-term goals by 2050, blue hydrogen and blue hydrogen-derived fuels cannot be the sole approach to

[9] ACWA Power, CWP Renewables, Envision, Iberdrola, Ørsted, Snam and Yara.

decarbonisation. This suggests that in the medium to long term it is essential that blue hydrogen is phased out in the US in favour of green hydrogen so that true decarbonised fuels are launched into the shipping sector.

5 Biofuels

Chapter summary

First generation (conventional) biofuels do not offer any reduction in overall CO_2 emissions. This is due to their high impact on land use, whereby highly carbon sequestering forests and grasslands are exchanged for low carbon sequestering croplands, which negates the carbon reductions that biofuels offer downstream.

Advanced biofuels enable a significant reduction in lifecycle CO_2 emissions, but production routes and supply chains are yet to be established at a scale that can enable any meaningful decarbonisation in the shipping sector. By the time advanced biofuel supply routes are established, the high demand for fuel from other sectors will outprice the maritime sector to choose other scalable alternatives.

The maritime sector does not have experience in handling biofuels or an established supply system. The aviation and automotive sectors have established networks for biodiesel and with the uncertain future of the fuel, it is economically unrealistic to warrant the use of biodiesel to replace low grade marine fuel, rather than aviation or automotive fuel. **Blending is required for use of most biofuels without modifications to current fuelling systems or engines.**

The cost of production for biofuels can be very different to the prices that will be set by the market. Demand will be significantly higher than the supply of biomass and, in the long term as supply constraints are reached by a decarbonising and growing global economy, the price of biofuels will either be set to exceed the costs of SZEFs or be set at a level to enable substitution with scalable energy commodities.

It is expected that the energy required for a single large ship may consume the annual production from a medium-sized biofuel facility. As such, use of biofuels in the shipping industry will probably be very low compared with SZEFs.

Biofuels are produced from biomass such as plant crops, algae and animal fats, and can be categorised by their feedstock and different production processes. As such, they should not be considered collectively.

Table 5.1 describes the different categories or generations of biofuels based on their feedstock. A range of crops or bio-waste can be converted into either liquid or gaseous fuels, each with different lifecycle GHG emissions and socioeconomic implications.

Table 5.1 Biofuel nomenclature

Generation	Feedstock
First	sugar, starch and lipids directly extracted from plants
Second	woody crops, purpose-grown non-food feedstock and waste/residuals
Third	autotrophic organisms (e.g. algae)
Fourth	genetically modified autotropic organisms

First generation fuels are extensively used with commercial-scale production and have widespread distribution networks. It is necessary to blend first generation biofuels with fossil fuels such as diesel, making them ideal for the automotive sector. Blend ratios vary by region and are dependent on policy, fuel availability and compatibility constraints. The US blends around 10% ethanol and 5% biodiesel in gasoline and diesel respectively; the EU uses a 7% blend of biodiesel and diesel [71]; while Brazil, as a result of its policy to support sugarcane ethanol, has achieved a 27% blend with gasoline and 11% biodiesel to diesel blend due to the rapid expansion of Brazil's soy industry [72].

First generation biofuels do not offer emission reductions. In particular, soy oil and palm oil feedstock-fed biofuels produce enough emissions from fuel production and combustion to make overall GHG emissions equal to that of marine gas oil (MGO) [71]. This is due to the additional land required to plant oil seeds for biofuels that would instead be forestry or grassland which sequesters higher levels of CO_2 [71]. That practice has become increasingly ethically challenging, given that the growing global population puts biofuels in competition with food crops thus carrying a socioeconomic impact. After many years of debate the EU has adopted a measure which limits the use of first generation biofuels after 2020 due to the high indirect land use change [73].

Advanced biofuels (2nd–4th generation) can offer 70–100% emission reductions thanks to their low impact on land use, large uptake growth and relatively low use of fossil fuels during their conversion [71]. This will be discussed in the following sections.

Overall, biofuels are attractive for the maritime sector because of their compatibility with conventional fossil fuel ICEs and bunkering systems, with blending [45], [71].The overarching challenges for biofuel use in the maritime sector are supply constraint and the inexperience of using biofuels as a shipping fuel. Five biofuels are considered potential candidates for the shipping industry: fatty-acid methyl ester (FAME); hydro-treated renewable diesel (HVO); Fischer-Tropsch (FT) diesel; dimethyl ether (DME); and bio-methanol[10] [74].

5.1.1 Comparison of potential biofuels

Table 5.2 outlines key information for each biofuel considered, including feedstocks, generation and on-board emission reductions compared with diesel.

Table 5.2 Potential maritime biofuel comparison

Fuel category	Fuel	Generation	Machinery compatibility	Emission reductions (%)		
				SO_x	PM	NO_x
Biodiesel	FAME biodiesel	1st or 2nd	Blends up to 20% require no modifications, neat requires modification [75]	Very high	40–90	Variable
Renewable diesel	HVO diesel	1st or 2nd	Drop-in-fuel (neat or blended)	100 (if neat)	30	Up to 20
	FT diesel	2nd	Drop-in-fuel (neat or blended)	100 (if neat)	30	Up to 20
	DME	2nd	40% blend [76]	100	Up to 60	Variable
Methanol	Bio-methanol	1st or 2nd	Methanol or DF engines	100	Up to 60	Up to 90

Table notes: Emission reductions compared with MDO. Biodiesel is produced through a transesterification process, whereas renewable diesels are produced by various other processes including hydro-treating, gasification, pyrolysis and other biochemical and thermochemical technologies [114].

Fatty-acid methyl ester

Commonly known as biodiesel, FAME is manufactured using a well-established production method called transesterification: a chemical reaction between vegetable oil or animal fats and alcohols (traditionally methanol or ethanol) [74]. Vegetable oil (including waste oil) and animal fat feedstocks can be obtained from a variety of sources and quality and availability vary by region. Vegetable feedstocks such as soybean are mostly used in the US and South America; plant feedstock such as rapeseed are typical used in the EU; and oil palm is common in South America and South Asia [77]. FAME is relatively simple to produce and widely available, with an established distribution network and both large-scale and smaller decentralised plants.

FAME is deemed a suitable fuel for diesel engines, including low- to medium-speed marine engines [77]. Theoretically it is possible to run neat (fully replacing diesel), although this requires modification to the engine. Thus blends of 20% are commonly used, with recent sea trials reaching FAME blends of up to 30% [75],[78]. FAME, unlike other biofuels with lower sulphur content, restores lubrication and protects against wear in the fuel and injector pumps, while reducing PM emissions. Due to its higher

[10] FAME, HVO and bio-methanol can be either first or advanced generation depending on the feedstock; FT diesel and DME are both advanced biofuels.

oxygen content, FAME has lower thermal energy than conventional diesel, so as well as having a higher price, the blended FAME and MDO will increase fuel consumption [79]. With biodiesel prominent in the automotive sector, it is economically unrealistic to produce FAME in large volumes for replacing marine fuel when it could be more suitable for other sectors, probably in a blended format [77].

Hydrogenated renewable diesel or hydro-treated vegetable oils

HVO (also known as renewable diesel or green diesel) is seen as the most attractive diesel replacement biofuel due to the large production potential through hydro-treatment at existing oil refineries [77]. Hydro-treatment combines vegetable oils or animal fat with hydrogen in the presence of a catalyst.

An advantage over FAME is the possibility for HVO to be used as a drop-in fuel with no changes to engines or bunkering infrastructure [71]. Moreover, the hydrogenation process removes all the oxygen from the vegetable oils, creating a fuel with higher fuel efficiency and a longer shelf life [77]. On the other hand, much like FAME, the current low level of production means that HVO will need to be blended with conventional diesel fuels to gain a foothold in the market.

HVO is viewed as a key driver for biofuel growth, as production is set to reach 13 billion litres in 2024, more than doubling from 2018 (5.5 billion litres) [80]. New production facilities are expected to use waste feedstocks creating a second-generation biofuel. A large proportion of this growth is expected in the US due to expansions of current facilities and new plants [81].

Fischer-Tropsch diesel

The FT process is a well-established technique used to produce liquid synthetic fuels using coal or natural gas. These fossil fuels can be replaced by gasification of biomass, creating a biofuel. Several process modifications are needed to make this possible, and making FT diesel is technologically challenging because it is an immature biofuel technology that is still under development, with production volumes being low.

Fuel manufactured using the FT process is comparable to conventional diesel in terms of energy density, volumetric density and viscosity, making FT diesel a suitable drop-in fuel for fully replacing or blending with diesel.

Dimethyl ether

Second-generation sources (forest products, agricultural by-products, organic waste, energy crops and black liquor) are used as feedstock to produce DME. The biomass is first converted to methanol and then to DME by a two-step syngas conversion and catalytic process [82].

Much like other advanced biofuels, DME is not yet produced at scale, even though the production method is technologically mature. In the transport sector, DME is still in its demonstration phase [82] with heavy-duty trucks, which require a specialised engine modification if using it as a drop-in fuel [71]. DME can be blended up to 40% with diesel, although system modifications are required to withstand the low ignition temperature [71]. DME is therefore expected to be predominantly used in engines designed for DME or potentially for methanol engines with extra on-board processing, designed by MAN Energy Solutions [74].

Bio-methanol

Methanol is one of the most synthesised fuels from a feedstock of natural gas or coal [83], and it has been adapted to use biomass for the production of bio-methanol. The biomass can be first generation crops such as sucrose, starch or cellulose; or second-generation lignocellulosic energy crops, by-products or agriculture residues (e.g. wheat starch or corn stover). Use of second-generation feedstock has been successfully proven but is still in its infancy because of the added processing required to obtain the energy in second-generation crops [84].

Biomass can be converted to methanol biochemically or thermochemically, but production is still immature. Gasification of biomass at elevated pressure and temperatures is not economically feasible and cannot compete with the gasification of natural gas or coal [82]. Consequently most large-scale projects to develop bio-methanol from biomass have stalled [77].

Bio-methanol can be used in specifically developed methanol engines that require a small amount of MDO as a pilot fuel, or within DF ICEs. Currently, there are 26 vessels that have large methanol engines installed [85], but recent interest from ship owners and shipyards has seen a milestone order of 8 new engines for large container ships, and these are due to enter service in 2024 [86].

5.1.2 On-board emissions

Operational biofuel emissions are an improvement compared with the distillate fuels they are blended with or replacing due to lower levels of SO_x and PM produced. FAME diesel can be classed as an ultra-low SO_x emitter, while HVO, FT diesel, DME and bio-methanol contain zero sulphur, so they produce no SO_x when burnt. For all such fuels, sulphur reduction technologies are not necessary.

Concerning NO_x emissions, the comparison with fossil fuels is somewhat different. Some biofuels offer a reduction in NO_x: for example, HVO and FT diesel achieve 20% lower NO_x emissions than diesel (depending on the engine loading and type) [87]. Bio-methanol offers reductions from 50% to 90% compared with diesel, whereas using FAME or DME result in slight increases in NO_x [50]. In general, all biofuels will require NO_x reduction systems, as do conventional diesel fuels.

5.1.3 Costs

The price of biofuels is subject to the supply and demand constraint of bioenergy, with the majority of the cost linked to feedstock. Geographical location, regulation, taxation, labour costs and seasonal variability in supply all have a defining impact on the price of biofuels. Consequently, the price is highly variable, but in general, it is known that biofuels are more expensive than distillate fuels. The US has introduced the Renewable Fuel Standard and Low Carbon Fuel Standard [88], which is intended to make biofuels cost competitive or cheaper for qualifying cases.

The cost of production for biofuels can be very different to the prices that will be set by the market. This is because the sustainable biomass supply is constrained and likely to be significantly lower than the overall future demand for biomass. This means that in the long run, as supply inelasticities are reached (by a decarbonising and growing global economy), the price of bioenergy will either exceed the costs of SZEFs or be set at a level to enable substitution with scalable energy commodities.

5.1.4 Availability and suitability as a shipping fuel

Biofuels are attractive for maritime transport because of their similarity to distillates and compatibility with conventional fossil fuel engines and bunkering systems [50]. However, running a diesel engine exclusively on biofuel requires extensive modifications to most existing engines. In general, biofuels require blending with conventional fuels for compatibility with conventional machinery [71]. The challenges for biofuels use in the shipping sector are the inexperience of handling biofuel and, most of all, the supply constraint. In particular, is it expected that the energy required for a single large ship may consume the annual production from a single medium-sized biofuel facility [77], and therefore market share will be very low compared with other alternative fuels.

6 Methanol

Chapter summary

Grey methanol production based on natural gas feedstock results in overall GHG emissions around 5% higher than that of HFO. It is therefore crucial for cleaner production routes to develop (blue or green routes), otherwise, using methanol as a shipping fuel is a non-starter.

Green methanol costs five times as much as grey methanol. Production is small scale due to the technological immaturity of essential direct air capture (DAC) technology**.** By 2050, green methanol is expected to be the same price range as conventional diesel fuels were in 2020. Further price competitiveness is likely in the light of prospective carbon taxes on fossil fuels.

Carbon capture and utilisation (CCU) provides an alternative at lower cost, although net-zero methanol is unattainable via this route. If CO_2 is captured from fossil fuel emissions, CCU cannot produce a fuel that has zero emissions on a lifecycle basis. Further, CCU may indirectly incentivise fossil fuel combustion to provide a source of CO_2. If the CO_2 to be captured originates from biogenic origins, CCU may then produce a fuel that has very low GHG emissions on a lifecycle basis. However, biomass is not a scalable solution.

The current annual production capacity for methanol is 110Mt, which is more than present-day demand therefore, in terms of supply, methanol may be able to satisfy a short- to medium-term demand as a maritime fuel. Despite this, only around 0.2% annual methanol production is green methanol (mainly bio-methanol). Unless there is a rapid expansion of DAC or CCU technology in the short term, methanol uptake is not viable.

A significant advantage over other alternative fuels is that methanol is a liquid at ambient temperature. **Thus, existing bunkering infrastructure can be utilised for methanol, with some modifications.**

Methanol is essential in society today as it is one of the main ingredients in many common commodities ranging from plastic packaging, paints and coatings to building materials [89]. As an energy source, methanol has the highest hydrogen-to-carbon content of any liquid fuel making it an effective hydrogen carrier with a slightly higher energy density than ammonia. According to the International Renewable Energy Agency (IRENA), global methanol production could increase five-fold by 2050, but only if 50% of this comes from decarbonised ‘e-methanol’[11], which is currently an undeveloped supply route [89].

The total global demand for methanol (conventional and green) is 80Mt annually, with a production capacity of 110Mt in 2021 as a result of the growing interest in the fuel in the past few years causing an rise in production facilities [89]. The growth has mainly come from the east, where 60% of the global demand is consumed in China and India [50]. China uses methanol extensively (neat or blended with petrol) as an alternative transportation fuel.

Climate awareness has driven interest in methanol outside of Asia, thanks to cleaner production pathways and lower levels of NO_x, SO_x and PM [50]. For instance, in the US, the capacity of methanol production grew by 45% from 2019 to 2020 making use of low-cost natural gas, especially in the oil fields in US southwest (Permian Region) [90]. This trend is expected to continue, with new plants coming online in the next few years including Yuhuang’s St James 1 being the largest production facility in the US [91]. Together with the fact that methanol can utilise existing bunkering infrastructure and the potential growth of fuel supply, the shipping sector is attentively watching developments surrounding methanol.

[11] The cleanest form of methanol produced from hydrogen with renewable energy via electrolysis, combined with captured CO_2 from DAC or CCU from point source emitters.

6.1.1 Production routes

Methanol is extensively produced at a commercial scale using natural gas or coal. It can also be produced using biomass or using renewable electricity and carbon capture to produce e-methanol. In turn, the feedstock is the source of lifecycle GHG emissions.

The conventional method of producing grey methanol depends on natural gas and SMR to produce a mixture of hydrogen, carbon monoxide and CO_2 with the resulting syngas being converted to methanol [92]. China instead predominantly uses coal as the feedstock through gasification to produce the synthesised gas called brown methanol [89]. Both routes are energy- and carbon-intensive resulting in upstream emissions slightly higher than conventional distillate fuels [83].

As detailed in Section 5.1.1, biomass can be used as a feedstock to create bio-methanol, using the same process as natural gas and coal by creating a synthesised gas. Using a renewable energy as the source of thermal energy for heating biomass would ensure carbon neutrality.

E-methanol or green methanol production comprises two processes: production of hydrogen via electrolysis followed by combination with carbon from CO_2 captured through industrial CCU or directly from the air (DAC) to form methanol.

Carbon capture and utilisation

CCU is the process that captures CO_2 from industrial processes such as the production of other chemicals, predominantly hydrocarbons (e.g. plastics and fuels). If the CO_2 emissions originate from fossil fuels, use of CCU does not result in a zero emissions fuel. If the source is biogenic, the upstream emissions are close to zero; however, this is limited by biomass supply.

Direct air capture

DAC is a relatively simple technology that extracts CO_2 directly from the atmosphere. Although the technology is relatively simple, extraction of CO_2 from the air is energy intensive and is yet to be commercialised at scale. Capital expenditure and operating costs are high, but these are expected to decrease with increase in demand in production and scale [93].

6.1.2 On-board emissions

Methanol could play a part in short-term shipping decarbonisation: its potential for low operational emissions is attracting interest from ship owners, shipyards and fuel suppliers. Thanks to its low carbon content compared with diesel, methanol has been shown to emit 15–20% less CO_2 than gasoline and 10% less than HFO. However, when considering overall lifecycle emissions of grey methanol, the overall well-to-wake carbon emissions are 5% higher than using HFO [50]. Blue or green methanol offer a significant reduction in upstream emissions and can come close to being carbon neutral.

Methanol is also a clean burning fuel with levels of PM and SO_x significantly lower than fuel oil [71]. Sulphur emissions are virtually eliminated conforming with IMO Regulation 14 [94] thus not requiring sulphur reduction technologies such as scrubbers.

The level of NO_x emissions depends on the technology used: a 30% reduction is expected for 2-stroke engines; while approximately 60% reduction of NO_x is expected for 4-stroke engines [50]. However, the levels will not be below Tier 3 limits (as set out in IMO Regulation 13), meaning engines will still need to be fitted with NO_x reduction technologies (such as EGR or SCR) to comply with regulations on ECAs and IMO Regulation 13 [94].

6.1.3 Cost

Based on research by IRENA published in 2021 [89], the price of fossil fuel-derived methanol (grey or brown) ranges between USD 100/t and USD 250/t and is therefore considered competitive compared with distillate fuels. The price of e-methanol is highly influenced by the costs of renewable electricity and thus is dependent on the region of supply. With the additional cost of CCU, this constitutes a methanol price between USD 800/t and USD 1,600/t[12]. If carbon is captured by DAC, the price of e-methanol would increase to a range of USD 1,200–2,400/t. With production volumes potentially increasing and renewable energy consistently becoming cheaper, by 2050, this is expected to reduce to USD 250–600/t, and therefore highly competitive with distillates, especially with the prospect of carbon taxation.

Bio-methanol is currently produced at between USD 320/t and USD 770/t at low production levels. An increase in short-term demand would significantly influence this price and, by 2050, this is expected to reduce to USD 220–560/t [89].

6.1.4 Availability and suitability as a shipping fuel

The current annual production capacity of 110Mt has outstripped present-day demand so it is acknowledged that, in terms of supply, methanol could fulfil the short- to medium-term demand as a shipping fuel [50]. This is based on predictions that, as a shipping fuel, methanol is expected to gradually grow and remain at a moderate level [95]. Despite this, only 0.2% of annual methanol production is green (mainly bio-methanol) [89] and, unless there is a rapid expansion of DAC or CCU technology, methanol will not be an appropriate SZEF for shipping.

The existing marine bunker infrastructure caters predominantly for liquid fuels, so it could be used for methanol, albeit with some modifications. That approach would be significantly cheaper and faster to implement than for other alternative fuels, most of which need pressurisation or cryogenic cooling for containment.

MAN Energy Solutions has developed 2-stroke methanol DF diesel engines that are now commercially available, while Wärtsilä is to add methanol DF engines to its catalogue by 2024 [96]. There are now 26 large ships running on methanol using DF engines [85]. A potential alternative would be to use methanol within PEMFCs, whereby a fuel reformer can convert methanol into hydrogen. SOFC and high-temperature PEMFC (HT PEMFC) technologies are also compatible with methanol. However, such technologies are not yet proven, but development over the coming decade may see commercial-scale production by the mid-2030s.

[12]This assumes the carbon is captured from a bioenergy conversion plant, suggested as the most scalable carbon capture technology available, with costs of USD 10–50/tCO_2 [113].

7 Zero emission fuel pathway

Chapter summary

The shipping industry is calling for more ambitious decarbonisation targets. The consensus among many industry leaders is that the sector must align with the Paris Agreement goal of zero carbon emissions by 2050. **A number of initiatives and declarations were launched at COP 26, and at a debate held at IMO MEPC 77 to consider updating the IMO's strategy to a "zero by 2050" target. These actions show significant momentum building to accelerate shipping's decarbonisation to a 1.5ºC-aligned target/trajectory.**

In order to achieve zero emission shipping goals by 2050 a progressive stance must be taken now to establish green fuel supply chains in the immediate future, so that when the transition unfolds, a platform can be utilised and scaled up to lead the trajectory to zero emissions. **Research by the Getting to Zero Coalition indicates that to ensure the utmost likelihood that a 2050 zero emission pathway will occur, green fuels must reach a minimum threshold of 5% of the fuel mix by 2030.**

For the S-curve scenario to be met (shown in Figure 7.1**), the green fuel mix would be approximately 5%, 60% and 100% by 2030, 2040 and 2050, respectively**. It is estimated that the overall renewable energy required to produce 5% of the fuel mix is 0.64EJ or 15.8Mt HFO equivalent.

The Getting to Zero Coalition found that around 10% of shipping's total fuel consumption has ideal conditions for transitioning to SZEF during the 2020s. These first mover routes are all domestic, regional or only require small groupings of countries that can incentivise the use of hydrogen by plurilateral action (groups of like-minded countries acting together) and can show that the decarbonisation of shipping, as well as other associated industries (i.e. energy), is commercially viable.

To meet the short- to medium-term hydrogen demands, the conversion of grey hydrogen and ammonia facilities into blue may be an option through the development of CCS. **As the transition progresses, more stringent regulations will limit the lifecycle CO_2 and CO_2eq emissions (methane included) both upstream and downstream.** This carries a significant risk to any blue investments, because the likelihood of them becoming stranded assets is considerably high, given they do not fit with a transition towards decarbonisation especially as renewable electricity supply is scaled up.

Methanol and biofuels are seen as a 'bridging' mechanism. From a technological standpoint these fuels are currently further developed than hydrogen and ammonia, but they are unable to deliver adequate emission reductions to be classed as a long-term solution.

Since the change of US administration in January 2021, a formal pledge has been made ensuring a commitment to work with the IMO to achieve zero emissions in the shipping industry by 2050 [97], joining the UK [69]. This is ambitious compared with the initial IMO target set to reduce GHG emissions by 50% by 2050 compared with 2008 levels; the difference being that the fuels in this pathway ensure a transition that is aligned with the 1.5°C target. With support from sizeable international maritime nations in the lead up to the Glasgow Climate Change Conference (COP 26), the 1.5-aligned target gained a great deal of traction, and a strong signal has been sent by the US and 21 other countries through the signing of the Clydebank Declaration making a commitment to setting up green shipping corridors through international cooperation [98].

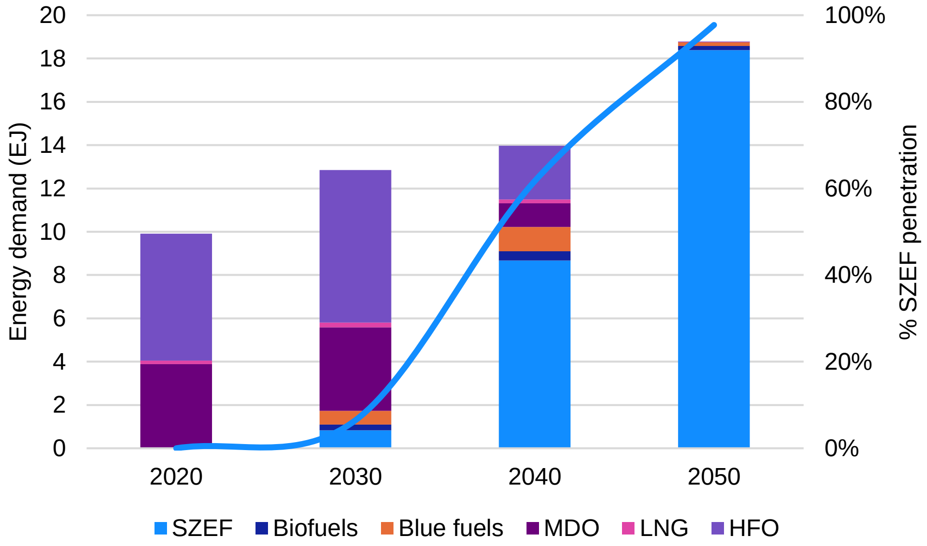
At the 77th meeting of the IMO Maritime Environment Protection Committee (MEPC 77), the majority of member states that spoke expressed support of zero GHG emissions by 2050 (of the 65 member states that spoke, 40 supported zero or net-zero by 2050, 34 specifically supported zero by 2050) as proposed by Kiribati, Marshall Islands and Solomon Islands [99] [100].

With this in view, this section presents a viable pathway to a zero emission future in shipping by 2050. It outlines a fuel mix (see Figure 7.1), incorporating the candidate fuels (hydrogen, ammonia, biofuels, and methanol) discussed in the previous sections and considers the action required to achieve an equitable transition. Section 9.10 then outlines the potential policies, initiatives and regulatory frameworks that may expedite the uptake of SZEF.

Following the "diffusion of innovation" theory, a minimum threshold of 5% of the global fuel mix being replaced by SZEF by 2030 would significantly increase the likelihood of decarbonisation by 2050 [70]. This level of adoption requires a diffusion of synthetic fuels into the market in the early transition phase; from here on, economies of scale will start to develop, allowing the industry to mature and making a SZEF pathway towards 2050 possible [101].

7.1 Global zero emissions pathway

The proposed pathway envisages the proliferation of SZEF as the cornerstone of a zero emissions pathway. Blue fuels are also captured in the mix although, as discussed throughout the report, their use is a short-term solution to create market potential and, with inevitable emission regulations on methane leakage, it is likely that blue fuels will be superseded by green/synthetic fuels in the medium term. In many analyses, including this one, biofuels have a very small share in the mix overall, without an obvious role in the long term: they are interim solutions with potentially lower costs in the short term. Figure 7.1 represents the mix graphically, while the remainder of this section identifies the necessary actions that must occur, and how that shapes the trajectory and fuel mixes.



Source: Adapted from [101]

Figure 7.1 Global fuel transition mix towards decarbonisation in 2050

It is important to note that the US, being one of the countries identified as having a strong potential for the production and distribution of SZEFs, would be expected to have a quicker transition than the global average illustrated in Figure 7.1. This is strengthened by the analysis presented in various studies that singles out routes that are especially well placed to be converted to green corridors as identified by the Getting to Zero Coalition transition strategy [101]. US-based fast moving consumer goods companies that use shipping extensively to transport their products have also committed to increasing the demand for zero-carbon shipping [102], which also complements the First Movers Coalition declaration during COP 26 [103].

7.1.1 Renewable electricity feedstock

Achieving decarbonisation by 2050 necessitates a fast transition to establish robust supplies of SZEF, which implies that renewable electricity and electrolyser costs would need to fall substantially in the 2020s to reach economic viability. Governments will need to incentivise and invest in renewable electricity production beyond that needed for meeting existing electricity demand (see Section 9.1 for US specific initiatives). By 2030, synthetic fuels could be competitive with fossil fuels based on a renewable electricity price of around USD 19/MWh [5].

7.1.2 Role of first movers in the transition to zero emission fuels

Scaling up of production and use of SZEF throughout the 2020s is essential in order for these fuels to make up at least 5% of the global shipping sector's energy mix by 2030. For the S-curve scenario to be met, the SZEF fuel mix would need to be approximately 5%, 60% and 100% by 2030, 2040 and 2050, respectively [70]. Whilst these percentages represent the global transition pathway, developed nations such as the US are expected to have a steeper trajectory, especially in this decade. The Getting to Zero Coalition's transition strategy proposed that such countries could decarbonise up to 30% of their domestic emissions by 2030 [101].

Leading economies have announced large-scale ambitions that could see rapid scaling up in the coming decades and will contribute to the energy requirements in 2030 and beyond. It is estimated that the overall renewable energy required to produce 5% of the fuel mix is 0.64EJ or 15.8Mt HFO equivalent (based on ammonia being the primary fuel) [70]. To mention a few: the EU Hydrogen Strategy aims for the production of 10Mt of renewable hydrogen by 2030; Japan is aiming to generate power from hydrogen equating to around 10Mt annually by 2030; and China has a long-term goal to provide 60Mt by 2050 [47]. The Green Hydrogen Catapult, instigated by seven world-leading companies, aims to supply 25GW of green hydrogen electrolyser capacity by 2025 at USD 2/kg [70]. In addition to the initiatives mentioned above, policy and regulations must work in parallel and be appropriately aligned with the 1.5°C international target.

Work conducted by UMAS found that around 10% of shipping's total fuel consumption has favourable conditions for transitioning to SZEF during the 2020s [101]. These first mover routes are all domestic, regional or only require small groupings of countries that can incentivise the use of hydrogen by plurilateral action (groups of like-minded countries acting together) and can show that the decarbonisation of shipping, as well as other associated industries (i.e. energy), is commercially viable.

Japan, the US, China, and the EU and Norway are all potential candidates that are well positioned – either on routes between them, or with third countries within their key trade routes [101]. Routes within or between these trading zones benefit from regular journeys on relatively simple routes, with limited stops, and are near to low-cost hydrogen production. Examples of the most promising routes include China–Australia, Japan–Australia, Japan and China, US–Japan and US–China [101] (see Figure 7.2). Given the urgency, creating alignment between these nations and establishing early deployment of SZEF could make a significant impact on the global fuel transition, while demonstrating to other nations that a zero emission pathway is possible. Detailed analysis of the current status and potential for the US-flagged fleet and port clusters is provided in Section 4 of a related report [10].

Source: Reference [101]

Figure 7.2 First mover bilateral trade routes

7.1.3 Limited role of blue fuels

There is potential for blue fuels to act as a driver in the transition to zero emission fuels. Over 95% of the 70Mt of hydrogen is currently produced by fossil fuels [24] and it is estimated that global demand will rise to 212Mt by 2030 [104] to align with climate goals. To meet the short- to medium-term hydrogen demands, a conversion of grey hydrogen and ammonia facilities into blue may be an option, through the development of CCS.

As the transition progresses, more stringent regulations will limit the lifecycle CO_2 and CO_2eq emissions (methane included) both upstream and downstream. These regulations will most likely come in the form of economic instruments (see Section 9.1) and, consequently, blue fuels will lose their advantage over green. This is a significant risk to any blue SZEF investments as the likelihood of them becoming stranded assets is considerably high given that they do not fit with a transition towards decarbonisation, especially as renewable electricity supply is scaled up [105].

7.1.4 Limited role of methanol and biofuels

Interest from early adopters seeking a lower capital expenditure is leading to the use of methanol and biofuels. From a technological standpoint these fuels are further developed than hydrogen and ammonia, so a small share of the fuel mix is expected. However, this approach is strictly applicable only in the short term, because scaling and supply issues will make biofuels more expensive than SZEFs and thus uncompetitive.

For first generation biofuels, there is no justifiable reduction in lifecycle emissions compared with HFO to warrant their use. Advanced biofuels do provide emission reductions, but their technological immaturity means availability is a limiting factor, thus resulting in their low share in the fuel mix.

8 Machinery transitions

Chapter summary

The long life expectancy of ships (around 25–30 years) creates a challenge for machinery selection. There is a risk that existing ships and ships built in coming years, before a clarification of the most competitive SZEF, locks in certain machinery choices and therefore limits future fuel choices.

On the positive side, the modern 2-stroke engines (used in most ships trading internationally) have some flexibility and, with modification, could be adapted to use most of the SZEFs currently under consideration (including ammonia, methanol and hydrogen). This means that machinery solutions can be chosen that have a single engine with multiple fuels (currently, predominantly DF) operation. Alternatively, a ship could be designed with anticipation to retrofit the machinery (including the fuel storage and handling system) at mid-life.

Ships that are associated with shortsea shipping may be designed with machinery solutions optimised now to use a SZEF with lower risk than ships trading internationally, if they are able to ensure availability of the SZEF and bunkering infrastructure due to operating in a smaller area/region.

Fuel cells are an alternative to conventional ICEs, and a number of different fuel cell technologies can also be used with candidate SZEFs. Most commonly fuel cells are associated with hydrogen as a fuel, but they can be used with other candidate SZEFs (including ammonia and methanol), including future variants of these technologies.

Estimates of the comparative costs of operating on a fuel cell versus an ICE suggest that, in most cases, especially for ships trading internationally, the ICE will be more competitive than a fuel cell – including for the foreseeable future. However, this may change if there are technology developments in fuel cells, particularly regarding higher efficiencies that may develop in certain candidate technologies currently under development.

This section discusses the machinery technologies that are available for use with alternative fuels and compares their environmental impacts, efficiencies and the level of development – all of which need to be considered in the discussion regarding the trade-off between the technologies, and how and when they will be utilised in the shipping sector.

8.1 On-board shipping technologies

The long design lives of ships (many ships are in service for around 30 years) can mean that the technology selections made in their original design restrict the available pathways for decarbonisation and optionality for different fuels.

There are two solutions to enable more flexibility, both of which require some consideration at the point a new ship is designed:

- A ship can be built with a DF engine and multi-fuel supply system, with a view to operate on conventional fuel initially and switch to alternative fuel at the appropriate point in time
- A ship can be built with a conventional ICE and oil-derived fuel supply system, and retrofitted mid-life to add a new fuel supply system.

Both options are explored below, along with potential future technologies – fuel cells.

8.1.1 Dual fuel internal combustion engines and multi-fuel supply systems

A DF engine is currently an ICE that enables a ship to operate consuming either conventional liquid marine fuels (HFO, MDO, MGO, low sulphur HFO) or one of a number of alternative fuels (methanol, LNG, LPG, hydrogen, ammonia, ethanol), extending the ship's operational flexibility. When running on alternative fuel, the engine is designed to predominantly consume alternative fuel, but often a small amount of pilot fuel is required (e.g. diesel) for initiating the ignition process. This means that two fuel supply systems[13] are required in the ship, increasing costs and complexity, but this often means the fuel selection can then be switched relatively seamlessly during operation. Table 8.1 summarises the characteristics of some of existing DF engines (i.e. 2-stroke and 4-stroke), their commercial readiness for various fuels and types of ships that could utilise such engines.

Table 8.1 Two-stroke and four-stroke engine characteristics

Engine	Size	Efficiency	Fuels available	Activity type	Ship types
DF 2-stroke ICE	Large engines 4–85 MW	~ 50%	**Commercially available:** HFO and various distillates, methanol, ethanol, LNG, LPG **In development**: ammonia	Deep sea shipping	Containers and tankers, among others
DF 4-stroke ICE	Small to medium <3–20 MW	~40–45%	**Commercially available**: MDO and various distillates, Methanol, Ethanol, LNG, LPG **In development**: ammonia and hydrogen	Shortsea shipping	Workboats, research vessels, tugs, operations vessels

Retrofit compatibility

The modern 2-stroke engine has been shown to have good flexibility to run a wide variety of fuels. With modifications to the injection and fuel supply systems and the addition of an extra fuel tank, a ship can be transitioned to a DF engine operating on conventional fuel alongside a SZEF. For example, a MAN Energy Systems ME-GI engine is designed to run on HFO, MDO, LNG or biofuels. But with modifications, this can be retrofitted to use ammonia, methanol or LPG. The same can be said for 4-stroke engines, albeit with the addition of more pilot fuel to help the combustion process.

Not all engines have the same flexibility, with manufacturers developing retrofit packages particularly for their latest models. So to maximise the potential to be able to retrofit a new fuel system, careful selection of the main machinery specification of a conventionally fuelled ship is important. However, in future it may be that the more disruptive and therefore higher-cost modification at mid-life arises from retrofitting a new fuel system to supply fuel to modified machinery. This can involve placement of new fuel tanks, which often requires deck space and so can disrupt existing layouts and systems, and a new fuel handling system. Many alternative fuels have different explosivity indices, toxicities and compatibility with materials compared with conventional oil-derived fuels and this can mean that a large amount of modification is needed.

In short, while there is good potential to retrofit ships to enable them to use an alternative fuel, this can be a costly and disruptive process. If retrofit is anticipated during the design of a ship, steps can be taken to make space available for these modifications and therefore reduce the costs of a retrofit – even without knowing in advance which alternative fuel to prepare for.

Bunkering and availability

At the time of writing, designing a ship with a single alternative fuel system represents a greater risk than a DF system for international shipping operations. This is because there is not wide-scale availability of alternative fuels, particularly SZEFs, and there is large uncertainty about which SZEF will become dominant for international shipping. This explains why, currently, nearly all active projects involving SZEFs and international shipping are implementing DF engines and associated fuel systems.

This contrasts with the approach for smaller shortsea shipping vessels, where a mixture of fuel cells (which can be more restricted in the variety of fuels they are compatible with) and DF engines are being implemented. This is because shortsea shipping vessels can often be designed for a specific operating

[13] Fuel supply systems consist of storage tanks, pumps, fuel lines and fuel injectors that carry and supply the fuel to the engine(s).

area where bunkering and fuel availability can be more certain. These ships are also smaller and therefore lower cost and represent less of a financial risk.

This suggests that there are different strategies for machinery selection that can be taken to manage the uncertainty and risk while retaining appropriate levels of flexibility to suit the availability of different fuels and associated bunkering infrastructure. International shipping has the choice of designing ships to an estimate of future fuel and bunkering availability (DF), or to build conventionally fuelled ships but anticipate retrofitting these to alternative fuels as bunkering and availability of alternative fuels becomes clearer. Shortsea shipping can also take these options or may already be in a position to make a judgment on using a SZEF now, because availability of the fuel and bunkering in the area where it is operating are known.

8.1.2 Fuel cells

A fuel cell is a power stack that converts chemical energy (usually in the form of hydrogen) to electrical energy via electrochemical reactions that occur between an anode and cathode within a membrane. Unlike DF ICEs, currently many fuel cells can only run on one fuel, although potential developments in SOFC could mean switching fuels seamlessly may be feasible in the future.

There are various fuel cell types available, but research conducted by UMAS and the Getting to Zero Coalition has identified the three fuel cells most promising for maritime applications: PEM, HT PEM and SOFC (see Table 8.2).

Table 8.2 Fuel cells for the shipping sector

Fuel cell type	Efficiency	Typical size (kW)	Maturity level	Advantages	Disadvantages
Proton exchange membrane (PEM)	50% to 60%	1–250	High	• High power to weight ratio • Proven technology in maritime applications	• Hydrogen requires purification
High-Temperature PEM (HTPEM)	60%	1–250	Low	• Can run on un-purified hydrogen from more hydrogen sources	• Requires hybridisation with batteries, due to slow dynamics • Requires the most development to become commercially available
Solid oxide fuel cell (SOFC)	60% 85% with waste heat recovery	1–2,000	Low	• Offers greater fuel flexibility – diesel, ammonia, hydrogen, methanol, LNG, LPG • High efficiency	• Requires hybridisation with batteries, due to slow dynamics • Requires development before being commercially available

Contrary to DF ICEs, which can still produce air pollutants due to the high temperatures at which combustion occurs, fuel cells are inherently clean technologies and, because of the absence of combustion if using a fuel such as hydrogen, harmful waste products (including air pollutants) are eliminated. The only by-product of the electrochemical reaction of hydrogen and oxygen is water.

Fuel cells use a well-understood technology that has existed for a long time, but the rapid development of combustion engines and the relative ease of obtaining crude oil meant that, for vehicles, fuel cells have been largely ignored. However, as a result of the global consensus to cut GHG emissions, research and development of fuel cells has received significant investment in recent years and is perceived as a technology that may have a significant role to play in decarbonising the global economy.

PEMFCs are now becoming mature and more prevalent in the maritime environment. Many pilot and demonstration projects are utilising the technology to showcase zero emissions shipping within numerous operations (i.e. ferries, research vessels, tugs). The relative maturity means that the efficiency (see Table 8.2) is unlikely to improve, but costs are expected to reduce owing to large-scale production and savings and efficiencies across the fuel cell supply chain.

HT PEMFC and SOFC are relatively young technologies so costs are still high and these fuel cells are not yet commercially available. However, large-scale investments from companies such as Shell, which is heavily involved in the development of SOFCs [47], will drive down costs and accelerate the implementation of fuel cells in the maritime sector. The efficiencies set out in Table 8.2 have been demonstrated, but with further developments it is possible that SOFC efficiencies could reach as high as 85% [47], making this a very promising technology in the long term. This is partly due to the fact that the high heat by-product can be used in a waste heat recovery system.

8.2 Trade offs

8.2.1 Total cost of ownership and capital expenditure

DF engines and fuel cells exhibit strengths and shortcomings that can best be understood by comparting the benefits for their use in different shipping activities. For example, fuel cells might appear to be the ideal solution due to their lower air pollution emissions (particularly important for NO_x emissions), but there is a premium in their costs over DF engines (for a given power output), and that is likely to remain the same for the coming decades.

To understand how the different costs for these machinery components affect the overall competitiveness of different SZEF and machinery combinations, UMAS has used its proprietary modelling framework to model the total cost of ownership (TCO) of both DF ICE and fuel cell technologies for new-build container ships between 2020 and 2050 (see Figure 8.1). The model factored in the capital expenditure on machinery (i.e. engine or fuel cell), fuel and storage costs, pollution reduction devices such as exhaust gas treatment costs (if required) and revenue impact (i.e. loss of cargo). The seven possible options for SZEFs for new-build (NB) shipping are H_2 (hydrogen), MeOH (methanol) and NH_3 (ammonia) coupled with different production pathways for those fuels (i.e. PEM electrolysis for green production, and NG-CCS SMR for blue production), and different main machinery selections (FC and ICE).

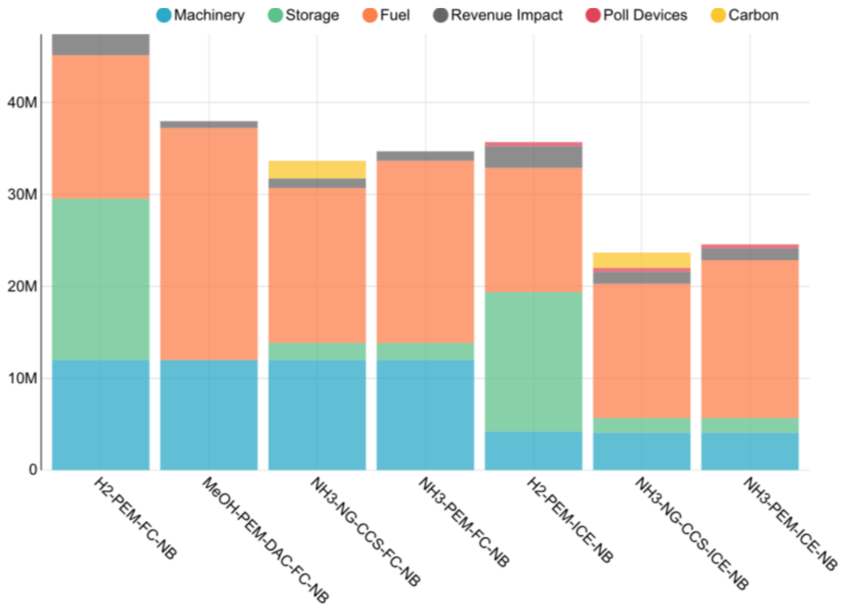


Figure 8.1 Total cost of ownership breakdown for fuel options in new-build shipping in 2030 (in USD)

Figure 8.1 shows that there is a premium of approximately USD 10 million if a container ship were to operate with a fuel cell over a DF engine, and that this is primarily due to the higher machinery cost. This is explained by the fact that the efficiencies of both technologies are around 50% and the fuel, storage and revenue costs are therefore similar. Despite the need for exhaust treatment technologies in DF engines to manage air pollutant levels, this does not come close to offsetting the premium in the machinery costs for a fuel cell.

Figure 8.1 shows projections for the costs for each component for the year 2030 only. However, for two of the candidates, the same relationship is presented for the period of decarbonisation from 2020 to 2050 in Figure 8.2. Fuel cell premiums are approximately halved over the period to 2050; however, even with that level of cost reduction, the model suggests that the TCO of a fuel cell is unlikely to reach that of a DF engine until after 2050 (assuming that further cost reductions occur).

It is important to note that SOFC technology could present a different TCO result to that of a PEMFC[14] and could potentially exhibit cost competitiveness with a DF engine once it is commercially available. The higher efficiencies (+85%) achievable compared with those for a DF engine (~50%) means less fuel is required, consequently reducing fuel and storage costs, while having a lower impact on revenue thanks to smaller cargo space losses. However, achieving those benefits will depend on how their price point evolves and what level of efficiency can be achieved in practice for the technology.

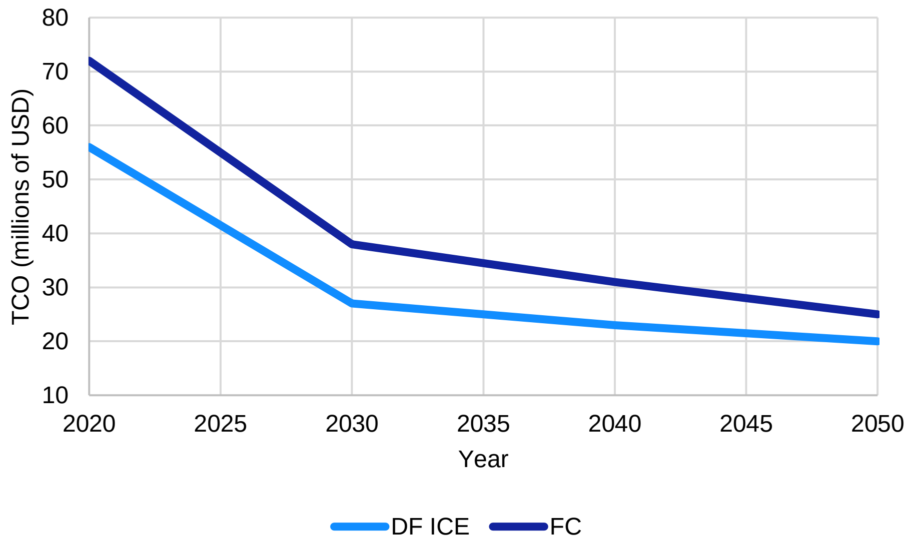


Figure 8.2 Total cost of ownership of dual fuel internal combustion engines vs. fuel cells (2020–2050)

[14] PEM electrolysers were only modelled against DF ICE because there is limited literature on the price of HT PEM and SOFCs.

9 Supporting uptake of SZEF in the US

Chapter summary

A wave of support for climate progressive action suggests the US government is embarking on a new paradigm. Re-joining the Paris Climate Agreement and setting out a USD 2 trillion clean energy investment to fully decarbonise the power sector by 2035 has cemented the administration's ambitions regarding climate change.

In order to utilise blue hydrogen in the pursuit of deep decarbonisation, there is a substantial need to upscale CCS, but it is also crucial to understand the issues of methane leakage and apply a regulatory framework throughout the supply chain. The Trump administration removed methane as a regulatory pollutant in 2020, but the US congress repealed the rule in June 2021, thus making a step in the right direction. The US Environmental Protection Agency (EPA) planned to propose the "nation's strongest rules against methane emissions" within the Clean Air Act 2021.

To proceed with the US target on zero emissions by 2050, the US DOE must rethink its hydrogen program plan. The plan was released in November 2020 and, with the new administration being inaugurated in January 2021, there is potential to reflect on the progressive new stances on climate change and align with a rethought long-term hydrogen plan that envisages green hydrogen as a fundamental element. This could look similar to the EU Hydrogen Strategy, which predominantly aims to accelerate "renewable hydrogen" (green) but recognises the role of blue hydrogen initially and envisions a gradual trajectory to carbon neutrality by 2050.

Thus far there are a limited number of policies, initiatives and regulations specific to the US; however, the new administration has spoken distinctly about its ambitions in the sector. There are numerous ways in which the maritime sector can accelerate the uptake of low-carbon fuels and reduce the price gap between fossil fuels and zero emission fuels. These include economic instruments (i.e. market-based measures), command-and-control policies and voluntary initiatives.

Taking into account local shipping segments favourable for decarbonisation, localised regulations, regional fuel availability, and other factors such as innovation clusters, proactive local actors and communities, **there are four key geographic regions (i.e. the west coast, the Gulf, the Great Lakes, and the east coast) identified as being the most promising for the early adoption of SZEFs.**

The west coast has a growing hydrogen production industry under development and is also developing hydrogen fuelling infrastructure. Moreover, Washington state and California have a well-developed shortsea ferry industry that can be a possible test bed for hydrogen and electric propulsion.

The Gulf also has a well-developed chemical tanker industry that exports ammonia and could potentially use it as an on-board fuel. **Here, infrastructure can provide a useful steppingstone to decarbonisation in the long term, by providing existing storage, safety experience and production assets to develop blue and green alternatives** while acting as a testbed for pilot projects.

The east coast has similar potential benefits to the west coast and the Gulf, but is behind in terms of ammonia and hydrogen infrastructure. Here, a focus on local land-based industries can be synergistically developed with shipping demand for hydrogen (e.g. potential consideration for using hydrogen in public transport and district heating).

Due to the closed nature of the Great Lakes, a bunkering supply network could be developed to serve a larger proportion of shipping than in other regions, while ensuring the uptake of zero-carbon fuels locally to combat air pollution (NO_x, SO_x and PM).

Although there is a need for further trials and pilot uses of different candidate SZEFs, it is clear that the scalability of any of these future fuels is dependent on the availability of low-carbon hydrogen – either to be used directly as a fuel, or as a feedstock for the different candidate fuels. For the US to play a role in shipping's decarbonisation, one clear requisite is therefore the expansion of its low-carbon hydrogen production network and low-carbon hydrogen supply chains.

One way to do this is to significantly increase renewable energy output and hydrogen production via electrolysis. Alternatively, if blue hydrogen-derived fuels were to take a share of the fuel mix at least in the short term, it would be necessary to upscale CCS across hydrogen and ammonia grey production facilities, while limiting the levels of methane leakage from all sources in the supply chain of natural gas as well as in the production process of hydrogen from natural gas. However, both of the above require progressive policies, initiatives and regulatory frameworks, to avoid a BAU approach being followed, whereby zero emission fuels would be very unlikely to become cost competitive with fossil fuels.

With this in view, this section outlines policies and initiatives pledged by the US within upstream, mid-steam and downstream operations; and discusses potential future policies and initiatives, in addition to concurrent regulatory frameworks that are necessary to ensure the uptake of zero emission fuels and to achieve the complete phase out of fossil fuels by 2050. It also considers regional factors that may influence a faster adoption of alternative fuels in the US.

9.1 Policies and initiatives

9.1.1 Upstream and mid-stream

Since the inauguration of the new administration, a wave of support for climate progressive action suggests the US government is embarking on a new paradigm. Re-joining the Paris Climate Agreement and setting out a USD 2 trillion clean energy investment to fully decarbonise the power sector by 2035 [106] has cemented the administration's ambitions towards climate change. The DOE understands the role that hydrogen will play in hard-to-abate sectors and is consequently supporting research and development into a wide range of technologies to produce hydrogen economically, via net-zero pathways. For example, the DOE has launched the Energy Earthshots initiative – particularly the Hydrogen Shot – which seeks to reduce the cost of clean hydrogen by 80%, to USD 1/kg by 2030 [107]. On the other hand, in the DOE's meaning of the word, "clean" hydrogen refers to both blue and green production routes; and as discussed in Section 4.1, the role of blue hydrogen and the pursuit of full shipping decarbonisation are somewhat unaligned. In order to utilise blue hydrogen in the pursuit of deep decarbonisation, there is a substantial need to upscale CCS, but it is also crucial to understand the issues of methane leakage and apply a regulatory framework throughout the supply chain. If it continues to be challenging to fully remove methane or other GHG emissions from blue hydrogen production, that fuel will play only a transient role and production will in turn need to switch to green hydrogen production only.

The US is a global leader in CCS, already operating the technology at 10 large-scale facilities. The sustained support from the DOE's CarbonSafe initiative has led to six of the eight new facilities in the US. Of these, there is one hydrogen production facility operational and another in early development with CCS [108]. Moreover, the 45Q tax credit – which promotes the sequestering of CO_2 through CCS – exemplifies the trend towards CCS in the US and, together with the hydrogen program plan, it suggests a blue hydrogen economy is emerging. If this were to happen, it would be essential that blue hydrogen production is aligned with methane leakage regulations, otherwise the industry could be back-pedalling on its way to zero emissions.

The US EPA has voluntary programmes and initiatives on methane reduction strategies, but no regulations to limit the amount of leakage. After the Trump administration removed methane as a regulated pollutant in 2020, the US congress repealed the rule in June 2021, thus making a step in the right direction. Current regulations are by no means stringent enough because they do not align with decarbonisation by 2050, but the EPA planned to propose the "nation's strongest rules against methane emissions" within the Clean Air Act 2021 [109]. However, it is unclear whether such regulations will be imposed for SMR and ammonia plants as, seemingly, the proposal only incorporates the oil and gas sector [109]. Hence, to ensure hydrogen and ammonia producers cannot exploit a loophole by being disregarded in methane regulations, greater clarity is necessary from the EPA.

The cornerstone of achieving zero emissions in many hard-to-abate sectors is utilising green hydrogen, but as yet there is limited involvement of green hydrogen in the US hydrogen program plan. This could result in a potentially slow growth in green hydrogen production and use, undermined by the relative competitiveness of existing hydrogen production facilities.

Therefore to proceed with the US target on zero emissions by 2050, there must be a greater role for green hydrogen in the long-term plan. Currently, there are private sector and non-government initiatives/partnerships such as the Western Green Hydrogen Plan, part of the Green Hydrogen Coalition, which "assists interested states and partners in advancing and accelerating the deployment of green hydrogen" [109]. Indeed, this initiative will assist the development of green hydrogen infrastructure: but without ambitious targets to meet or federal strategies, inevitably green hydrogen will lag behind blue in the US.

Thus, federal supporting policy is crucial for the uptake and scaling of green hydrogen, including enough availability for the shipping sector to reach significant levels of use of hydrogen generally, but increasingly use of green hydrogen.

There is potential to reflect on the progressive new stances on climate change and align with a rethought long-term hydrogen plan that envisages green hydrogen as a fundamental element. This could look similar to the EU Hydrogen Strategy, which predominantly aims to accelerate "renewable hydrogen" (green) but recognises the role of blue hydrogen initially and envisions a gradual trajectory to carbon neutrality by 2050.

9.1.2 Downstream

Thus far there are a limited number of policies, initiatives and regulations specific to the US shipping; however, the new administration has spoken distinctly about its ambitions in the sector and has since united in global efforts to drastically curb emissions from shipping. For example, the US has joined the Mission Innovation Initiative and, along with Denmark and Norway, leads the zero emission shipping stream, which includes 22 countries and the European Commission along with the Global Maritime Forum and the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. The mission sets the course for global zero emission shipping by accelerating international public and private involvement in green maritime solutions to ensure 5% of the global fuel mix by 2030 is made up of zero emission fuels. Looking at its the involvement and leading roles, it is clear that the US is committed to the deep decarbonisation of the shipping industry; however, such activities are merely a call for investment and are pursued to fill the gap where regulatory frameworks do not exist. Thus, it is essential that regulatory policies are established in parallel with such activities.

There are numerous ways in which the maritime sector can accelerate the uptake of low-carbon fuels and reduce the price gap between fossil fuels and zero emission fuels. These can be split into command-and-control policies, economic instruments (i.e. market-based measures) and voluntary initiatives.

Command-and-control measures (see Table 9.1) can be employed to make low-carbon fuels and technologies cost competitive with fossil fuels.

Table 9.1 Command-and-control measure examples

Standard	How does it work?
Performance or emissions standards	Setting specific performance or emissions goals (e.g. specifying the maximum GHG emissions allowable from certain activities)
Product standards	Defining set characteristics for products that contribute to pollution
Technology standards	Identifying certain technologies that must be used without determining the overall outcome

Economic instruments are regulatory policies that incentivise the use of low-carbon shipping fuels by any of the methods listed in Table 9.2.

Table 9.2 Economic instrument examples

Standard	How does it work?	Key to effectiveness
Emissions tax/levy	A predefined price is set by a regulator relative to the amount of fossil fuel consumed or CO_2eq or GHGs emitted, and therefore results in a higher fossil fuel price	Setting an appropriate price relative to wider environmental goals is crucial in driving emission reductions and achieving the desired output [110]
Emissions trading systems	• Either an emissions target or baseline is set by a regulator to create a cap-and-trade or baseline-and-credit system respectively • Cap-and-trade systems allow auctioning or distribution of allowances under the cap in the market • Baseline-and-credit systems allow credits to be issued, which can be banked or sold to other entities exceeding baseline emission levels	Setting an appropriate baseline target relative to environmental goals
Subsidies	A subsidy is provided by the state or a public body to support research and development or to lower the cost of low-carbon fuels	Subsidies are best utilised in parallel with other policies or regulations

Voluntary initiatives (see Table 9.3) involve activities taken by companies and non-government organisations that act outside of (usually in parallel with) regulatory initiatives and which incentivise the transition to zero emission fuel.

Table 9.3 Voluntary initiative examples

Initiative	How does it work?
Collaborations	Formal collaborations between industry members and/or non-government organisations to set internal sector goals and promote environmental action holistically
Information programmes	Enable behavioural change by raising awareness by supplying information to the public

9.2 Regional factors

Having discussed current and future policies and regulations that will encourage the uptake of low-carbon fuels or legislate against fossil fuels, it is important to identify regional factors that will facilitate the faster uptake of alternative fuels.

Apart from national-level factors that can affect the uptake of alternative fuels in the US, the candidate liquid fuels for shipping decarbonisation in the USA will also be affected by specific regional factors. Regional factors can facilitate the faster adoption of certain fuels in shipping by taking advantage of geographical niches with favourable local conditions [111]. Based on evidence gathered by UMAS and combined with historical fuel transitions, some of the key regional factors that have the potential to facilitate a fuel transition include the following:

- **Local shipping segments favourable for decarbonisation** – shortsea shipping, potential liner routes, shortsea ferries, hydrogen/ammonia carriers
- **Localised regulations** – unique local port rules, by-laws and state legislation that facilitate a favourable environment for establishing alternative fuels

- **Regional fuel availability** – vicinity of potential bunkering infrastructure, non-shipping demand for alternative fuels, potential plans for import/export terminals for hydrogen/ammonia
- **Other factors** – existence of innovation clusters, proactive local actors who can function as industry champions for decarbonisation, communities that are willing to support and facilitate decarbonisation.

The "heat map" analysis in Figure 9.1, shows the specific regional differences in how favourable the current environment is for SZEFs. The analysis outlines the most promising US regions and states within those regions, for early adoption of zero-carbon marine fuels. The four key geographic regions identified (i.e. the west coast, the Gulf, the Great Lakes and the east coast) are all busy international shipping hubs. The significant port infrastructure and associated port-based industries mean that any local developments taking place in the short to medium term (e.g. small-scale adoption of hydrogen/ammonia by local niche shipping segments) can be adapted and expanded to serve international shipping and position the US at the forefront of a global zero-carbon fuel transition in shipping.

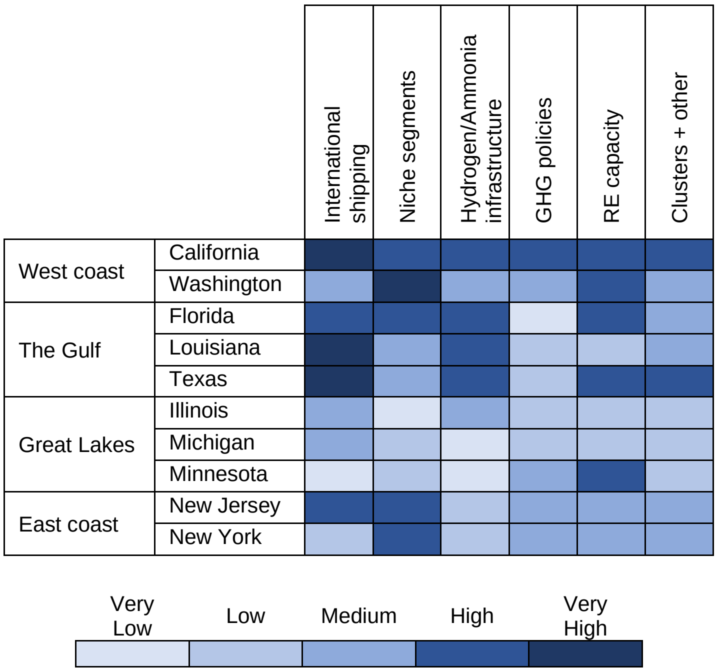


Figure note: The analysis is based on a series of both qualitative and quantitative data from multiple sources, including in-house UMAS analysis of shipping routes and port-based domestic and international traffic in the US. The categories take into account multiple factors and have been weighted to take into account the diverse number of variables that could make a location favourable for hydrogen/ammonia adoption.

Figure 9.1 Heat map of regional factors that can facilitate hydrogen/ammonia uptake in the US

Niche industry segments explored while developing the heat map include domestic shortsea bulk and container routes, and shortsea ferry routes which, due to the nature of the vessels and the relatively short travel distances reduce requirements for large-scale hydrogen/ammonia bunkering infrastructure investment. In addition, those segments might be less price sensitive and, owing to their domestic nature, might provide a wider range of options for government and state policy intervention. In the west coast, Washington state and California have a well-developed shortsea ferry industry that can be a possible test bed for hydrogen and electric propulsion (i.e. most evident in the Puget Sound area, including Seattle and neighbouring settlements). Other regions have varying levels of shortsea ferry traffic (i.e. with New York and Florida in the lead), but all also contain significant domestic bulk and container traffic.

The Gulf also has a well-developed chemical tanker industry that exports ammonia, which could potentially be used as on-board fuel. The hydrogen and ammonia infrastructure currently in existence in the US is mostly limited to brown/grey hydrogen and ammonia. However, this infrastructure can provide a useful steppingstone to decarbonisation of these sectors in the long term, and it is likely that corporations will use existing storage and production assets to develop blue[15] and green hydrogen/ammonia in the longer term. The Gulf, where many ammonia-producing plants (and exporting ports) are located (e.g. Beaumont, Donaldsonville, Faustina and Freeport), has a significant advantage over all other regions, given the existing ammonia handling expertise, safety experience and infrastructure, making it a good testbed for pilot projects utilising ammonia as a ship fuel. The west coast on the other hand has a growing hydrogen production industry under development (e.g. Douglas, Lancaster and Richmond) and is also developing hydrogen fuelling infrastructure, particularly in California. Even though this industry is currently too small to support shipping demand and the infrastructure developed is for road users, this geographical segment has potential for expansion and growth to serve shipping in the future. In addition, the existence of land-based demand for hydrogen provides potential for resource pooling, investment risk sharing and research, design and development.

All of the geographical regions that were assessed have a range of existing state-level GHG policy measures, from fuel standards to decarbonisation targets and carbon pricing schemes. The west coast, followed by the east coast, is at the forefront of these developments. However, these policies are not focused specifically on shipping and further efforts are needed to bring shipping into the local policy focus at a state-level. Other developments, such as renewable energy capacity growth and the existence of innovation clusters (i.e. both in shipping and more broadly in hydrogen/ammonia developments) make the west coast and the Gulf interesting areas for early adoption of hydrogen and ammonia. Renewable electricity (i.e. in Texas and in California through wind and solar) offers a way to move rapidly towards green hydrogen and ammonia, while local innovation clusters can support the innovations necessary around pilot development.

The east coast has many similar potential benefits to the west coast and the Gulf but is behind in terms of infrastructure developments regarding hydrogen and ammonia – something that could be overcome with targeted local policies, small scale pilot project grants (i.e. taking into account the entire fuel supply chain) and focus on local land-based industries that can be synergistically developed with shipping demand for hydrogen (e.g. using hydrogen in public transport and district heating). Finally, the Great Lakes area, even though less developed in terms of existing hydrogen/ammonia availability and fewer existing shipping niches, has two attributes that could make it a good testbed for hydrogen/ammonia shipping. First, the closed nature of the Great Lakes water system means that a well thought-out bunkering supply network could be developed to serve a larger proportion of shipping than in other regions. Secondly, as happened in the Baltic Sea, with SO_x, NO_x, and PM emission concerns in a closed, sensitive body of water, the Great Lakes could have multiple environmental benefits, beyond GHG abatement from adoption of zero-carbon fuels.

In short, when planning for early adoption of zero-carbon marine fuels, local conditions have to be taken into account to design policies that can have the most pronounced impact, at the lowest cost and at the shortest time horizon.

[15] Assuming that blue hydrogen can be developed in a way ensures it is a truly decarbonized fuel, through utilisation of CCS and near zero lifecycle emissions. The possibility of this being viable on an industrial scale is still an area of debate.

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Appendix A – Summary of alternative fuels: advantages and challenges

The table below provides a summary of the findings of each fuel discussed in Chapters 3–7.

Table A.1 Summary of alternative fuels advantages and challenges

Fuel	CO_2 emissions (HFO = 1) [112]	Fuel volume (HFO = 1) [112]	Key advantages	Key challenges
Hydrogen	0.00[16]	4.46	• The cleanest fuel available (no CO_2 emissions on board) • If produced by renewable electricity via electrolysis and consumed in a fuel cell, both upstream and downstream emissions are zero (including NO_x, SO_x and PM) • Most abundant fuel on the planet, meaning there are no limitations in principle for the long-term supply of hydrogen • Dual fuel hydrogen engines and large-scale fuel cells are in development and expected to become commercial by the mid-2020s • For multiple hard-to-abate sectors hydrogen and hydrogen-derived fuels are deemed to be the most viable candidate fuels to enable zero emissions	• Lower energy density than liquid fossil fuels, carrying capacity affected • Requires cryogenic or high-pressure containment • Hydrogen ICE still require NO_x reduction technologies • Immaturity of bunkering infrastructure • Low commercial maturity of CCS technology (blue hydrogen) and electrolysers (green hydrogen) means lower-carbon hydrogen comes at a high cost • Hydrogen is flammable and explosive if mixed with air, high risk on board, requires regulations and safety systems in place
Ammonia	0.00[16]	2.72	• If produced by renewable electricity via electrolysis and consumed in a fuel cell, both upstream and downstream emissions are zero (including NO_x, SO_x and PM) • Existing production and transportation networks for the ammonia fertiliser industry can be utilised and scaled up • Safe handling and storing of the fuel have been learned through years of experience in the fertiliser industry • Ammonia-ready engines will be commercially available by the mid-2020s • Requires only moderate pressure or non-cryogenic cooling containment	• Lower energy density than liquid fossil fuels, carrying capacity affected • Ammonia ICE still require NO_x reduction technologies • Low commercial maturity of CCS technology (blue hydrogen) and electrolysers (green hydrogen) means lower-carbon hydrogen comes at a high cost • Ammonia is highly toxic and soluble in water causing issues to aquatic wildlife so additional safety measures must be taken to avoid spillages
1st generation biofuels	1.00 [71]	1.20 or less	• Can be used as a drop-in fuel, allowing blending with conventional HFO or distillates • Can utilise existing diesel bunkering infrastructure, fuel supply systems and engines • Reduced on-board emissions (NO_x, SO_x and PM) compared with fossil fuel counterparts • Relatively inexpensive compared with other alternative fuels • High energy density compared with other alternative fuels	• Biomass feedstock in direct competition with food crops • In most cases, first generation biofuels do not reduce lifecycle GHG emissions compared with distillate fuels • Must be blended with existing fossil fuels and cannot act as a replacement
Advanced biofuels	0.00 – 0.25 [71]	1.20 or less	• Can be used as a drop-in fuel, allowing blending with conventional HFO or distillates • Can utilise existing diesel bunkering infrastructure, fuel supply systems and engines • Reduced on-board emissions (NO_x, SO_x and PM) compared with fossil fuel counterparts • Relatively inexpensive compared with other alternative fuels • High energy density compared with other alternative fuels	• The production volumes are very small compared with diesel • Prices are expected to increase due to supply constraints
Methanol	0.90[17]	2.39	• Existing bunkering infrastructure can be utilised with minor modifications • Widely available in many ports around the world • An effective hydrogen carrier requiring no energy to store • Significant reduction in SO_x, NO_x and PM on-board emissions compared with HFO • Dual-fuel engines are commercially available (both 2-stroke and 4-stroke)	• If methanol is produced using fossil fuels and without CCS, the lifecycle GHG emissions (well-to-wake) are merely equivalent to MDO • Lower volumetric energy density meaning a lower range or loss of cargo space
LNG	0.85[18] [15]	1.65	• Widely and safely used for power and heat generation • Reductions in CO_2, SO_x, NO_x and PM on-board emissions • Currently the cheapest alternative fuel to HFO • Dual-fuel engines are commercially available (both 2-stroke and 4-stroke)	• Fugitive LNG/methane (methane slip) can diminish or offset the reduction of on-board emissions • Methane is 28 times more potent at heating the atmosphere than CO_2 over a 100-year period and 81 times more potent over 20 years • Requires cryogenic or high-pressure containment
LPG	0.83 [50]	1.46	• Requires only moderate pressure or non-cryogenic cooling containment • Widely available, particularly in the US and is price comparable to conventional HFO • Reductions in CO_2, SO_x, NO_x and PM on-board emissions • Dual-fuel engines are commercially available (both 2-stroke and 4-stroke)	• Immaturity of bunkering infrastructure • Unburnt LPG (LPG slip) can counteract the reduction of on-board emissions • LPG is 3 to 4 times more potent at heating the atmosphere than CO_2

[16] With electrolysis to produce green hydrogen.

[17] Potentially 0 with green hydrogen production and DAC (see Section 6.1.1).

[18] Fugitive methane emissions not considered.