Low Carbon Fuel Options for Shipping

Project Neptune: UK Government Clean Maritime Demonstration Competition

P0122-RPT-013-01

Project Title:	CMDC Project Neptune
Document Title:	Low Carbon Fuel Options for Shipping
Classification:	UNCLASSIFIED
Descriptor:	
Document Number:	P0122-RPT-013-01
Version:	01
Date:	01 Mar 2022

Marine Engineering & Systems
Babcock International Group

Rosyth Royal Dockyard Limited
Rosyth Business Park
Dunfermline, Fife, KY11 2YD

www.babcockinternational.com

DOCUMENT CHANGE RECORD

Version/Issue	Description of Change	Date
V01	First Formal Issue	01/03/22

DOCUMENT APPROVAL

	Name	Signature	Date
Authored	*Grant Williamson* *Stephen Woodcock*		01/03/2022
Checked	*Fidel Olaye*		01/03/2022
Approved	*Maria Taboada*	MARIA TABOADA *Signed electronically*	01/03/2022

ABBREVIATIONS

Abbreviation	Definition
ABS	American Bureau of Shipping
AC	Alternating Current
BECCS	Bioenergy with carbon capture and storage
BOE	Barrels of Oil Equivalent
BOG	Boil-Off Gas
CCC	Committee on Climate Change / Climate Change Committee
CCS	Carbon Capture and Storage
CMDC	Clean Maritime Demonstration Competition
CO_2	Carbon Dioxide
DC	Direct Current
DfT	Department for Transport
DME	Dimethyl Ether
DWT	Dead Weight Tonnes
E-fuels	Fuels made from electricity
EEDI	Energy Efficiency Design Index
EJ/Year	Exajoules Per Year
ETO	Energy Transition Outlook
EU	European Union
FAME	Fatty Acid Methyl Ester
GHG	Greenhouse Gas
HAZID	Hazard Identification
HFO	Heavy Fuel Oil
HHV	Higher Heating Value
HVO	Hydro-treated Vegetable Oil

Abbreviation	Definition
IACS	International Association of Classification Societies
ICE	Internal Combustion Engine
ICS	International Chamber of Shipping
IMO	International Maritime Organisation
Li-ion	Lithium-ion
LFSS	Liquid Fuel Supply System
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LR	Lloyd's Register
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
N_2O	Nitrous Oxide
NOx	Nitrogen Oxides
PEM	Proton-Exchange Membrane
PPE	Personal Protective Equipment
SCR	Selective Catalytic Reduction
SMR	Steam Methane Reforming
SOFC	Solid Oxide Fuel Cell
SZEF	Scalable Zero Emission Fuel
TEU	Twenty-Foot Equivalent Unit
TRL	Technology Readiness Level
UMAS	University Maritime Advisory Services
ZES	Zero Emission Services
ZEV	Zero-Emission Vessels

1.0 CONTENTS

Tables

TABLE OF FIGURES

2.0 INTRODUCTION

2.1 Neptune Project

The Neptune project is an innovation project winner of the Clean Maritime Demonstration Competition (CMDC). As a winner of the CMDC, the project is receiving support funding from the Department for Transport (DfT) in partnership with Innovate UK. The project is being delivered by a consortium managed by the University of Strathclyde and include Ricardo, Babcock and the Shetland Islands Council. The project will develop a desk-based decision modelling and support system tool that will help to analyse, scope and develop plans for supporting the Shetland Islands' maritime sector energy transition.

This report is work package four of the project. It covers the potential low carbon emission sources of power that could be used to decarbonise the marine industry. The report will feed into work package 5 which will look at fuel options on a range of individual ships.

2.2 Scope

This report is split into 4 sections:

2.2.1 Key Representatives Driving a Change in Shipping

This section will look at what governmental bodies and regulators are saying about the future of low carbon fuels.

2.2.2 Energy sources

The main driver for low carbon shipping is not the vessels themselves but the availability of low carbon fuels. This section will look at biofuels, renewable electricity and sources of hydrogen on a wider scale than just Shetland.

2.2.3 Energy carriers

The main impact low carbon fuels have on the design of ships is the fuel storage. This section will cover energy density, safety and give examples of their use where available. The carriers being considered are batteries, hydrogen, ammonia, methanol and biofuels.

2.2.4 Forms of Energy conversion

The way fuel is converted can have a significant impact on efficiency and cost of a vessel. The efficiency of the conversion will impact on the amount of fuel required. This section will look at internal combustion engines and fuel cells.

2.3 ORION Project

The ORION project is simultaneously underway alongside the Neptune project. It aims to provide Shetland with secure and affordable clean energy whilst developing a new energy export industry. ORION's strategic partners, the Shetland Islands Council, Net Zero Technology Centre, University of Strathclyde and Highlands and Islands Enterprise are working with industry and key stakeholders to evaluate opportunities to transition Shetland from an established oil and gas centre to a renewable energy hub. The Orion project has three key aims:

- Create renewable hydrogen for export at industrial scale by harnessing offshore wind power.
- Transform Shetland's current dependency on fossil fuels to affordable renewable energy.
- Enable the offshore oil and gas sector transition to net zero by electrification.

Orion has clear synergies with the Neptune project. The production infrastructure has the opportunity to provide renewable e-fuels to the island's economy including the maritime sector.

2.4 Shetland

Shetland is an archipelago of islands north of Scotland with abundant wind and tidal energy resources. Its remote location limits the ability to export this energy via the national grid. A 600MW interconnector is currently under construction to allow the export of energy from a range of sources, the largest being the 443MW Viking wind farm.

After the interconnector's capacity has been exceeded, the plan is to both export the excess energy in chemical form and use it locally to decarbonise. Conceptualised projects give the islands a maximum potential of nearly 14GW.

3.0 KEY REPRESENTATIVES DRIVING A CHANGE IN SHIPPING

3.1 Introduction

With a few exceptions, low carbon fuels are less energy dense, more dangerous and more expensive than current fossil fuels. This makes them significantly less competitive across nearly the entire marine industry. There is little prospect of this changing in the coming decades without regulations or carbon cost drivers.

National governments and organisations will be key to providing incentives or regulations to decarbonise shipping. This section of the report considers some of the key representatives with the potential of driving a change in the shipping industry, noting where possible their ambitions for the way that shipping needs to change. The section then looks into the reports offering possible pathways to meet these ambitions.

There are many other important organisations not mentioned in this section to keep it manageable. It also does not cover key companies like engine manufacturers and energy companies. While most companies are keeping their options open, it is notable that several large companies are focusing on one fuel more than the others, for example, Shell favours hydrogen whereas Maersk favours methanol.

3.2 The International Maritime Organization

The International Maritime Organization (IMO) is currently the best placed organisation to co-ordinate marine decarbonisation worldwide. This is how the IMO describe themselves [1]:

> *The IMO was established by Governments as a specialized agency under the United Nations to provide the machinery for intergovernmental cooperation in the field of regulation of ships engaged in international trade. IMO is responsible for the global regulation of all aspects of international shipping and has a key role in ensuring that lives at sea are not put at risk, including security of shipping, and that the environment is not polluted by ships' operations.*

In 2018, the IMO adopted an initial strategy on the reduction of Greenhouse Gases (GHGs) emissions from ships. IMO's strategy identifies levels of ambition for the international shipping sector as detailed below. [1].

- ***Carbon intensity of the ship to decline through implementation of further phases of the Energy Efficiency Design Index (EEDI) for new ships.*** *To review with the aim to strengthen the energy efficiency design requirements for ships with the percentage improvement for each phase to be determined for each ship type, as appropriate;*
- ***Carbon intensity of international shipping to decline.*** *To reduce Carbon Dioxide (CO2) emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008; and*
- ***GHG emissions from international shipping to peak and decline.*** *To peak GHG emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out as called for in the Vision as a point on a pathway of CO2 emissions reduction consistent with the Paris Agreement temperature goals.*

Although there have been significant efficiency savings, mainly through slower speed, the EEDI is unlikely to be able to smoothly force the significant jump from fossil fuels to carbon-neutral fuels. The IMO plan to review this strategy in 2023.

The International Chamber of Shipping (ICS) and several other industry representatives put forward to the IMO a $2/ton surcharge on marine fuel. This could raise $5 billion over 10 years to help fund research and development into building a zero-carbon shipping industry.

3.3 The European Union

The European Union (EU) has a set target for itself to achieve climate neutrality by 2050. As part of their steps towards achieving this target, the EU has set an intermediary target of reducing emissions by at least 55% by 2030 in comparison to 1990 emission levels. The ‘Fit for 55’ package has been produced in line with this intermediary target. The package comprises of proposals to revise and update their legislation so as to align their legislation with their targets.

The ‘Fit for 55’ package consists of many proposals including proposals to [2]:

1. Include maritime transport emissions in the EU’s emissions trading scheme.
2. Set a target for net removals of GHGs of at least 310 million tonnes of CO2 equivalent by 2030 at an EU level.
3. Increase the EU’s target of at least 32% renewable energy sources in their overall energy mix to 40% by 2030.
4. Accelerate the deployment of infrastructure that can provide alternative power supply for ships in ports.
5. Reduce the GHG intensity of the energy used on-board ships by up to 75% by 2050 through the promotion of usage of greener fuel by ships.

The ‘FuelEU’ requirement shall apply to ships above 5,000 gross tonnage and excludes naval ships, fishing ships, government ships, dredging, ice-breaking, pipe laying and offshore installation activities.

The target reduction rate for shipping is slower than other industries due to the challenges the shipping sector faces.

3.4 The UK Government

The UK Government (and many other governments) have set more ambitious carbon targets than the IMO. The UK aims to be ‘net zero’ by 2050 including shipping. This still leaves room for the marine industry to produce emissions if they are offset elsewhere. However, it is not expected that the UK marine industry will have significant offsetting available.

The UK Government vision for 2050 in maritime is that the UK will have taken a proactive role in the transition to zero emissions. In the clean maritime plan, the UK Government’s vision is stated as:

In 2050, zero emission ships are commonplace globally. The UK has taken a proactive role in driving the transition to zero emission shipping in UK waters and is seen globally as a role model in this field, moving faster than other countries and faster than international standards. As a result, the UK has successfully captured a significant share of the economic, environmental and health benefits associated with this transition. [3]

The UK government plans to achieve this vision through the following goals [3]:

- By 2025: All new vessels being ordered for use in UK waters are being designed with zero emission propulsion capability.
- By 2035: The UK has built a number of clean maritime clusters. These combine infrastructure and innovation for the use of zero emission propulsion technologies. Low or zero emission marine fuel bunkering options are readily available across the UK.

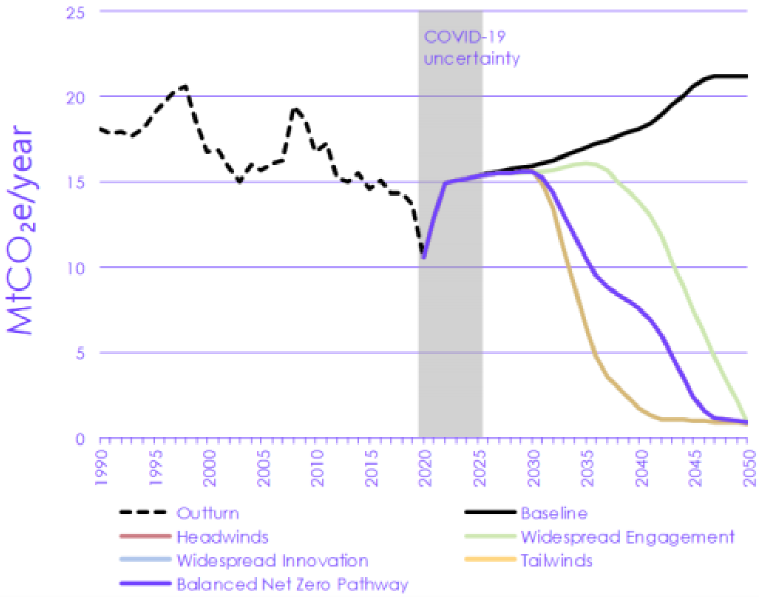
3.5 Climate Change Committee

The Climate Change Committee (CCC) is an independent, statutory body. Their purpose is to advise the UK and devolved governments on emissions targets and to report to Parliament on progress made in reducing GHG emissions and preparing for and adapting to the impacts of climate change [4].

Their assessment of the shipping sector is that there is clear potential to reduce emissions to close to zero by 2050 through the use of carbon-free fuels, for example, through the adoption of ammonia produced via low-carbon methods. In the CCC's The Sixth Carbon Budget from 2020, it was deemed that the cost to apply GHG saving methods would be expensive given the added costs of using low carbon ammonia and the price of retrofitting, but due to the size of the maritime sector, the overall costs per sector are smaller than many others [5].

The CCC expect the shipping sector to be decarbonised mainly through ammonia with hydrogen as a backup.

Figure 1 shows the significant variation in decarbonisation dates between different CCC models.



Source: BEIS (2020) *Provisional UK greenhouse gas emissions national statistics 2019*; CCC analysis.
Notes: Widespread Innovation and Tailwinds follow the same trajectory. Headwinds and Balanced Net Zero Pathway follow the same trajectory.

Figure 1 – The Sixth Carbon Budget – 'Emissions Pathways for Shipping' summary by the CCC

3.6 University Maritime Advisory Services

The University Maritime Advisory Services (UMAS) is a sector focussed, commercial advisory service that draws upon the world leading expertise of the University College of London Shipping Team combined with the advisory and management system expertise of UMAS International Ltd [6]. The analysis was used by the CCC to help produce 'The Sixth Carbon Budget –Shipping'.

The UMAS Transition Strategy Report [7] details how the currently used fuel types in the maritime sector will transition as the shipping industry reduces its GHG emissions and works towards net zero. The key points made through the Transition Strategy Report are:

1. **The necessary transition is feasible – it can and must accelerate.** UMAS have researched and realise that transitions from one technology to another has happened before. Due to this, it is possible to learn from the past to help transition away from fossil fuels.
2. **The transition is not all about the IMO. Far from undermining the IMO's authority, national and regional regulation have an important role to play.** This key point recognises the IMO's actions that kick-started the transition and how their input is a continuous driver. It is further explained how previous transitions were introduced through smaller groupings and the private sector, making a country become the first to introduce a standardised method that becomes a global commonplace. In order to achieve this, it requires all decision makers and industries to work together and help each other to make strong progress.
3. **The fuel pathway is not predetermined, but will be laid brick-by-brick, and all actors have a responsibility to ensure it is well built.** There has been a considerable effort to research into fossil fuel alternatives and to determine the future of these fuels. The outcome is that the actors and their actions will determine the most likely fuel used, with retrofits on existing ships being comparable to new ships being built that use zero emission fuels. Infrastructure will be critical to ensure that the fuels are sustainable, remain cost competitive and readily available.
4. **There are abundant opportunities for Scalable Zero Emission Fuel (SZEF) use this decade. Enabling this early use requires concerted action now.** The most urgent action revolves around scaling up production of SZEFs to begin transitioning to them as soon as possible. Applying these fuels to the largest GHG producers in the fleet, on the most used trade routes, to begin making a difference and lead the transition.

Looking further into the report, UMAS cover how global trends show shipping to increase as more goods and raw materials are required due to populations and wealth increases, causing a rise in CO2 emissions. From looking at the trends, there are multiple pathways to help reduce GHG emissions. These include a possible reduction in demand for shipping, increasing fossil fuel efficiency or reducing the GHG intensity of the fuels. Efforts have been made by a reduction in speed, increasing the size of the vessels and improvements to the technical specification but overtime these will likely face diminishing returns.

UMAS look into a few different scenarios that drive the transition, with the most likely outcome being a part of each scenario driving the transition up to the 2050 target. It can be observed that the three scenarios are already taking hold, with the IMO's initial strategy governing the global transition, Emissions Trading Schemes that help with the transition in regions such as the European Union and then local nations such as Norway and the UK driving country level actions.

Overall, it is clear that national governments, regional bodies and industry stakeholders need to work together from different angles to decarbonise the maritime industry. UMAS note that the future is unknown and a step-by-step process will need to be undertaken to ensure the end result in 2050 is stable and sustainable.

3.7 International Association of Classification Societies

3.7.1 Introduction

The International Association of Classification Societies (IACS) is an organisation of classification societies that is dedicated to keeping ships safe and seas clean by establishing and ensuring the application of maritime standards [8]. Currently, IACS consists of [9]:

a. American Bureau of Shipping (ABS)
b. Bureau Veritas
c. Chinese Classification Society
d. Croatian Register of Shipping
e. DNV
f. Indian Register of Shipping
g. Korean Register
h. Lloyd's Register (LR)
i. Nippon Kaiji Kyokai
j. Polish Register of Shipping
k. RINA
l. Russian Maritime Register of Shipping

These member organisations are actively involved in decarbonising the marine sector in varying degrees. The sections below will focus on three key member organisations.

3.7.2 DNV

DNV, formerly DNV GL, is a world leading classification society and recognized advisor for the maritime industry. They have gathered valuable information about energy usage and sources and modelled how the future could look with the current advancements in energy carriers. They have produce a large number of reports on the energy transition covering all sectors as well as the marine industry.

The DNV estimate future growth of energy carriers, predicting nearly 13 EJ/year required by 2030 as shown in Figure 2 [10].

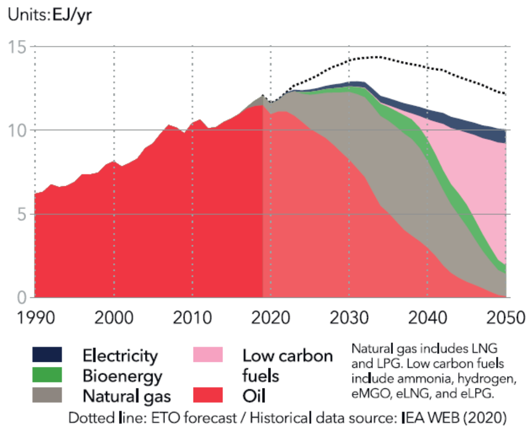


Figure 2 – World Maritime subsector energy demand by carrier (Revised) [11]

Oil usage is predicted to fall, whilst it is predicted there will be an increase in the use of Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG), Ammonia, Hydrogen and E-fuels. This all balances on successful implementation of regional decarbonisation efforts [10]. Following on from the release of the Pathway to Net Zero Emissions report [11] from the DNV, a requirement to reduce oil usage completely and reduce the amount of LNG by 2050 has been introduced, with a minimal increase in the demand on shipping, as shown in Figure 2. DNV recognises that it is not possible to completely remove fossil fuels, especially in large nations such as the African nations. Therefore, wealthier nations will need to go beyond zero emissions to counteract this to achieve net zero.

The DNV notice that the potential for electricity in shipping is limited mainly to small vessels and short range routes, due to the energy density of batteries being low and likely to remain low in comparison to other fuel options. With battery-electric options not significant enough for decarbonisation in shipping, ammonia, hydrogen, biofuels and synthetic fuels become the only low/zero-carbon fuels available.

From the Energy Transition Outlook (ETO), several special reports have been released focusing on different aspects of the energy transition from now to 2050. These reports cover individual areas such as the technologies that will drive the change, the cost of this change, how to close the gap to net zero, and also a report on the maritime forecast.

In the Maritime Forecast to 2050 [12], the DNV layout three key fundamentals that will drive ship decarbonisation throughout the next decade:

- **Regulations and other governmental policies remain key drivers for ship and fleet decarbonisation, and the IMO is the most influential regulator** – The IMO in 2018 introduced their strategy that has remained a key driver for fleet decarbonisation, but this shouldn't be solely relied upon and it's up to governments to enforce and build upon the regulations set by the IMO.
- **Access to finance will depend increasingly on being able to meet decarbonisation targets over ship life cycles** – Through Environmental, Social and Governance reporting, companies can prove that their vessels are sustainable and meet emissions targets therefore being applicable for the necessary funding. Through sustainability bonds, businesses can provide key performance indicators so that decarbonisation efforts can be tracked and satisfy the requirements of the bond.

- **We can expect ships and shipping companies that perform poorly on emissions to be less attractive on the charter market** – With the IMO establishing carbon intensity ratings and transparency to all customers, there is predicted to be less business conducted through the more carbon intensive options. With a possible carbon tax being introduced, companies will strive to achieve an acceptable intensity rating and in turn reduce GHG emissions to keep their business flowing.

The Maritime Forecast to 2050 [12] goes further into detail, reviewing ship technology, fuels and their availability. From the current market, it has been seen that methanol is available now and has already seen its first commercial use, with bio-based methanol being the most promising carbon-neutral fuel for the near future [12]. DNV expect that by 2025, ammonia and hydrogen will likely have been demonstrated within shipping and begin paving the way for zero-carbon ships for 2030. If ammonia and hydrogen prove to be efficient and readily available then these will prove to be an important fuel option for meeting the IMO’s ambitions.

Furthermore, the forecast considers how future development will be constrained by both access to capital and infrastructure. With a rise in greener energy sources and a demand for energy carriers from all sectors and not just shipping, a possible problem is if there will be enough capacity to support the maritime industry. A problem also occurs with funding for shipping. With a global demand for decarbonisation, funding is allocated to the largest GHG emitters to reduce emissions. Shipping is low in comparison to other GHG emitters but requires considerable costs for retro fitting, carbon capture systems and fuel storage and safety measures both on-board and on land. Carbon Capture and Storage (CCS) features heavily in the transition to new fuels, not just in shipping. If this cannot be kept at a competitive level then there is little capital left for capacity for new fuels.

3.7.3 Lloyd’s Register

LR is a global professional services company specialising in engineering and technology for the maritime industry. They are the world’s first marine classification society, created more than 260 years ago to improve the safety of ships. They define their marine and offshore sector as the following [13]:

Our Marine and Offshore business is a leading provider of classification and compliance services to the marine and offshore industries, helping our clients design, construct and operate their assets to the highest levels of safety and environmental compliance.

In the race to zero emissions, our solutions, technical expertise and industry-firsts will support a safe, sustainable maritime energy transition.

From the Decarbonisation Transition Pathways report [14], LR consider the possible futures for the marine industry, all with a commonality of driving down fossil fuel usage in order to reach the IMO’s target of a 50% reduction by 2050. There are three main pathways considered when looking at the fuel used on-board to reduce emissions, all of which see a large reduction to fossil fuel usage each decade until 2050. These are:

1. **Renewable energy dominates shipping** - This pathway sees electricity providing a major role in the fuels used for shipping. This includes electricity for batteries, the production of hydrogen, ammonia and e-fuels such as e-methanol.
2. **Bio-energy dominates shipping** - This pathway assumes bio resources and bioenergy are largely available and becomes the dominant fuel used in shipping. E-fuels also play a role in shipping but only a fraction compared to bioenergy.

3. **An equal mix of both energies** - This pathway assumes both bioenergy and e-fuels play a similar role in the maritime industry.

The three possible pathways all achieve at least 50% reduction in GHGs by 2050 and each shows going further than a 50% reduction to show that zero is possible. LR explain that at this stage, one route, fuel or technology is difficult to decide on and in order to take early action, there is a need to monitor and understand the fuel supply, production and the interaction on board ships.

LR also note the use of batteries in the transition to zero emission fuels. They mention that batteries should not be underestimated due to their use for onshore power connections and hybrid vessels. It is likely batteries will play a big role for small ships and short-range vessels but due to their high cost and low energy density, they will only play a small role within shipping and the larger vessels.

From the Decarbonisation Transition Pathways report [14], LR conclude how this decade will be characterised by prototypes of Zero-emission Vessels (ZEVs). The next ten years will rely heavily on research and development so that the following years can focus on scaling and commercialisation. These changes will include policy development, influence from the public and development of international standards and rules. This puts pressure on acting as soon as possible to help meet future demand.

LR further mention that zero-carbon fuel producers need to start entering the marine market in the early 2020s. Doing this will allow for an understanding of the demand, the sustainability and the growth. There will likely be a risk to critical path decisions due to the uncertainty of which fuels will be available in large quantities, cost competitive and sustainable for long term usage. By 2030, zero-carbon fuels will need to be cost competitive with conventional marine fuels. Technology availability and readiness along with the associated costs will affect the price of the fuels and be a major driver for the economic case of a ZEV.

From the conclusions section in the Decarbonisation Transition Pathways report [14], it is mentioned how there are a number of aspects to consider in transitioning to ZEVs. These aspects consist of the safety and space required for fuel storage and equipment. The storage space required all depends on the type of fuel used, its energy density and the efficiency of the machinery. The future is uncertain and zero-carbon fuels, depending how they develop and evolve, may require new technologies and research that could add extra cost. Based on these conclusions, there is an urgency for pilot projects and prototypes, as these will provide a better understanding of what these costs could be and identifying how they could be reduced.

From LR, it is clear they offer a valuable insight into the future of the maritime industry. The goals set by the IMO and the multiple pathways to achieve this laid out by LR all have to be considered as it is unclear how the maritime industry will progress. The key takeaway from the LR report is that the change needs to be implemented now concerning zero-emission fuels and their standards/policies, and progress on ZEVs already started, so that by 2030 a future pathway to the 2050 goal is not unknown.

3.7.4 American Bureau of Shipping

ABS is a world leading classification organisation. They offer solutions for addressing the key sustainability goals of the IMO as they relate to vessels, fleets and managing organizations. From their reports, they follow the IMO's policies and ambitions, proposing ways of applying these now and how the future might look as the IMO's ambitions are achieved.

From ABS Pathways to Sustainable Shipping Outlook [15], ABS highlights the challenges associated with the IMO and their expectations. The purpose of this report is to set a guide on how the IMO's ambitions can be achieved. ABS looks further into the different fuels and opportunities available within shipping. ABS recognises that to reduce carbon emissions in future vessels and the overall carbon footprint of the marine sector, the use of low- and zero-carbon fuels is essential. The choice of fuel and propulsion system will be determined by the vessel's operation. This will then determine the requirements for bunkering and capacity [15].

From this report, it is noted how there are three potential fuel pathways to meeting the IMO's goals to decarbonise the global fleet. The three fuel pathways can be seen in Figure 3 and are detailed as [15]:

1. Light gas – These fuels include LNG, bio-LNG, and synthetic natural gas or renewable natural gas and hydrogen.
2. Heavy gas and alcohol – These fuels include LPG, methanol, ethanol and ammonia.
3. Biofuel or synthetic fuels - Currently, the most widely used component is Fatty Acid Methyl Esters (FAME) or biodiesel, Hydro-treated Vegetable Oil (HVO) is a second generation biofuel.

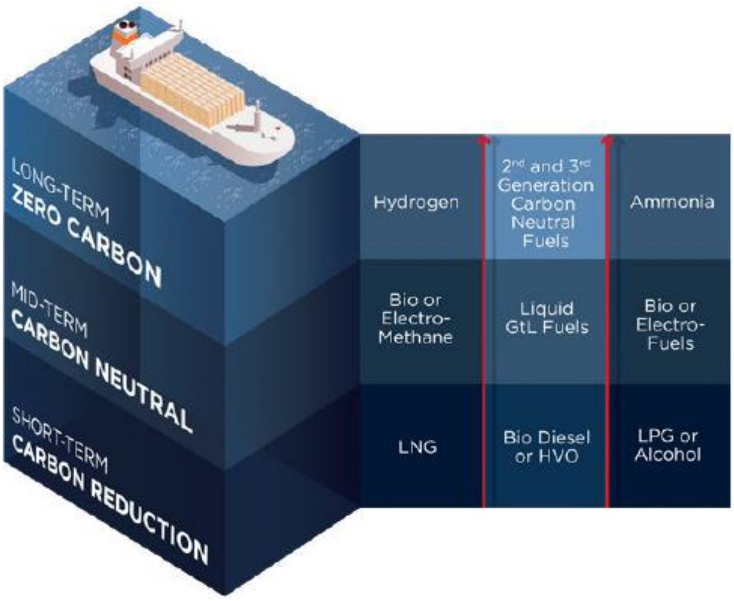


Figure 3 – ABS's three fuel pathways to carbon-neutral and zero-carbon shipping [15]

These three pathways start with fuels that can be utilised in existing propulsion and power systems and can reduce CO2 and other emissions and, in some cases, eliminate emissions.

ABS has also written a number of papers on the different fuels that could be considered and how they can be implemented in to large scale. Taking ammonia as an example, they define the difficulties associated with this gas, mainly from its toxicity, and how this can be burned either in an internal combustion engine (ICE) or used in fuel cells [16].

From ABS Pathways to Sustainable Shipping Outlook report, there are a number of key takeaways that can be considered [15]:

- Through decarbonisation of all industries, not just marine, there is likely to be a considerable change to the types of commodities traded. These changes to commodity types, volume and trading patterns will have an effect on the evolution of shipping and the overall fleet from now until 2050.
- Until the technology and infrastructure of zero- and low-carbon fuels becomes more cost effective, it is likely, as we transition to these fuels, the cost of operating and purchasing low- and zero-emission vessels will be high.
- New regulations and safety standards will be required and adopted for the alternative fuel types and their associated technologies and operational framework. The new regulations could also have an impact on the type and volume of cargo as well as the volume of trade in general.

The key points from ABS's report provide possible pathways and likely outcomes for the next 30 years of shipping, following closely with the IMO's policies and ambitions and reaching 50% emissions by 2050. As with the other commercial drivers looked into, ABS understands the future is uncertain and provide different scenarios, all of which could be a possibility. Each scenario will have different impacts and effects, primarily on regulations, technology, infrastructure and trade volumes, which until a transition occurs, will not be fully understood.

3.8 Conclusions from Literature Study

There are areas of agreement and disagreement between the governments, committees and regulatory bodies.

3.8.1 Timing

There is agreement that net carbon emissions need to be reduced to zero. There is disagreement on how fast, both with the end date and how fast reduction should be getting to zero. The IMO are aiming for a carbon reduction 50% by 2050 compared to 2008. Many governments have included shipping in their 2050 net zero pledge.

Some groups are targeting a 1.5°C increase whereas others are looking at 2°C or above. This has a significant impact on how quickly reductions need to happen. Even if there is a set target, it is still unknown at what rate shipping will decarbonise as shown by Figure 1. There is a general agreement that shipping will start to significantly decarbonise later than other industries.

There is also uncertainty around the future size of the shipping sector.

3.8.2 Stepping Stone Technologies

There are 2 stepping stone technologies that can be used to reduce emissions faster without eliminating them.

1. LNG/LPG
2. Blue hydrogen

LNG is growing in popularity as it is the cleanest abundant fuel available currently. It has the potential to reduce carbon emissions by 25% but methane slip does reduce that overall benefit. There is disagreement about how prevalent it will become this is mainly due to the expected time to decarbonise. The faster the decarbonisation the less prevalent LNG will become. However, if shipping has to reduce its equal share, there are few other options apart from reducing speed.

Blue hydrogen, using carbon capture with natural gas to make hydrogen, has the potential to speed up the conversion to hydrogen based fuels. It is necessary to meet the targets in a lot of models. Its emissions will need to offset by 2050.

3.8.3 Long Term Fuels

There is agreement on which fuels/technologies are worth considering strongly:

1. Grid batteries
2. Hydrogen
3. Ammonia
4. Methanol
5. Biofuels (there are a wide range of fuels in this category)

There is agreement that biofuels are good fuels for shipping. There is also argument that there are not enough biofuels to power the whole marine sector. There is wide disagreement over what percentage of the total marine energy biofuels can provide. There are also significant regional variances in the amount and type of fuel available, as well as the amount of carbon emissions in there production. Biofuels can also produce harmful emissions other than carbon dioxide.

There is agreement grid charged batteries look promising for very short range craft. Batteries are also likely to support other fuels in a range of craft.

There is agreement that ammonia has the potential to be the cheapest and most efficient and fuel for deep sea shipping. There is disagreement and unknowns about how safe ammonia will be and which ships it will be suitable for.

Compressed hydrogen may find a niche in short range craft that can’t use batteries.

Liquefied hydrogen can’t compete with the ease of storage of ammonia but may see a role if ammonia is not safe enough. Although there are also safety issues with hydrogen.

E-Methanol is seen as a safer and more energy dense alternative to both hydrogen and ammonia however, there is considerable cost and energy required to capture the carbon from the air required to make it.

3.8.4 Other Fuels/Technologies

There are other options that deserve a mention:

Wind has significant potential to support the propulsion in the correct craft and routes.

Nuclear ships will likely have a niche similar to where it is used now, mostly in submarines but also on a select few surface vessels. Nuclear is seen by some as the only low carbon form of shipping available now for large long range craft. It will prove very challenging to operate a nuclear ship outside of state control however, there are several companies that are currently investing in micro-reactors and other related research projects. In addition to this, some classification societies are in discussion with companies to build rules relating to nuclear ships.

Solar and human power will also support similar to their current use, where the power requirement is small.

4.0 ENERGY SOURCES

4.1 Introduction

Low carbon fuels need to come from a low carbon source. Producing these low carbon fuels is harder than converting the vessels to the new fuels. The UMAS and Energy Transitions Commission estimate that to decarbonise shipping, 87% [17] of the cost would be for creating the supply of fuel and its bunkering. The remainder being spent on converting ships. This will have a significant impact on the dominant fuels. Understanding the availability of energy sources is also important as it helps with timing the market.

The three main potential sources are:

1. Bioenergy,
2. Renewable electricity,
3. Blue hydrogen.

Understanding the availability of fuels is critical as there is a significant trade-off between a fuel that is a good energy carrier for a ship and a fuel that is abundant or efficient/cheap to produce. Manually powered vessels provide the cleanest, most efficient option of vessel propulsions but is only suitable for the smallest of vessels making this a poor choice for any vessels larger or heavier than a dinghy. Wind is an abundant, free and clean form of propulsion but again is not suitable for large heavy vessels. It doesn't scale with ship volume and is not reliable. It can still be useful to assist the main propulsion system in the correct scenarios.

The main energy carriers considered for shipping are listed below. Roughly, the energy carries higher up this list are more efficient/more abundant whilst the energy carriers nearer the bottom of this list make better fuels for a vessel:

1. Batteries
2. Compressed Hydrogen
3. Ammonia
4. Liquid Hydrogen
5. LNG
6. Ethanol
7. Biofuel

Zero carbon energy availability is one of the major limiting factors in decarbonising shipping. This leads to the trade-off leaning towards more efficient fuels, but there are limits to what the energy carriers at the top of the list can achieve.

Throughout the following sections, the different fuel sources will be considered and explained.

4.2 Bioenergy

4.2.1 Bioenergy Introduction

Bioenergy can be split into biomass and biofuel. Biomass is any organic material which has absorbed sunlight and stored it in the form of chemical energy. Biofuel is usually reserved for liquid or gaseous fuels used in transportation. There are a large number of processes that can turn biomass into biofuels.

Bioenergy can come from waste products or be grown directly. Capturing and using waste methane can be particularly beneficial as it is a strong GHG if not captured or burned.

4.2.2 Biofuels

Biofuels are a very appealing drop-in solution for the marine industry. They would allow the current fleet to have a relatively easy refit and for there to be little change in safety or operating profile. They are also currently very cost competitive when compared to other renewable sources [18].

Unfortunately, they have a limited supply and are very appealing to a lot of different industries. This will cause the price to rise significantly or necessitate legislation to be brought in to limit its use. The complication in this are beyond the scope of this report.

There are also regional variations in type and quantity of biofuel available. Biodiesel is common in Europe. Ethanol is the most common in the Americas where growing sugar and starch based crops (sugar cane and maize) is easiest. The EU and other countries also import resources and biofuels to meet the requirements.

Ethanol and biodiesel are the two most common biofuels but there are a wide variety that are viable depending on the source. To highlight the complications a list of some of the biofuels, their properties and where they come from, can be seen in Table 1 below.

Fuel Type	Typical Specific Energy (MJ/kg)	Energy Density (MJ/L)	Applications	Sources
Bio-Methanol	22.7	15.6 – 18.2	Building block for plastics, paints, car parts and construction materials. Fuel for motor vehicles, ships boilers and cook stoves and fuel cells.	Currently made from natural gas but possible production line from biogas/methane.
DME – Dimethyl ether	28.8 – 31.7	19.2 – 21	A potential substitute for propane/LPG, used in industry and households as fuel. Diesel engines and gas turbines.	Dehydration reaction of Bio-Methanol.
Bio-Ethanol	19.9 – 29.8	21.2 – 24	Varnish and perfume manufacturing, preservative for biological specimens, as fuel and a gasoline additive.	Fermentation of Sugar/Starch based crops, also produces acetone and butanol.
Bio-Butanol	36.1	29.1	Plastics, polymers, lubricants, brake fluids, fuel source for ICEs.	Fermentation of Sugar based crops, also produces acetone and ethanol.
Biodiesel / FAME	38 – 40.2	33.3 – 35.6	Fuel for ICEs or diesel additive, heating oil, energy generation	Transesterification of oils or fats
HVO	44	33 – 37.3	Fuel for ICEs or diesel additive	Hydrogenation and hydrocracking of oils or fats in high temperatures and pressures

Fuel Type	Typical Specific Energy (MJ/kg)	Energy Density (MJ/L)	Applications	Sources
Bio-Methane	48.7 – 55.6	23.5	Fuel for turbines, homes, ovens, water heaters, motor vehicles, rocket fuel (refined methane)	Bio Gas produced from anaerobic digestion of organic material

Table 1 – Different Types of Biofuels and their attributes [19] [20]

Bio-methane is currently produced from biogas by removing the impurities, mainly CO_2. This makes it a cleaner fuel than biodiesel. It is currently fed into the national gas network but could be used to replace LNG.

4.2.3 World Production

From Figure 4, it can be seen that there are nearly 2 million BOE per day of liquid biofuels used worldwide in all industries. For comparison, there is roughly 97.1 million barrels of oil used globally a day, with global international bunkering for shipping accounting for over 4 million BOE per day [21].

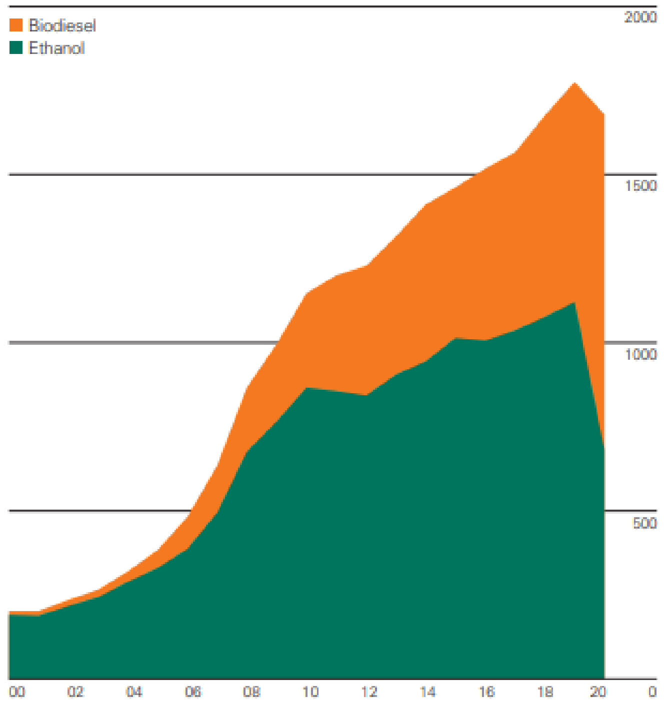


Figure 4 – From BP statistical review – World biofuel consumption (thousands of BOE per day)

There is scope for biofuels to increase as a lot biomass is not converted to liquid biofuels. For example, in the UK, about 2GW of electricity is generated from bio-mass this is the energy content of 28 thousand BOE per day.

4.2.4 Expanding Biofuels

Great care is required to ensure any growth is sustainable and does not compete heavily with food, land requirements or biodiversity. Low intensity agriculture can be net zero carbon but has yields that are too low. High intensity agriculture is energy intensive and therefore currently not net-zero. In the future, fertiliser and farming machinery can be decarbonised to help mitigate this.

If not properly managed, using biofuels could do more damage than climate change and also increase emissions [22]. If properly regulated there will be renewable biofuels available, but the bulk supply will likely be taken by sectors that are harder to decarbonise than the marine industry such as aviation and used to produce products we need. Biomass can also be useful for carbon reduction by using Bioenergy with Carbon Capture and Storage (BECCS).

4.2.5 Expectations for Use in the Marine Industry

There are differences in expectations between important bodies. For example, the EU Sustainable and Smart Mobility Strategy [23] estimates that approximately 50% of international marine fuels could be liquid biofuels or biogas. In one report, DNV has scenarios [24] that go even further than this, but do caveat that they have not looked at availability in those scenarios. LR predict a small but steady increase in bioenergy for each of its pathways, where ammonia and hydrogen also play a considerable role [14].The shipping industry also has a 'low' applicability to biofuels due to its availability according to the 'All hands on deck' report by Shell [25].

The CCC predict that biofuels in surface transportation (vehicles, ships and trains) will not serve in the long term due to other viable low-carbon options. The CCC mention that for shipping, biofuels will be used mainly as a transitional fuel as it is expected by 2050 there will be other alternative low-carbon fuel options that will be more suitable.

4.2.6 UK

The UK currently uses both biodiesel and bioethanol. Biodiesel in the UK is predominately produced from waste oil and used cooking oil, while bioethanol is created from wheat and sugar beet. Only 12% of the verified renewable fuel used in the UK was from the UK, the rest was imported. 24% came from used cooking oil in China [26].

The UK does get a large proportion of it energy from biomass. In 2020, it accounted for about 61% of renewable sources. It can be seen in Figure 5 that it has been growing faster than renewable electricity.

	Thousand tonnes of oil equivalent					
	1990	**2000**	**2010**	**2018**	**2019**	**2020**
Solar PV, active solar and geothermal	6	12	42	1,143	1,136	1,186
Wind and marine	1	81	885	4,894	5,487	6,482
Hydro (small and large scale)	448	437	309	468	503	581
Landfill Gas	80	731	1,725	1,298	1,202	1,160
Sewage gas	138	169	295	407	434	440
Wood (domestic and industrial)	174	458	667	1,050	1,104	1,115
Municipal Waste Combustion	101	375	632	1,464	1,625	1,677
Heat pumps	1	0	778	1,034	1,081	1,125
Transport biofuels	0	0	1,218	1,371	1,736	1,638
Cofiring	0	0	625	0.2	0.3	0.0
Biomass*	72	265	1,054	7,806	8,451	8,952
Total	**1,021**	**2,529**	**8,229**	**20,928**	**22,758**	**24,355**

**Includes plant and animal biomass, anaerobic digestion and biogas injected into the gas grid*

Figure 5 - UK renewable energy production per year [26]

It is important to note that the UK imports a lot of its biomass. For solid biomass, in 2019, the UK produced 4.7 million tons of oil equivalent and used 8.1 million tons of oil equivalent [27]. For comparison, the UK shipping sector will require around 6 million tons of oil equivalent.

The guidance coming from the UK government is there will be very little biofuel for the marine industry.

4.2.7 Shetland

The most likely source of biofuels on Shetland is the marine industry. Waste from the fishing industry and using seaweed need to be further investigated.

4.3 Renewable Electricity

The only long term scalable source of energy for the marine industry nowadays is via renewable electricity generation. Electricity can be used directly via fixed cables or batteries. This is a very efficient way to use the available energy but is only available to fixed or short range vessels.

To power the majority of shipping, a more energy dense fuel is required. This can be achieved by using electrolysis to produce hydrogen. The hydrogen produced can be used directly or be further converted into ammonia, methanol or a range of ‘synthetic fuels’ for improvements in energy density and safety.

4.3.1 Efficiency Problem

The main problem is there is significant energy losses in converting and storing hydrogen based fuels. These losses can be as high as 75%. Other industries, for example the car industry, are going from small inefficient engines (~20%) to highly efficient electric motors (~87%) saving significant amount of carbon for the amount of electrical energy used. Shipping on the other hand, is going from large efficient engines (~50%) to a very inefficient fuel chain. This makes shipping one of the least efficient users of renewable energy in terms of carbon reductions. It also makes the fuel expensive. If the electricity is generated via fossil fuels, a hydrogen vessel will result in an increase in carbon emissions.

Low carbon shipping is only possible where there is an abundance of renewable electricity generation.

Even though renewable electricity is particularly inefficient in the marine sector, solar power is still more efficient per unit of land than growing biofuels. Offshore wind also greatly increases the area available.

4.3.2 Store of energy

The generation of green electricity has two technical problems. The first one is scaling it up in time and in a cost effective manner. The second one is intermittency. The production and use of hydrogen provides a store of energy that can help balance the load. This does have to be balanced with the high cost of electrolysers that will be underutilised and storage costs.

4.3.3 UK Renewable Electricity Sources

Figure 6 shows sources of energy for the UK national grid. Renewable energy sources have grown significantly to now account for over 40% of generation. There is still a lot of work to be done to produce an abundance of renewable electricity generation.

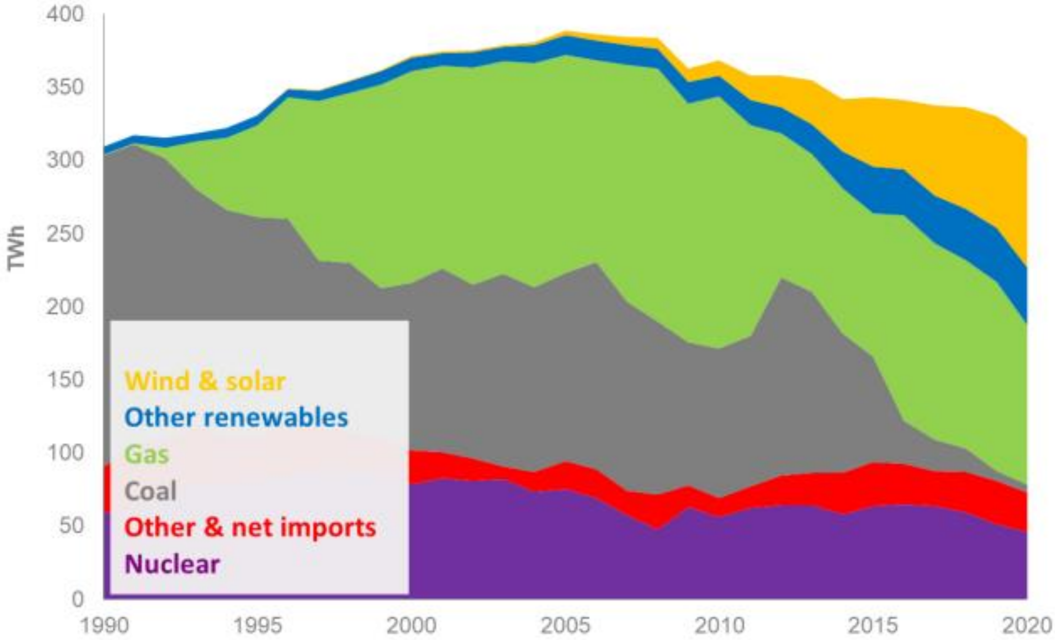


Figure 6 – UK electricity supplied by fuel type, 1990 to 2020 [27]

To add to the challenge, the electric grid will need to grow significantly to accommodate the decarbonisation of other sectors, for example electric cars and heating. This will at least double the amount of electricity required by 2050 [28].

For context, UK shipping is expected to require 70 TWh/year if powered entirely from ammonia, being split 25% and 75% between domestic and international shipping respectively [29].

It is clear that without significantly increasing the rate of deployment of renewable energy, there won't be an abundance of renewable energy for shipping available any time soon.

4.3.4 Shetland

The figures for electricity generation for the UK are not representative of Shetland. Shetland will have an abundance of electricity to make e-fuels, due to a large amount of wind and low population. It has the potential to decarbonise the fleet well before the rest of the UK.

4.4 Low Carbon Hydrogen Sources

The UK has 4 main potential sources of low carbon hydrogen:

4.4.1 Electrolysis

Hydrogen can be produced from renewable electricity via electrolysis. The limitations on scaling up renewable energy is covered in section 4.3. Figure 7 Is the UK government's prediction on price of green hydrogen out to 2050. This is just for production and is the HHV value. It also doesn't reflect the current high price of electricity. Prices vary considerably but it has risen from about £50/MWh to over £150/MWh.

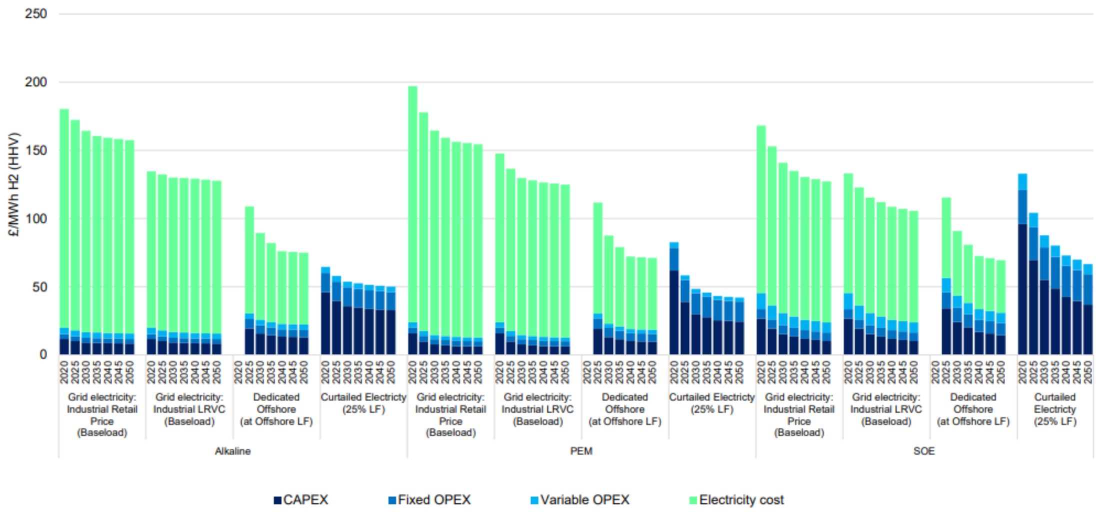


Figure 7 - Predictions of Green Hydrogen Price [30]

For comparison the current bunker price of Very Low Sulphur Fuel Oils VLSFO is currently high at around $700/MT. This is about £43/MWh.

4.4.2 Natural Gas and CCS

CCS can be used with Steam Methane Reforming (SMR) to produce low carbon hydrogen or blue hydrogen. It is seen by many as the only way hydrogen can be scaled in time however, the technology is still untested at scale.

There is significant inefficiency in the fuel conversion and not all of the carbon can be captured. The capture rate will depend on the amount of money and energy that is used on the capture system but there are diminishing returns that mean it will never reach zero. Methane slip has the potential to counter some of the emissions saved.

4.4.3 Biomass

It is possible to turn biomass into hydrogen. This has the added bonus that the carbon from the biomass can be captured and stored resulting in negative emissions. This could be used to offset the emissions generated from blue hydrogen. Like blue hydrogen, this is untested at scale.

4.4.4 Imported

The other long-term option is for low carbon marine energy to be imported from where renewable energy is cheaper. These areas can be seen in Figure 8. (It should be noted that this graph does not cover offshore wind, which the UK has a significant amount of).

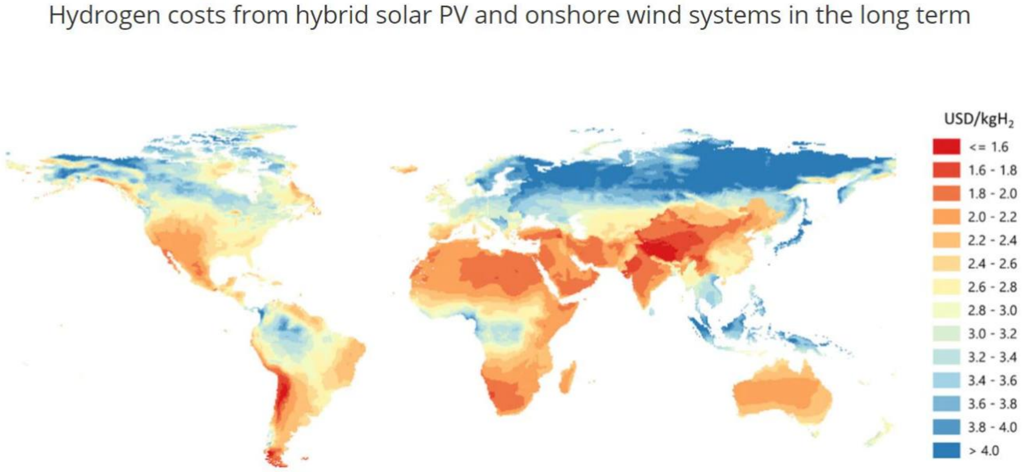


Figure 8 – From the IEA - The future of hydrogen [31]

The hydrogen would probably be imported in the form of ammonia.

4.4.5 CCC Predictions on Hydrogen Production

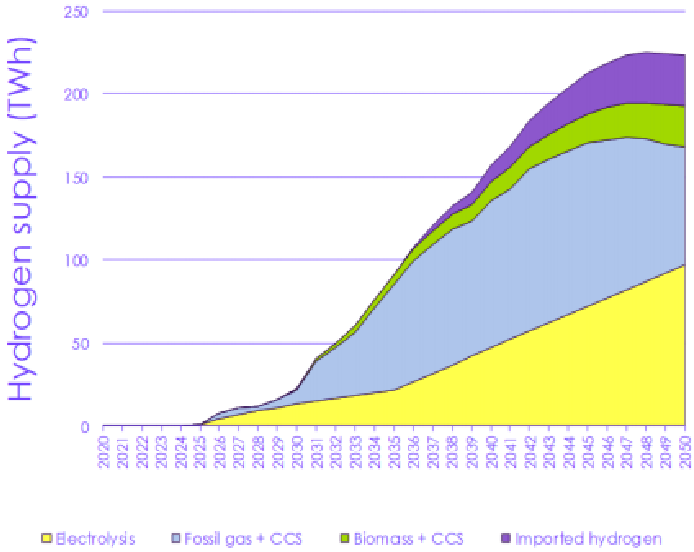


Figure 9 – Hydrogen Supply from the UK Climate Change Committee

Figure 9 demonstrates, the CCC prediction on hydrogen supply. It is clear that hydrogen is only expected to scale after 2030.

4.4.6 Other Uses of Hydrogen

Even when hydrogen is available, the marine industry does not offer a high 'bang for buck' in its use of hydrogen as there are higher transportation, storage and capability losses. For example, the current ammonia industry is large and accounts for roughly 1% of CO_2 emissions [32]. If a renewable ammonia plant is opened, more carbon is saved by shutting a non-renewable hydrogen/ammonia plant than converting ships to use the additional hydrogen/ammonia.

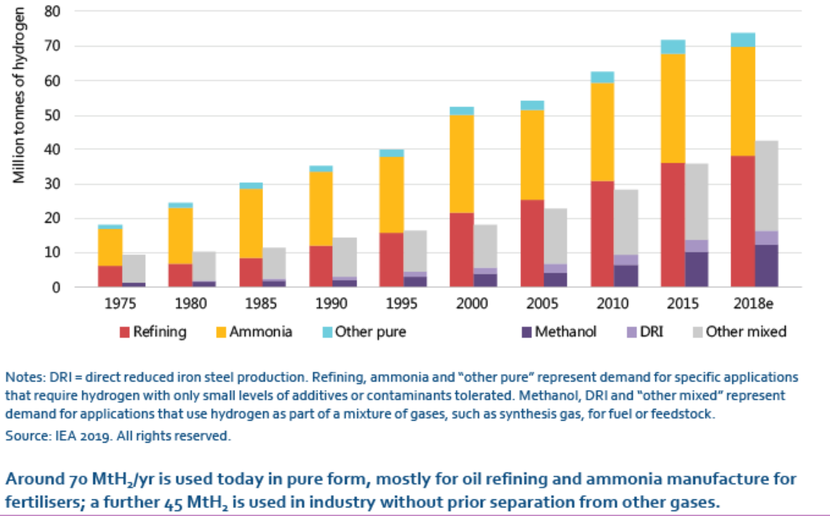


Figure 10 – IEA, Global demand for hydrogen, 1975-2018

To get a sense of scale for Figure 10, 70Mt of hydrogen contains about half the energy currently generated from renewables worldwide, or more than the total European electricity consumption. Merchant shipping uses more than 330Mt of marine fuel each year [33]. This is equivalent to about 110Mt of hydrogen.

It has been highlighted that a significant proportion of hydrogen is used in refining and there will be significantly less oil to refine in 2050. However there will still be a demand for substances made from petrochemicals. It is likely a large supply of hydrogen will be required to continue to produce these chemicals.

4.4.7 Blue Methanol Problem

The terms blue hydrogen, ammonia and methanol are used to describe fuels made from hydrogen created from the carbon capture of natural gas. The problem with blue methanol is that you have to add the carbon back in. This carbon has to come from somewhere renewable. Either a bio-resource is used or it is captured directly from the air. It would be more efficient to use the natural gas and offset it with carbon captured from the air.

4.4.8 Shetland

As Shetland will have abundant electricity that it can't export via a cable it make sense to produce hydrogen with it. This is likely to happen earlier than the rest of the UK.

4.5 Conclusion

Only electric based fuels will have the ability to scale so will have to make up the majority of marine fuel. With the exception of batteries, e-fuels are unlikely to be seen in significant quantities until after 2030. If the target is net zero by 2050, this is too late for the marine industry to do simple replacements at the end of life as ship typically last 30 years. It will put a huge strain on the dockyards to make significant retrofits to a large proportion of the fleet. A significant number of prototype/demonstrator ships will be required well before 2030 to prove, develop and get industry up to speed on different low carbon technologies. It will also mean ships will need to be designed so that they can be retrofitted with low carbon fuels or have shorter design lives.

5.0 ENERGY CARRIERS

5.1 Introduction

The storage of low carbon fuels is expected to make the largest difference to space and weight on converting a ship to low carbon. This section will look at the different options.

5.2 Batteries

With electric vehicles becoming more commonplace, battery technology has seen some considerable improvements over the past decade. This is not limited to the batteries themselves but also support equipment like the chargers are seeing order of magnitude improvements in size and weight.

There are different types of batteries all with different attributes making them useful for certain applications. The battery market is also complex and constantly changing. It is helpful to split batteries into 3 groups depending on the purpose.

1. Low capability but cost effective – A non-demanding role where price is more important than capability. This would be a slow boat that does a low number of short range trips. This is ideally suited to a type of lead acid battery.
2. High energy storage - This is suitable for a boat the needs range but can be charged slowly. A form of cobalt oxide lithium-ion (Li-ion) battery is ideal here.
3. High power – This is suitable for a boat that needs to charge rapidly, e.g. a short range ferry. An iron phosphate Li-ion battery is more suitable here.

5.2.1 Battery Energy Limitations

Using batteries will significantly increase both space and weight required for the fuel storage. Weight sees the largest increase.

When looking at marine gas oil (MGO), it has a specific energy of roughly 12 KWh/kg. In comparison a marine Li-ion battery will have a specific energy of around 0.12 KWh/kg. This significantly limits the capability of a battery powered vessel. The significantly higher efficiency of batteries offsets this but there is still a 50 times increase in weight.

It is important to note that some batteries have a much higher specific energy, for example, the battery used in a Tesla is capable of double this. The difference being that a fire is more dangerous on a vessel as you can't just get off it if there is a fire. This need for safety significantly increases the size and weight of a battery for a ship.

When sizing batteries it is also important to note the size of the battery. The energy density drops as batteries get larger, due to access and safety constraints.

5.2.2 Charging

With larger vessels, charging becomes increasingly challenging, especially when rapid charging is required. There are two separate problems that need to be addressed. The effect on the local electricity grid and power transfer to the vessel itself.

The power grid can be improved but this can be a significant problem depending on the location. A cheaper solution could be to install land based batteries to buffer the supply.

The other issue is power transfer to the vessel itself. There are several different option to this depending on size and power requirements. It is also complicated by large tidal ranges and ship movement.

5.2.2.1. Wired

A wired solution is by far the simplest as it can be similar to an electric car plug. However, it gets more challenging as the amount of power that needs to be transferred increases. The cable reaches a size where a robotic arm or a crane is required to make the connection. This is still a valid solution for large plugs but there are problems when a large number of connections need to be made as there can be contact wear. It can also be slower than other methods of charging.

One such example is the Navtek quick charge station used for the Zeetug.

5.2.2.2. Wireless

An example of a wireless charging system is from Wartsila as shown in Figure 11.

Figure 11 – Wartsila Wireless Charging

Wireless systems are best suited when a large number of charging cycles is required. The best example would be a ferry that does a significant number of trips a day and needs to be charged before each trip. It is also a very safe solution.

5.2.2.3. Pantograph

Pantograph systems are commonly seen on the top of electric trains and trams. It is also possible to use a stationary version on ships. These are ideal for large power systems that need repeated charging a day.

Care does have to be taken as there will be exposed live conductors that need to be kept out of reach.

Stemmann-Technik have several example under the brand name FerryCHARGER.

5.2.2.4. Battery Transfer

It is also possible to transfer the battery itself. This is suitable for very small systems where the battery can be man handled. It can also be used on container ships where it is easy to swap out battery containers.

Zero Emission Services (ZES) have built a container module that can be recharged on the dockside and swapped with a container currently on-board to continue providing electricity whilst also providing storage for the grid and a charging point for other EV's. ZES are currently using this method on the MS Alphenaar, where it takes

15 minutes to swap the container over. The MS Alphenaar is a container ship and has the capability of holding two ZES containers.

Figure 12 – MS Alphenaar

5.2.3 Example Vessels

There are a significant number of example battery power craft from around the world.

A small craft can be powered by batteries from the car industry. This allows them to have significantly higher energy densities than large craft. The e-Voyager, funded by MarRI-Uk, was put together using batteries from Nissan Leaf vehicles.

Figure 13 – e-Voyager in Plymouth UK

A range of small batteries and electric motors are available commercially from a variety of companies. Torqeedo is currently the leading manufacturer in the world. They use BMW batteries. There is a range of both inboard and outboard engines available up to 80HP equivalent (60kW).

Figure 14 – Example of Torqeedo's larger outboard motor and battery

There are several boat's using Torqeedo. On the market is the Magonis Wave e-550, with a range of 55 Km at 2.7 knots, and currently in build is a fleet of 12 electric commuter ferries to be used by the Bangkok metropolitan authority as part of a plan to reduce traffic and CO2 emissions.

The largest representatives for electric boats come from the leisure industry. Several manufacturers such as Nautique, Marian, X shore and VitaX all currently create an electric boat that is less than 10 meters long with ranges pushing 100 miles at low speeds, mainly on calm waters. These boats are built to be used for luxury passenger ferries (6 people) across lakes or for water sports such as wakeboarding or water-skiing.

The next largest representative of electric vessels comes from the larger ferries transporting vehicles and passengers, having lengths between 60 and 140 meters with an average capacity of around 4MWh. The Ellen E-Ferry can carry 31 cars and 200 people over 22 nautical miles (40km) [34]. It does this with a 4.3MWh battery.

Figure 15 – Ellen E-Ferry in Denmark

A select few shipping vessels are being trialled as electric. The most notable being the Yara Birkeland. This is going to be the first unmanned shipping vessel with a 7MWh battery, capable of carrying Dead Weight Tonnes (DWT) between Herøya and Larvika of approximately 30 nautical miles.

Figure 16 – Yara Birkeland

In Figure 17, the systems can be shown for the recently built Amherst Islander II from Damen Shipyards Group, comprising of charging points, switchboards, batteries, shore connections and control systems. This ferry will be operating on the Ontario Lake covering a short distance between Amherst Island and Millhaven of roughly 4 km.

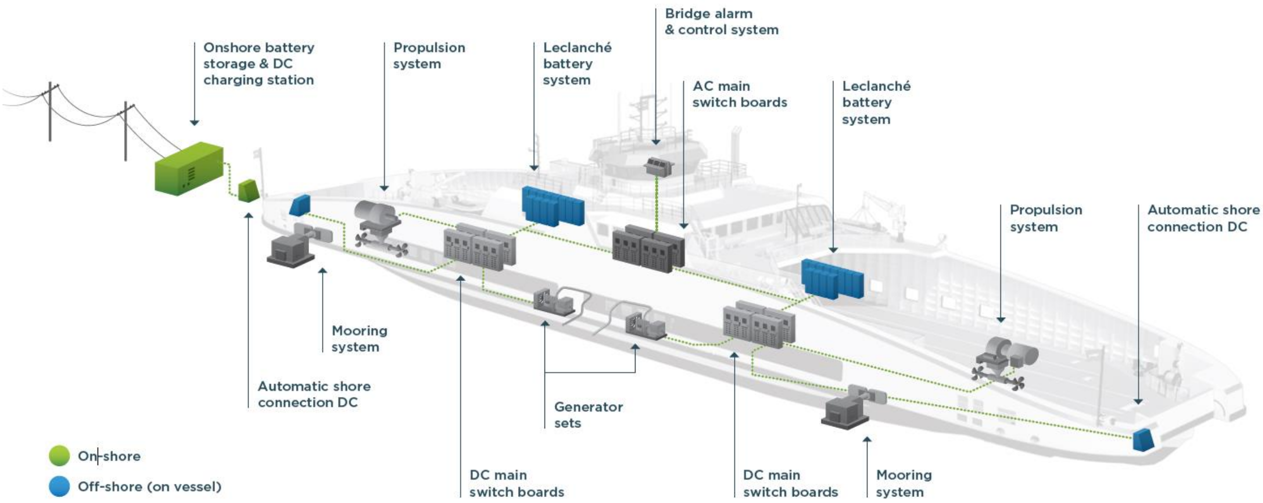


Figure 17 – Amherst Islander II Electrical systems [35]

This ferry has a battery capacity of 1.9MWh and utilises the Leclanche Marine Racking System for securing the batteries [35]. Comparing this to the brochure for the marine racking system, it is likely that there are 4 to 5 MRS10s installed, where each MRS10 is 2.4 x 3.7 x 0.4 meters, weighs approximately 3.9 tonnes and has a capacity of 464kWh [36]. For reference, the Amherst islander is 71.7 meters long and 20.2 meters wide. With this system installed, it can be seen a considerable amount of weight is added and space taken up from the batteries alone.

5.2.4 Safety

The safety concerns of Li-ion batteries are well publicised. Even small batteries can cause significant fires. The worst case scenario with a battery is thermal runaway. This is where a fault causes a cell to overheat which then causes neighbouring cells to break down and also produce heat causing a large chain reaction. The overheating can result in the release of toxic, corrosive and explosive gas. Thermal runaway of batteries can be addressed but it comes at the cost of space and weight.

With lead acid batteries, when cycling, a small amount of hydrogen gas can be released from the battery. Under fault conditions, a significant amount of hydrogen and hydrogen sulphide can be produced. Adequate ventilation systems are required in battery spaces to ensure that the concentration of these gases does not reach hazardous levels.

5.2.5 Advantages

- Batteries have a high efficiency.
- Can reduce CO2 emissions now.
- Batteries have a very high power output.
- Technology already exists.
- Other industries are putting large sums of money in improving batteries.
- The economics of scale from other industries are reducing prices.

5.2.6 Disadvantages

- The range of batteries is significantly limited by the amount of energy batteries can stored.
- There is currently very high demand for batteries in other industries. This will put strain on the availably for raw resources to make batteries, increasing their price.
- Charging can put a strain on the local grid system for large vessels.
- Large plugs, cables and connections are required that can be too heavy to manually handle so additional equipment will be required to connect large vessels up for charging.
- Plugs that are continuously used experience wear and tear and eventually become problematic.

5.2.7 Conclusion

Batteries will likely dominate the low carbon marine market at very short ranges due to their very high efficiency. They are already competitive in very small craft and if some form of carbon tax is introduced they will become competitive in larger craft as well. There are issues with availability of batteries and the charging infrastructure required can be problematic depending on location.

As the duration required increases into hours the advantages of batteries quickly disappear. Batteries will be used in longer range craft but in more of a supporting role.

5.3 Hydrogen

Attention on hydrogen technologies is increasing and other industries (such as heavy trucks and rail) are perusing hydrogen as a fuel. Although it has not been as successful as batteries so far the cost of development does not have to be borne solely by the marine industry. Many stakeholders consider hydrogen as a viable option for coastal and short-sea shipping due to it higher energy density than batteries. Some groups see greater potential for longer ranges using liquid hydrogen if ammonia can't overcome its safety concerns.

5.3.1 Regulation

Hydrogen is still novel in the marine sector, as a result there is limited guidance and rules around its implementation. There are no prescriptive rules in place for hydrogen, whereas the process is well developed and understood for traditional oil powered designs. This requires the use of the "Alternative Design Process" as coined by DNV to describe risk or hazard identification (HAZID) based design techniques to provide an argument to the safety, reliability and robustness of alternative systems which must be benchmarked to a minimum of a comparable oil powered platform. The methods for how this is done are discussed as part of SOLAS II-1/55 but the process does not appear to be fully defined.

DNV have produced a handbook called 'DNV Handbook for hydrogen fuelled vessels' (2021-06) [37]. This should be read by anyone working with hydrogen in the marine environment.

5.3.2 Higher Heating & Lower Heating Values

Great care needs to be taken when talking about the energy in hydrogen as there are two different figures Higher Heating Value (HHV) and Lower Heating Value (LHV). HHV is the amount of energy released during complete combustion including the energy in the steam. The LHV assumes steam as an output and does not count the latent heat of vaporisation as being stored in the water.

Electrolysers like to use the HHV figure and fuels cells like to use the LHV figure.

The HHV is 18% higher than the LHV figure and is missed out of a lot of calculations. This report will use LHV.

5.3.3 Storage

Hydrogen can be stored as a cryogenic liquid, a pressurized gas, in other materials such as metal hydrides or inside other carrier substances such as ammonia (however, the latter two methods are not as widely available or utilised). Marine storage of hydrogen is still in its infancy stage.

5.3.4 Compressed Hydrogen

Compressed hydrogen is the most efficient low carbon fuel that can be produced from renewable electricity or natural gas with carbon capture. However, compared to batteries, it will need about three to four times as much input energy.

When looking at just the fuel, hydrogen has about three times the energy per unit mass as diesel but takes up about nine times more space. However, when the fuel tanks are taken into consideration, hydrogen is heavier and takes up significantly more space.

The actual space and weight required depends on a number of factors and needs to be calculated on a case by case basis. This is done by selecting the correct sized pressurised cylinders and fitting them in the craft. However there are several complications that need to be accounted for. Access to periodical check the cylinders is required. There are also safety risk with using pressure cylinders that are too large. In some cases, the space required can approach what is needed for a battery, although it will be considerably lighter than a battery.

The most common pressures for compressed hydrogen are between 250 and 700 bar. Lower pressures are preferred as they are cheaper, lighter and safer, however, higher pressure does reduce the space required and the space required is a limiting factor for hydrogen. Currently, marine rated equipment is at the lower pressures but it is expected to rise where required.

It takes around 2kwh/kg to pressurise hydrogen to 350 bar and 3kwh/kg to 700 bar [38]. For comparison, hydrogen stores 33kwh/kg.

5.3.4.1. Bunkering

The time taken to refuel can add significant cost that needs to be accounted for. Due to the low energy density of compressed hydrogen, significantly more refuelling will be required.

Transferring compressed hydrogen to the vessel from onshore or vessel based bunkering stations is done by either pressure balancing or the direct compression of the hydrogen prior to the transfer to the vessel. If pressure balancing is used, there is a requirement for the hydrogen to be stored at a higher pressure at the bunkering station than required on the vessel. Direct compression transfer is more energy efficient but will require the utilisation of a booster compressor and will not be fast.

It is also possible to refuel the craft by transferring hydrogen bottles rather than moving hydrogen itself.

International bunkering standards do not yet exist and will be required.

Care needs to be taken when transferring hydrogen as it heats up due to adiabatically compression. This limits the transfer speed of hydrogen. The car industry cools the hydrogen before transfer in order to speed up refuelling.

Bunkering will need to be accounted for at the early design phase of a ship.

5.3.5 Liquid Hydrogen

Liquid hydrogen about halves the space required for the hydrogen itself compared to compressed hydrogen. It still requires about four times the space of diesel. The tank will need to be more than seven times larger than a diesel equivalent. Liquid hydrogen tanks have been designed for cars but it works best on large ships due to the volume to surface ratio of large tanks.

Storing liquid hydrogen presents the problem of boil-off gas (BOG) generation when considering long term storage applications, where the current land based rate for BOG generation is approximately 5% per day, although this is highly dependent on size and the level of vacuum used. It does not make a good solution for rarely used applications.

It takes 7-12kwh/kg to liquefy hydrogen. This is 20-36% of the energy stored in the hydrogen.

Care needs to be taken with liquid hydrogen as it can liquefy/solidify nitrogen, oxygen and water vapour out of the air.

5.3.5.1. Bunkering

Liquid hydrogen bunkering stations would be required to have liquid hydrogen source tanks, inert gas supply and a flexible bunkering hose assembly.

Helium is currently used as the inert gas but has limited supply. Other gases are problematic as the hydrogen can liquefy or even solidify them.

International bunkering standards do not yet exist and will be required.

Bunkering will need to be accounted for at the early design phase of a ship.

5.3.6 Safety & Impact on Ship Design

There are a large number of safety considerations required when dealing with hydrogen. The DNV handbook [37] does an excellent job of covering what is currently known.

The choice that has the biggest impact on the design of a ship is whether above or below deck hydrogen storage is used.

Above deck hydrogen is safer but it comes with the following complications:

- Harder to detect leaks
- Reduced stability due to the fuel being higher
- Less protection from green sea and weather leading to increased corrosion
- Reduced deck space.

Below deck hydrogen comes with the risk of a hydrogen detonation. On large ships, it is challenging to eliminate this risk. Vessels therefore may need to be designed to survive this explosion. A bulkhead or deckhead of hydrogen storage rooms would need to be specially designed with blast off panels to direct the blast out of the vessel. This blast path would have to be above the waterline and avoid manned and critical areas. The surrounding area my need to be strengthened.

Fuel cell or ICE engine rooms may also have a risk of detonation so the same precautions would need to be considered.

5.3.7 Examples of Hydrogen Fuelled Ships

There have been several very small hydrogen prototype boats over the last 20 years. In recent years, larger ferries have/are being built. These are more hydrogen test ships as they can run if the hydrogen system is not working.

MF Hydra is the first liquid hydrogen ferry. It uses liquid hydrogen, two 200 kW fuel cells, a 1.36 MWh battery, and two 440 kW diesel generators. The hydrogen tanks and the fuel cells are located on top of the ferry. MF Hydra is 82.4 meters long, a beam of 17.5 metres, and capacity for up to 300 passengers and 80 cars. The vessel can operate at a speed of 9 knots using Shottel thrusters. It has an 80m3 tank for hydrogen storage [39].

HySeas III project is a research project that has been running since 2013. It is designing and building a 120 passenger, 20 car ferry for a 25 minute route in Orkney. The vessel was meant to be built by Fergusons before it went into administration. The power train is currently undergoing a land test in Norway. It has six, 100kW fuel cells and plans to stores 600kg of compressed hydrogen and have 768kWh of batteries [40].

5.3.8 Advantages

- Carbon, sulphur and nitrogen pollution free. (*Nitrogen free only with a fuel cell)
- Currently established product on land

5.3.9 Disadvantages

- It requires a lot of space especially compressed hydrogen.
- Difficult and expensive to store
- Lack of experience in marine applications

- Safety concerns – explosion risk.
- A significant amount of green energy is needed to make and store the hydrogen.

5.4 Ammonia

5.4.1 Introduction

Anhydrous ammonia or NH3 is the combination of one nitrogen molecule and three hydrogen molecules. It is produced in large quantities to make fertiliser, but does have a range of other uses. It is currently mostly made from natural gas and its manufacture accounts for about 1-2% of global carbon emissions.

It can be made without carbon emissions via the Haber-Bosch process using nitrogen capture from the air and hydrogen from electrolysis of water.

The Haber-Bosch process requires high temperatures and pressures but it takes very little extra energy to make ammonia from hydrogen as the reaction is exothermic. However, as it is exothermic about 16% of the energy is lost in the reaction.

Ammonia offers a good compromise between energy density and efficiency to manufacture. It is both more energy dense and significantly easier and cheaper to store than liquid hydrogen. Ammonia also benefits from a pre-existing supply and distribution chain leading to a better current understanding of the storage, transport and handling hazards. There are already 120 ports with ammonia trading facilities around the world. It can be seen in Figure 18 that ammonia is likely to be the cheapest low carbon fuel for all ships that require a long range (assuming biofuels are not available/scarce.)

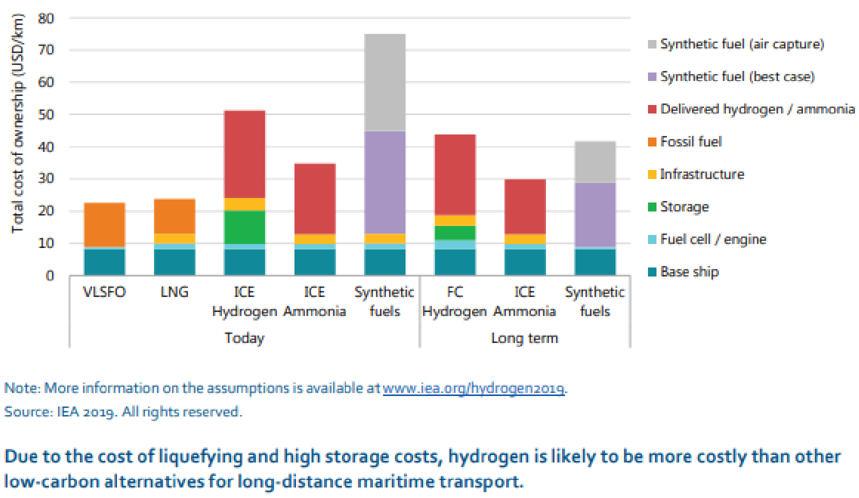


Figure 18 – From IEA - The Future of Hydrogen 2019 - Ammonia price prediction

5.4.2 Storage

Ammonia is in a liquid state at -33.6°C at 1 bar of pressure and at 20°C at 8.6 bar of pressure. Current industrial scale applications utilize low temperatures which requires energy to maintain. For large storage, liquefied ammonia is preferred as it is safer. For smaller storage pressurized Type C tanks at ambient temperatures and pressurized to approximately 18 bar can be used. This eliminates the need for on board re-liquefaction equipment and additional refrigeration equipment.

Due to the volumetric density of ammonia, approximately 2.4 times more tank volume is required when compared to conventional fuel oils to generate the same amount of energy.

Two of the most viable considerations for ammonia bunkering/transfer are as follows:

1. In the case where both the bunkering vessel tank and ship tank are pressurised, a general transfer pump can be used. During this process, and due to the time it takes for ammonia to condense, there can be a build-up of pressure which can cause the safety valve to open. To address this, considerations need to be made to incorporate a vapour return system back to the bunkering vessel.
2. In the case where the bunkering vessel is semi-refrigerated and transferring to a pressurised tank in the ship, a heater, vapour return system and booster pump are required. This is due to the ammonia being transferred having a lower temperature than the tank design temperature and lower pressure. Vapour return to the bunkering vessel must pass through a re-liquefaction plant.

5.4.3 Ammonia as a Fuel

No other industry is looking to use ammonia as a fuel, this means the cost will have to be borne by the marine industry alone. MAN and Wärtsilä are both developing an ammonia engine. They are expected to be used on ammonia tankers first.

5.4.4 Nitrogen Oxides

Ammonia engines can produce nitrogen oxides (NOx) including nitrous oxide (N_2O) also known as laughing gas. It is possible to use ammonia as the reducing agent in Selective Catalytic Reduction (SCR) technology to remove most of the NO_X from the exhaust. N_2O is a potent greenhouse gas 283 times stronger than CO_2. The temperature and pressure inside the engine need to be controlled to minimise its production.

5.4.5 Liquid Fuel Supply System

Ammonia engines will require a liquid fuel supply system (LFSS) to provide fuel to the engine in the required state. It is also needed for purging the engine while recovering the products from purging. This will either need to be inside the ship with an airlock or placed on the deck.

5.4.6 Safety

The key safety consideration is the toxicity of ammonia. Ammonia is toxic to humans and due to this, exposure to ammonia must be carefully mitigated against to ensure the safety of personnel on-board vessels, and in harbours.

In very low concentrations, it has a pungent smell and is an irritant to throats and eyes with no long term effects.

It is fatal at concentrations above 2500ppm, with the speed of fatality increasing rapidly as the concentration increases.

Liquid ammonia will expand at a ratio of 850:1. This means a large fatal cloud could be created by a release of ammonia.

The worst case scenario is a large release of ammonia that will affect the area on and around the vessel. Currently, this risk is managed on ammonia tankers by having a trained crew and keeping the tanker away from populated areas. It will be challenging to produce a safety case for having passengers on an ammonia fuelled ship. It will also be challenging to bring the ship into populated areas.

Ammonia is lighter than air however, when it is released it is very cold making it denser. It will rapidly absorb moisture from air and will form a dense, visible white cloud at high concentrations.

A video of a leak can be seen here: https://www.youtube.com/watch?v=qIi4_Poo2HY.

The best counter to ammonia is water. A water mist has the ability to remove ammonia gas from the air and turn it into a liquid. The liquid will then need to be dealt with.

Ammonia possesses corrosive tendencies in the presence of moisture and corrodes copper, brass, zinc and other alloys. Due to this, it is incompatible with common industrial materials and careful consideration must be taken when selecting materials for use in tanks, pipelines and structural components which ammonia will be in contact with.

5.4.7 Examples/Current work

There are currently no examples of ammonia ships in operation. Wärtsilä [41] and MAN [42] have marine ammonia ICE in development with deployment. These are planned to go on ammonia tankers.

An industry-wide collaborative project began in 2021 where several companies including LR's Maritime Decarbonisation Hub and the Mærsk Mc-Kinney Møller Centre for Zero-Carbon Shipping assessed the risk and safety concerns of using ammonia as a shipping fuel. This project will assist in the development of best practices for safeguards in the design of ammonia-powered ships [43].

A consortium of European industry and research organisations led by Eidesvik, Equinor, Yara and Wärtsilä are currently working on a project to retrofit Viking Energy, a supply vessel owned by Eidesvik, with a 2MW direct ammonia fuel cell. This ammonia will be green ammonia supplied by Yara produced by electrolysis. It will be delivered to the vessel containerised to enable easy and safe refuelling [44].

5.4.8 Advantages

- Low flammability risk
- Can be produced from renewable electrical energy
- Easily reformed from hydrogen and nitrogen
- Stored and transported as a liquid and practical pressure and temperature
- Currently established commercial product shipped in large quantities
- It is the cheapest long range low carbon fuel.

5.4.9 Disadvantages

- Toxicity
- Danger of using it on passenger ships or in populated areas around harbours.
- No other industries are pursuing ammonia as a fuel.
- Absence of regulations

5.5 LNG

5.5.1 LNG Sources

LNG is formed through the cooling of natural gas. Natural gas is treated, by dehydration and removal of the acidic elements, such as carbon dioxide and hydrogen sulphide, and any other elements that freeze at lower temperatures. What remains is a mixture of predominantly methane (more than 90%), with small amounts of ethane, propane, butane and nitrogen. The refined natural gas is then put through a refrigerated cycle and liquefaction process, which reduces the temperature of the gas down to around -162°C and it turns to a liquid, LNG. In this form, the volume of natural gas is reduced by 600 times, making it safer to transport and easier to transport large amounts [45].

5.5.2 Fuel

LNG has an energy density of around 53 MJ/Kg or roughly 15 kWh/Kg [20], making it the highest energy dense fossil fuel available. LNG has a boiling point of -162°C.

LNG is typically used in dual fuel engines, they come in two forms; low-pressure and high-pressure. Low-pressure gas engines use the Otto cycle and high-pressure gas engines use the diesel cycle. An Otto cycle uses a spark ignition as the ignition source with a mix of LNG and air. The diesel cycle, or compression engine, uses compression as the ignition source and mixes air with a diesel and LNG blend [46]. The MAN B&W ME-GI Engines have a minimum 5% Heavy Fuel Oil (HFO) for pilot oil with a maximum of 95% LNG due to LNG not being able to self-combust [47]. The MAN engine can run anywhere between 5% and 100% HFO, this can be useful if the supply of LNG can't be guaranteed.

5.5.3 Methane Slip

It is important to reduce methane slip wherever possible. Methane is a potent greenhouse gas and counteracts the benefit of using LNG.

5.5.4 Storage

The critical requirement of storing LNG is that it is kept below -160°C to keep it as a liquid. Inevitably, heat will get through to the LNG and cause the LNG to vaporise forming BOG. On LNG tankers, the BOG is reformed back into LNG but it can by fed into the fuel system instead.

LNG is stored in double wall insulated tanks. The materials used differ depending on where the storage is located. For transportation of LNG, an internal steel or aluminium compartment, with an external steel or carbon compartment and a vacuum separating them both to reduce heat transfer. For static locations, a pre-stressed concrete external wall and a high-nickel steel inner tank, with efficient insulation between the walls [48]. The materials used in storage tanks reduce heat from getting into the tank and increasing the vapour production whilst also being able to stand the below freezing temperatures that LNG is stored at.

5.5.5 Safety

LNG is a non-toxic liquid that is also non-corrosive due to having the corrosive elements removed during the process of converting natural gas to LNG [45]. The liquid itself is difficult to ignite but mix the vapours produced with air at around 5% to 15% vapour to air, then it becomes flammable. In order for it to catch fire, an ignition source of over 500°C will be needed, making this fuel a relatively safe fuel source. Ignition sources should still be kept at distance from the fuel containers and systems.

Due to the temperature it is stored, if a leak occurs then LNG will vaporise rapidly, mixing with air therefore becoming flammable. LNG has also been shown to be explosive when coming into contact with water. This is due to the temperature differences between the two substances and can lead to a rapid phase transition which causes the explosion. Checking components and fuel lines for degradation and freezing needs to be introduced to ensure a leak doesn't occur, especially when working with long charter vessels crossing the oceans [48].

Even though LNG vaporises quickly, due to the temperature of the liquid, it can cause cold burns to anyone handling the substance so it is advised to wear the correct Personal Protective Equipment (PPE) when working with or around LNG.

As LNG is composed mainly of methane, when it vaporises, it can reduce the amount of breathable air leading to the possibility of asphyxiation depending on the level of vapour in the air. Methane is lighter than air so it will rise into the atmosphere as LNG vaporises. This is good for people in the immediate area but not so good for the environment, so where possible vapour should be captured and fed back into the fuel system or reprocessed back into LNG. One recommendation is to remove confined spaces in and around the storage tanks to prevent a build of LNG and BOG that can cause asphyxiation should some enter the confined space [45]. LNG is a colourless, odourless liquid and so is the vapour produced, so it can be difficult to tell if an area has become enriched in LNG vapour.

5.5.6 Upgrade Path

LNG is not a permanent solution. It is just a bridging fuel until low carbon fuels are available. The optimal window of LNG might be small and the transition away from LNG may need to happen in the lifetime of the vessel and should be designed for.

Utilising bio-LNG on-board vessels will be an easy process to switch into as some vessels are already equipped to run LNG. Therefore, minimal changes to fuel systems and engines will be required. However, it is unknown how much bio-LNG will be available.

As LNG is a gas, it would be easiest to convert to hydrogen or ammonia if dual fuel engines are used. If a solid oxide fuel cell (SOFC) is used, hydrogen would be a strong contender.

5.5.7 Advantages

- LNG offers reductions of up to 25% CO2 emissions, 90% nitrogen oxide emissions and almost 100% sulphur and fine particle emissions [49].
- LNG has historically been cheap in comparison to diesel prices [50] .

5.5.8 Disadvantages

- LNG comes from natural gas, which is a fossil fuel and damages the environment through mining of this gas. As natural gas is a fossil fuel, it is unsustainable.
- LNG can have an issue with methane slip, where methane is far more damaging to the environment than CO2.
- As natural gas supplies dwindle, the price of LNG is likely to increase.
- There is a lack of LNG infrastructure at the most commonly used docks and ports [51]. As LNG is marketed as a transitional fuel, the drive for ports and docks to incorporate LNG storage and infrastructure is less appetising

5.5.9 Conclusion

As mentioned throughout this section, LNG is a good transitional fuel. It has a great energy density, reduced emissions and is a relatively safe fuel to use. However, it will potentially need to be phased out within the lifetime of the vessel. Care has to be taken to avoid stranded assets.

5.6 Methanol & Ethanol

Methanol and ethanol are very similar alcohols. Methanol has one carbon atom and ethanol has 2. They are currently made by very different methods. Methanol is mainly made from natural gas via SMR whereas ethanol is mainly made via fermentation of biomass. Although it is possible to use both methods to produce both fuels.

Ethanol is a more energy dense and safer fuel but methanol requires less carbon so would be more efficient to make from electricity.

Due to its better ability to scale via renewable energy, methanol has more potential than ethanol. The challenge with both fuels is getting an energy efficient way to get renewable carbon for its production.

5.6.1 Use as a Fuel

Both alcohols are less energy dense than diesel so will required about twice the space to store. The exact numbers can be seen in Table 2.

Fuel	Specific Energy (MJ/kg)	Energy Density (MJ/L)	Flashpoint (°C)	Explosive Limits (%)
Methanol	22.7	17.9	11-12	6-36
Ethanol	19.9 - 29.8	21.2 – 23.5	13	3-19
Diesel	42.6 - 45.8	35.8 – 38.6	52-96	0.6-7.5

Table 2 – Alcohol Fuel Comparison

Alcohols are hygroscopic, meaning they will absorb water directly from the air. Due to this, the fuel tank will needs to be tightly sealed. They are also low flashpoint fuels meaning they need an additional cofferdam to prevent leaks into machinery spaces.

Methanol and ethanol are liquid at room pressure and temperature so can be stored in tanks.

Ethanol is blended with petrol in car fuel. This is currently the most cost effective way to use its limited supply. If ethanol is used on ships without new supplies it will just move the emissions to the car sector.

5.6.2 Safety

Methanol and ethanol have similar safety concerns as petrol.

5.6.2.1. Toxicity

Methanol is toxic with just 10mL causing blindness and 30mL being fatal if not treated. It generally needs to be treated before symptoms start. Methanol poisoning normally happens from contamination of drinking alcohol. When it is used as a fuel, it does not need to be consumed to be dangerous, as it is possible to absorb methanol through skin or via the lungs as a vapour. Methanol has a wine-like odour but it is possible to have a low concentration that humans can’t detect but is harmful over an extended period of time. The antidote for methanol is ethanol.

Ethanol is in alcoholic drinks but in its pure form is significantly stronger than spirts. Ingestion of small quantities can cause alcohol poisoning.

5.6.2.2. Low Flash Point

Flashpoint is the temperature sufficient vapour is given off to ignite in air. So a lit match can't ignite diesel but can ignite petrol. As can be seen in Table 2, methanol and ethanol are low flashpoint fuels. Petrol, for comparison, has a flashpoint of -43°C.

5.6.3 Advantages of Methanol & Ethanol

- Only moderate changes to fuel storage are required.
- Ideal fuel solution for some rarely used vessels.

5.6.4 Disadvantages of Methanol & Ethanol

- Low flash point and therefore flammable.
- Ethanol feedstock are limited will compete with food supplies and biodiversity.
- Methanol is toxic and can be absorbed through the skin and lungs.
- Getting renewable carbon to make methanol is currently expensive and energy intensive.

5.6.5 Examples

Currently in operation are five methanol fuelled tankers with 3 more in build, predicted to be complete between 2021 and 2023. The tankers utilise a 2-stroke MAN B&W engine capable of dual fuel, where methanol is the dominant fuel type but the engine can be switched over to use MDO. The line of tankers are for a company called Waterfront Shipping. The tankers are capable of around 50,000 Dead Weight Tonnage (DWT) and measure 186 meters long and 32 meters wide [52].

Figure 19 – Waterfront Shipping Dual Fuel Methanol Tanker [52]

Maersk have ordered 12 methanol-fuelled 350m container ships. These have duel fuel engines so can be run on standard bunker fuel or on methanol with a pilot fuel.

5.6.6 Conclusion

Methanol and ethanol are very good ship fuels. They come close to being able to replicating the capability of current fuels. Their use will be limited by their supply. Ethanol is a limited biofuel in high demand. Methanol has to find a source of renewable carbon that is cost and energy efficient.

5.7 Biodiesel and HVO

If all biofuels were sustainable and available in large quantities then Biodiesel and HVO are the best energy carriers for the marine industry as they are both relatively safe and match the energy density of existing fuels. They also require minimal or no modification to existing engines, fuel systems and dock capabilities to be used therefore provide the easiest transition and a great opportunity to reduce emissions in the marine industry. These fuels will need to be continually used though and storage cycled to ensure the fuels do not go past there lifespan which can cause several issues in the engine and in the fuel storage tanks.

Biodiesel is safer than regular diesel and causes far less damage to the environment if spilled. This is because biodiesel has a higher flash point of around 130°C compared to around 52°C for normal diesel [53], and a boiling point of around 340-375°C in comparison to diesel of 150-380°C. Biodiesel is also safe to handle, store and transport with no adverse effects to skin, eyes or respiratory system and completely biodegradable.

HVO is similar to biodiesel in that it is non-toxic, safe to handle and completely biodegradable. It is an odourless oil so the need for ventilation is minimal. It has the added benefit of reducing CO2 emissions and decreasing nitrogen oxide, carbon monoxide and other particulate emissions. HVO is one of the safest options when looking at biofuels, for storing, transportation, the environment and human contact. If a spillage should occur, it is no different to cleaning up an oil spill. Therefore, bunds and spill kits will likely be required near the fuel tanks and refuel equipment. HVO complies with EN15940 [54], which is the British Standard for a paraffinic diesel fuel specification.

Warships and, if supplies allow, legacy ships that are hard to retrofit and rarely used, would be suited to utilise HVO or biodiesel as these fuels require minimal modifications and can be used immediately.

5.7.1 Advantages of Biodiesel/ HVO

- Higher energy density than other low carbon fuels
- Similar amount of fuel to fossil fuels can cover the same distance
- Higher flash point than regular diesel
- Non-toxic to humans
- Has an added effect of improving engine lifespan due to the additional lubricity they provide [55].

5.7.2 Disadvantages of Biodiesel/ HVO

- Has potential to produce NOx.
- It only reduces CO_2 emissions currently, it will be challenging to eliminate them.
- A high demand from other industries with limited availability for the marine industry.
- Long-term storage is not advised due to oxidisation and gelling.
- Not suitable for use at low temperatures
- Existing systems that use rubber fuel lines will require significant upgrading.
- Biodiesel has a slightly lower energy density

5.7.3 Examples

The Mediterranean Shipping Company (MSC) is one of the first companies to use biofuel blends. They are using between 30-47% biofuel content in its ships, where the fuel is being bunkered at Rotterdam. During 2020, the company estimated an annual usage of around 850,000 metric tons of biofuel [56].

Ocean Network Express and Eastern Pacific Shipping have completed successful trials of in-service ships utilising biofuels as the main fuel type. The biofuel used was made from waste and residue stream materials such as oil so it is likely biodiesel or even HVO were utilised. GoodFuels supplied the vessels in Rotterdam. The Ocean Network Express vessel made a transatlantic crossing carrying a capacity of 4800 TEU. The Eastern Pacific vessel loaded 254 metric tons of biofuel and carried 41,000 metric tons of cargo over an 11 day Atlantic crossing, where the biofuel was used to power its main engine. It was noted that there was no noticeable difference in engine performance with CO2 emissions being reduced by 70 metric tons a day from the main engines, achieving an overall net zero emissions. Overall emissions were negligible as conventional fuel were still used for the auxiliaries. The downside to using biofuel was an increase in the amount of fuel used, roughly a 10% increase, and it was noted there was an increase in nitrogen oxide emission. The benefit with this is that despite the age of the vessels, biofuels could be immediately used with only the fuel tank requiring a deep clean to ensure no foreign particulates [57].

5.8 Energy Density Comparison

Fuel or Source	Relative tank volume	Energy Density (MJ/L)	Specific energy (MJ/kg)	Ease of storage	Additional hazards over HFO
HFO	1	38.2	40	Easy	NA
MGO	1.1	36.6	43	Easy	NA
HVO	1.2	33	42	Easy	NA
Bio-Diesel	1.2	33.3	39	Easy	NA
LNG (-160°C)	1.7	22.2	50	Hard	Cold burns, Low flash point
Ethanol	1.9	24	27	Easy	Low flash point
Methanol	2.4	15.6	20	Easy	Toxic, Low flash point
Ammonia (-33°C)	2.6	11.5	17	Medium	Toxic to a wide area
Hydrogen (-253°C)	4.7	8.5	120	Very Hard	Cold burns, Detonation
Hydrogen (700 Bar)	>8	4.5	120	Medium	High pressure, Detonation
Hydrogen (350 Bar)	>16	2.8	120	Medium	High pressure, Detonation
Li-ion Battery (Corvus Blue Whale)	81	0.47	0.4	Easy	Arc flash

Table 3 – Comparison of different fuels

It should be noted that Table 3 does not include the size of the tank itself, just its internal volume. The insulation or cylindrical pressure can almost double the overall dimensions of the tankage required. The overall weight including the tank should also be used. This particularly affects hydrogen and the figure changes with the size of the installation. Energy density and specific energy can vary significantly depending on conditions. These figures are taken from a range of sources so are not all accurately comparable. They should be used just as a rough guide.

5.9 Conclusion

The fuel the marine industry uses needs to be replaced if carbon targets are to be met. The vast majority of shipping is likely to be powered by the following options:

- Batteries
- Hydrogen
- Ammonia
- Methanol
- Biofuels

They all have a range of drawbacks the main ones being:

- Batteries have very limited range.
- Hydrogen is very challenging to store.
- Ammonia is unsafe around the public.
- Methanol needs a source of green carbon.
- Biofuels have limited supply

Wind should not be ignored and in the right condition can support propulsion. Nuclear will likely be used as it is now in large military ships, submarines and potentially polar ships.

6.0 FORMS OF ENERGY CONVERSION

Currently, most large ships use ICEs. Gas turbines are used where energy density is important. The use of low carbon fuels may change this, for example, when hydrogen is used in cars, fuel cells become dominant.

Technology Readiness Levels (TRLs) are a method of measuring the maturity level of technology [58]. They provide a consistent approach of assessing the readiness of various technologies. According to the EU, the nine levels are defined as [59]:

TRL 1 – Basic principles observed

TRL 2 – Technology concept formulated

TRL 3 – Experimental proof of concept

TRL 4 – Technology validated in lab

TRL 5 – Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 6 – Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 7 – System prototype demonstration in operational environment

TRL 8 – System complete and qualified

TRL 9 – Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Figure 20 shows some of the potential future energy pathways with an estimation of their TRLs. The reality is far more complicated than this diagram can display as all combinations of energy carrier and energy conversion are being worked on. Some technologies like methanol fuel cells have been commercially sold to the marine industry for years but are not shown due to being small in scale.

It is likely this graphic will quickly become inaccurate as there is a significant amount of work being done on these pathways.

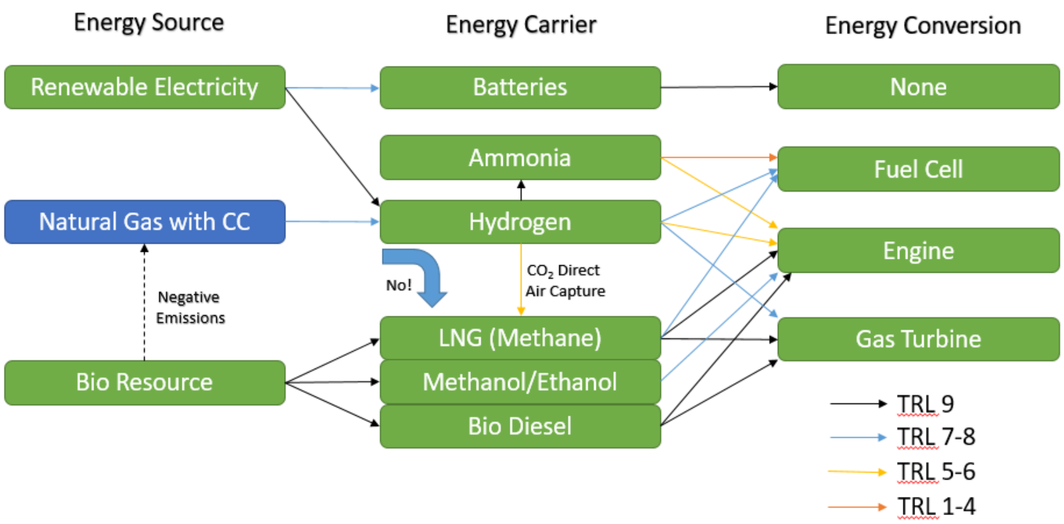


Figure 20 - Potential Low Carbon Energy Paths

6.1 Internal Combustion Engines

ICEs are cheap and well understood in industry. There are a large variety of engines available for carbon-based fuels. There are significantly fewer engines that run on low carbon fuels. Wärtsilä [41] are testing a four-stroke ammonia engine. MAN [42] are working on a two-stroke ammonia engine. BeHydro [60] and many other engine manufacturers are developing hydrogen ICEs.

6.1.1 Mono Fuel vs Dual Fuel Engines

A dual fuel engine can mix two different fuels in the combustion chamber. This can be used to overcome weaknesses in certain fuels. For example, ammonia has a high ignition energy and is slow burning.

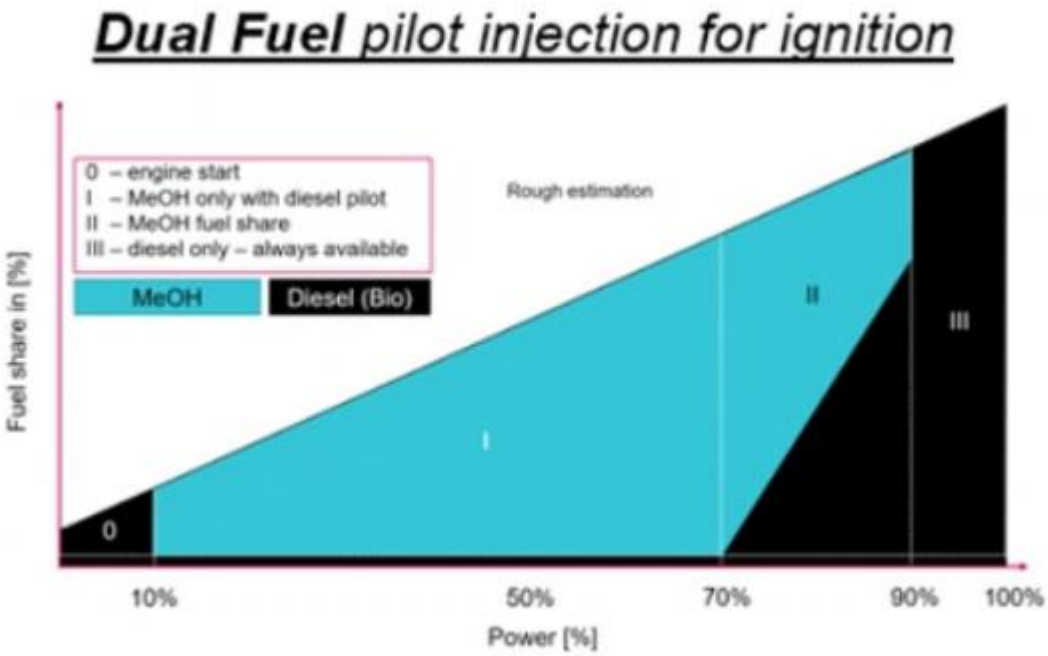


Figure 21 – MAN's estimate of diesel requirment in methanol engine

Figure 21 shows MAN's estimate of the ratios required. It is possible to run the engine with 100% diesel at all powers. This is very useful when there is uncertainty in the availability of a renewable fuels.

DNV have mapped potential fuel transitions paths in Figure 22.

Conventional and carbon-neutral fuels by primary-energy source and mapping of allowed fuel-transition routes in the GHG Pathway Model.

ENGINE / FUEL CELL AND FUEL SYSTEM						Blue ammonia	Blue hydrogen	
		e-MGO	e-LNG	e-LPG	e-methanol	e-ammonia	e-hydrogen	Electricity from grid
		bio-MGO	bio-LNG		bio-methanol			
	HFO	VLSFO/MGO	LNG	LPG				
MF ICE	Retrofit	Drop-in	Retrofit	Retrofit	Retrofit			
MF ICE with scrubber	Drop-in	Drop-in	Retrofit	Retrofit	Retrofit			
DF LNG ICE		Drop-in	Drop-in		Retrofit	Retrofit		
DF LPG ICE		Drop-in		Drop-in	Retrofit	Retrofit		
DF methanol ICE		Drop-in			Drop-in			
DF ammonia ICE		Drop-in				Drop-in		
DF hydrogen ICE		Drop-in					Drop-in	
Hydrogen FC							Drop-in	
Ammonia FC						Drop-in		
Battery EM								Drop-in

Retrofit   Drop-in

MF, mono fuel; DF, dual fuel; ICE, internal combustion engine; FC, fuel cell; EM, electric motor; HFO, heavy fuel oil; VLSFO, very low sulfur fuel oil; MGO, marine gas oil; LNG, liquefied natural gas; LPG, liquefied petroleum gas

©DNV GL 2020

Figure 22 – DNV-GL - MARITIME FORECAST TO 2050 - Energy Transition Outlook 2020 fuel transition

6.2 Fuel cells

Fuel cells are more efficient, quieter, less polluting, and require less maintenance than ICEs. However, they are larger and have a significantly higher capital cost. In some cases, the price of the required fuel cell can be higher than the cost of the current vessel.

The cost is predicted to fall significantly with mass production but there needs to be a large enough market for this. Mass production would also help reduce energy density and increase lifespan.

Batteries are currently outcompeting fuel cells in the car market so it is unclear where fuel cells will find large scale production.

A fuel cell creates DC power in contrast to the AC power produced by an ICE. This will have a significant impact to the electrical distribution system. The engineering challenges around this already have solutions but a lot of training will be required particularly on larger power systems.

There are a range of different fuel cells available. This report will only look at two of the most promising technologies. EMSA/DNV cover a greater range in depth for the marine industry in their 'STUDY ON THE USE OF FUEL CELLS IN SHIPPING' [61].

6.2.1 Proton-Exchange Membrane Fuel Cells

Proton-Exchange Membrane (PEM) fuel cells score the highest in the EMSA/DNV study. They have been used in small quantities for a considerable amount of time. They are not tolerant to CO_2 So care needs to be taken with blue hydrogen to make sure enough CO_2 is removed as a result they are ideally suited to green hydrogen. Their Efficiency is around 50-60% but tends to be lower in practise.

Ballard are the current market leaders in marine PEM fuel cells with marine accredited fuel cells [62] but other manufacturers have plenty time before hydrogen is widely available.

6.2.2 Solid Oxide Fuel Cells

SOFCs are not as mature as PEM fuel cells. They offer greater efficiency at around 60%. Their high temperature means with a form of heat recovery the efficiency can reach 85%. Unlike PEM fuel cells they are tolerant to carbon. This means they can run on LNG and allows them to enter the market before renewable hydrogen is available.

SOFCs are currently significantly more expensive than PEM fuel cells and they don't like to have their temperature cycled. Ideally, SOFCs should be run continually. It is possible to run them in reverse to produce hydrogen. This means they could produce their own hydrogen while in port to keep the SOFC running at all times.

6.3 Efficiency

The efficiency curve of a fuel cell is significantly different to an ICE. An ICE is most efficient near maximum load and drops as the load reduces. A PEM fuel cell is most efficient at 20-30% load. ICEs get more efficient as they get larger, whereas with PEM fuel cells you just add more fuel cells so they don't.

At part loads, fuel cells have a strong advantage. When using ICE on ships, part loading is partially mitigated by having multiple smaller engines. This also improves redundancy. This is only possible when the part loading is constant as engines don't like to be repeatedly cycled on and off. Where the loading varies rapidly, batteries can be used to smooth the load profile.

At full load, it is more challenging for fuel cells as there efficiency starts to drop. Ageing also affects fuel cells more at higher loads. Ageing reduces the efficiency of the fuel cell but the drop in efficiency is not linear with load. The efficiency drop at full load can be multiple times the drop at 20% load. The efficiency drop will eventually necessitate a replacement so a fuel cell that is used at full load will need to be replaced more often.

It is possible to increase efficiency of fuel cells by over installing. Unfortunately fuel cells are currently very expensive. This makes it hard to give efficiency figures for hydrogen fuel cells as it will depend on a cost trade off.

Efficiency reduces the amount of fuel used. This has two distinct benefits:

- It reduces fuel cost - This is especially important with the increased cost of low carbon fuels. It particularly benefits craft that are heavily used.
- It increases the effective range or reduces the amount of space required for fuel - This can be a strong benefit for hydrogen where range can be a challenging design constraint.

6.4 Conclusion

It is too early to say whether fuel cells or ICE engines will be better. It is likely both will have their place and it is likely some ships will have both. PEM fuel cells have the advantage where:

- Hydrogen is the fuel of choice
- The loads are small

- There is a significant amount of part loading
- Efficiency is really important
- The vessel is heavily used

A car can encompass most of these traits. Ignoring batteries, fuel cells have been the clear winner over ICEs in cars. Ships are larger and tend to have less issues with part loading due to having multiple engines so it is less clear.

The impact on a vessel changing from a fossil fuel ICE to a low carbon ICE is expected to be relatively simple compared with the change to fuel storage and handling. This is due to them being a similar size and weight.

7.0 CONCLUSION

Using low carbon fuels on-board marine vessels will result in reduced ranges, increased safety issues and a significant increase in costs. This will be challenging for some people to accept. The need to decarbonise shipping will require the IMO and/or regional governments to bring in regulation or carbon pricing to allow low carbon fuels to replace fossil fuels.

The shipping industry is currently very efficient but, the potential new marine low carbon fuels are not. This means it is preferable to decarbonise other industries first while there is limited renewable resource as this will lead to fewer carbon emissions overall. As a result, there is a lot of uncertainty about when the marine industry is likely to decarbonise.

Except batteries, low carbon fuels are not going to be available in large quantities until at least 2030. As vessels have an average life of 30 years, the vessels being built now will need to decarbonise within their potential lifetimes. If the net 2050 target is to be met, vessels build in the next decade, will need to either:

1. Have shorter lives,
2. Be designed to be refitted,
3. Use an expensive drop in e-fuel or biofuel.
4. Start life using a fuel that emits more carbon than diesel in the knowledge it will be made from a low carbon source in the future.

Table 4 list the most promising fuels, there key benefits, disadvantages and unknowns. There are also significant knowns about

- The future cost of fuels
- When fuels will be available.
- When and how regulation will come in forcing a change to low carbon fuels

Fuel Option	Strengths	Weaknesses/ Limitations	Unknowns
Batteries	Very efficient Available now Being developed by other industries	Range/Duration is very limited Needs grid connection High demand for batteries Battery fires	Maximum economic range
Compressed Hydrogen	More efficient than other fuels (excluding batteries)	Significant space is required to store the fuel limiting range Explosive Cost of fuel cells	How much the price of installed fuel cells will drop Level of safety for below deck hydrogen storage
Liquid Hydrogen	Long range fuel Safer then ammonia Does not require carbon to make	Very expensive to store Cost of fuel cells Range of safety issues Not currently transported by the marine industry	How much the price of installed fuel cells will drop
Ammonia	Most cost effective long range fuel Already transported on tankers in large quantities	Significant safety concerns around its toxicity. Should not be used with passenger or in populated areas.	Will it ever be safe enough to use on passenger ship and in cities.
Methanol	Easy to retrofit Relatively safe	Source of carbon to make the fuel Require a large amount of renewable electricity	Cost of green carbon capture
Biofuels	Similar to current marine fuels	Limited availability	Availability to the shipping industry

Table 4 – Summary of Viable Fuel Options

8.0 REFERENCES

[1] IMO, "ADOPTION OF THE INITIAL IMO STRATEGY ON REDUCTION GHG EMISSIONS," April 2018. [Online]. Available: https://unfccc.int/sites/default/files/resource/250_IMO%20submission_ OF Talanoa%20Dialogue_April%202018.pdf. [Accessed December 2020].

[2] Council of the EU and the European Council, "Fit for 55," 22 December 2021. [Online]. Available: https://www.consilium.europa.eu/en/policies/green-deal/eu-plan-for-a-green-transition/. [Accessed 24 January 2022].

[3] Department for Transport, "Clean Maritime Plan," July 2019. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815664/clean-maritime-plan.pdf.

[4] Climate Change Committee, "Climate Change Committee - About us," Climate Change Committee, 2008. [Online]. Available: https://www.theccc.org.uk/about/. [Accessed Nov 2021].

[5] Climate Change Committee, "The 6th Carbon Budget," Climate Change Committee, 2020.

[6] "UMAS - About us," University Maritime Advisory Services, 2014. [Online]. Available: https://www.u-mas.co.uk/about-us/. [Accessed Nov 2021].

[7] UMAS, "UMAS Transition Strategy Report," 2021.

[8] IACS, "About IACS," IACS, 2022. [Online]. Available: https://www.iacs.org.uk/about/. [Accessed 21 February 2022].

[9] IACS, "Members," IACS, [Online]. Available: https://www.iacs.org.uk/about/members/. [Accessed 21 February 2022].

[10] DNV, "Energy Transition Outlook," DNV, 2021.

[11] DNV, "Pathway to Net-zero 2021," DNV, 2021.

[12] DNV, "Maritime Forecast to 2050," DNV, 2021.

[13] Lloyd's Register, "Lloyd's Register - Who We Are," Lloyd's Register, [Online]. Available: https://www.lr.org/en/who-we-are/. [Accessed November 2021].

[14] Lloyd's register, "Zero-Emission Vessels: Transition Pathways," Lloyd's register, 2019.

[15] ABS, "Sustainability Outlook 2 Pathways," ABS.

[16] ABS, "Ammonia as Marine Fuel Whitepaper," ABS, 2020.

[17] U. a. t. E. T. Commission, "Global Maritime Forum," 20 01 2020. [Online]. Available: https://www.globalmaritimeforum.org/news/the-scale-of-investment-needed-to-decarbonize-international-shipping.

[18] Lloyd's register and University Maritime Advisory Services, "LR.org," 20 04 2020. [Online]. Available: https://www.lr.org/en/latest-news/lr-and-umas-publish-techno-economic-assessment-of-zero-carbon-fuels/.

[19] Neutrium, "SPECIFIC ENERGY AND ENERGY DENSITY OF FUELS," March 2014. [Online]. Available: https://neutrium.net/properties/specific-energy-and-energy-density-of-fuels/. [Accessed January 2022].

[20] The engineering Tollbox, "Fossil and Alternative Fuels - Energy Content," [Online]. Available: https://www.engineeringtoolbox.com/fossil-fuels-energy-content-d_1298.html. [Accessed November 2021].

[21] Crown Oil, "Guide to Bunker Fuel," Crown Oil, [Online]. Available: https://www.crownoil.co.uk/guides/bunker-fuel-guide/. [Accessed November 2021].

[22] European Commission, "Biofuels: a New Methodology to Estimate GHG Emissions Due to Global Land Use Change - A methodology involving spatial allocation of agricultural land demand, calculation of carbon stocks and estimation of N2O emissions," 2010. [Online]. Available: http://publications.jrc.ec.europa.eu/repository/handle/JRC59764.

[23] European Commission, "Sustainable and Smart Mobility Strategy – putting European transport on track for the future," 09 12 2020. [Online]. Available: https://ec.europa.eu/transport/sites/transport/files/legislation/swd20200331.pdf.

[24] DNV GL, "Energy Transition Outlook 2020," DNV GL, [Online]. Available: https://eto.dnvgl.com/2020/index.html#ETO2019-top.

[25] Shell, "Decarbonising Shipping: All Hands on Deck," 2020. [Online]. Available: https://www.shell.com/promos/energy-and-innovation/decarbonising-shipping-all-hands-on-deck/_jcr_content.stream/1594141914406/b4878c899602611f78d36655ebff06307e49d0f8/decarbonising-shipping-report.pdf.

[26] Department for Transport, "Renewable Fuel Statistics 2020 Final Report," 2021. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1032684/renewable-fuel-statistics-2020-final-report.pdf.

[27] E. &. I. S. Department for Business, "https://assets.publishing.service.gov.uk/," 2021. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1032260/UK_Energy_in_Brief_2021.pdf.

[28] The Climate Change Committee, “The Sixth Carbon Budget - Electricity Generation,” The Climate Change Committee, London, 2020.

[29] Committee on Climate Change, “Net Zero Technical Report,” May 2019. [Online]. Available: https://www.theccc.org.uk/publication/net-zero-technical-report/.

[30] Department for Business, Energy & Industrial Strategy, “Hydrogen Production Costs,” August 2021. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011506/Hydrogen_Production_Costs_2021.pdf. [Accessed 8 February 2022].

[31] IEA, “The Future of Hydrogen,” IEA, 2019.

[32] C&EN, “Industrial ammonia production emits more CO2 than any other chemical-making reaction,” [Online]. Available: https://cen.acs.org/environment/green-chemistry/Industrial-ammonia-production-emits-CO2/97/i24.

[33] IEA Bioenergy , “Biofuels for the marine shipping sector,” [Online]. Available: https://www.ieabioenergy.com/wp-content/uploads/2018/02/Marine-biofuel-report-final-Oct-2017.pdf.

[34] European Commission, “Horizon 2020 transport: World's first all-electric ferry takes maiden trip in Denmark,” [Online]. Available: https://ec.europa.eu/inea/en/news-events/newsroom/horizon-2020-transport-worlds-first-all-electric-ferry-takes-maiden-trip.

[35] Leclanche, “Zero Emission Ferry and Onshore Battery Energy Storage System,” 09 September 2021. [Online]. Available: https://www.leclanche.com/wp-content/uploads/2021/09/DAMENEUR-web-10.9.21.pdf. [Accessed November 2021].

[36] Leclanche, “Marine Racking System,” Leclanche, [Online]. Available: https://www.leclanche.com/marine-rack-system/. [Accessed November 2021].

[37] DNV, “HANDBOOK FOR HYDROGEN-FUELLED VESSELS,” 2021. [Online]. Available: https://www.iims.org.uk/wp-content/uploads/2021/07/Handbook_for_hydrogen-fuelled_vessels.pdf. [Accessed December 2021].

[38] Department for Business, Energy & Industrial Strategy, “UK Energy Statistics,” 26 March 2020. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/877047/Press_Notice_March_2020.pdf. [Accessed 26 January 2022].

[39] WESTCON, [Online]. Available: https://assets-global.website-files.com/5add8459c66eeb701d504fc3/6184f8aa1f99a165868d84ee_Bygg%2038%20Hydra%202021.pdf.

[40] Institut für Vernetzte Energiesysteme, [Online]. Available: https://elib.dlr.de/132926/1/ELMAR-REGWA%20Paper_v6.pdf.

[41] Wärtsilä, "World's first full scale ammonia engine test," 30 06 2020. [Online]. Available: https://www.wartsila.com/media/news/30-06-2020-world-s-first-full-scale-ammonia-engine-test---an-important-step-towards-carbon-free-shipping-2737809.

[42] MAN, "MAN B&W two-stroke engine operating on ammonia," 11 2020. [Online]. Available: https://marine.man-es.com/docs/librariesprovider6/test/man-b-w-two-stroke-engine-operating-on-ammonia_5510-0241-01_web.pdf?sfvrsn=6a88d2a2_6.

[43] J. Ovcina, "Industry majors to tackle safety issues linked to the use of ammonia as fuel," Offshore Energy, 20 April 2021. [Online]. Available: https://www.offshore-energy.biz/industry-majors-to-tackle-safety-issues-linked-to-the-use-of-ammonia-as-fuel/. [Accessed 1 February 2022].

[44] T. Brown, "Viking Energy to be retrofit for ammonia fuel in 2024," Ammonia Energy Association, 23 January 2020. [Online]. Available: https://www.ammoniaenergy.org/articles/viking-energy-to-be-retrofit-for-ammonia-fuel-in-2024/. [Accessed 7 February 2022].

[45] Shell, "LIQUEFIED NATURAL GAS (LNG)," [Online]. Available: https://www.shell.com/energy-and-innovation/natural-gas/liquefied-natural-gas-lng.html. [Accessed December 2021].

[46] ABS, "LNG AS MARINE FUEL," June 2020. [Online]. Available: https://absinfo.eagle.org/acton/media/16130/sustainability-whitepaper-lng-as-marine-fuel-abs. [Accessed November 2021].

[47] MAN Energy Solutions, "Flexible Dual Future - MAN B&W ME-GI Engine," 28 Feb 2013. [Online]. Available: https://www.youtube.com/watch?v=V0MVdIQYonM. [Accessed January 2022].

[48] Public Utilities Regulatory Authority - Connecticut Government, "What is LNG?," May 2021. [Online]. Available: https://portal.ct.gov/PURA/Gas-Pipeline-Safety/What-is-LNG. [Accessed December 2021].

[49] elengy, "LNG: AN ENERGY OF THE FUTURE," [Online]. Available: https://www.elengy.com/en/lng/lng-an-energy-of-the-future.html. [Accessed December 2021].

[50] U.S. Department of Energy, "Clean Cities Alternative Fuel Price report," July 2021. [Online]. Available: https://afdc.energy.gov/files/u/publication/alternative_fuel_price_report_july_2021.pdf. [Accessed December 2021].

[51] G. A. Livanos, G. Theotokatos and D.-N. Pagonis, "Techno-economic investigation of alternative propulsion plants for ferries and RoRo ships," *Energy Conversion and Management,* vol. 79, pp. 640-651, 2014.

[52] F. Bahtic, "Waterfront Shipping welcomes new methanol dual-fuel MR tanker," Offshore Energy, 7 October 2021. [Online]. Available: https://www.offshore-energy.biz/waterfront-shipping-welcomes-new-methanol-dual-fuel-mr-tanker/. [Accessed December 2021].

[53] Alternative Fuels Data Center, "Biodiesel Benefits and Considerations," [Online]. Available: https://afdc.energy.gov/fuels/biodiesel_benefits.html. [Accessed December 2021].

[54] Mitchell & Webber, "HVO Renewable Fuel Supplier," [Online]. Available: https://mitweb.co.uk/hvo-fuel-hydrotreated-vegetable-oil/. [Accessed December 2021].

[55] Conserve Energy Future, "What are Biofuels?," [Online]. Available: https://www.conserve-energy-future.com/advantages-and-disadvantages-of-biofuels.php. [Accessed December 2021].

[56] Ship & Bunker, "MSC Biofuel Blend Consumption Reached 850,000 MT last year," Ship & Bunker, 15 September 2021. [Online]. Available: https://shipandbunker.com/news/world/719248-msc-biofuel-blend-consumption-reached-850000-mt-last-year. [Accessed December 2021].

[57] The Maritime Executive, "Additional Shipping Lines Successfully Tested Biofuel Alternative," The Maritime Executive, 11 February 2021. [Online]. Available: https://www.maritime-executive.com/article/additional-shipping-lines-successfully-tested-biofuel-alternative. [Accessed December 2021].

[58] I. Tzinis, "Technology Readiness Level," NASA, 28 October 2012. [Online]. Available: https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level. [Accessed 21 February 2022].

[59] European Commission, "Register of Commission Documents," 22 July 2014. [Online]. Available: https://ec.europa.eu/transparency/documents-register/detail?ref=C(2014)4995&lang=en. [Accessed 21 February 2022].

[60] MarineLog, "BeHydro unveils 1 MW hydrogen-fueled engine," [Online]. Available: https://www.marinelog.com/technology/behydro-unveils-1-mw-hydrogen-fueled-engine/.

[61] EMSA, "Study on the use of Fuel Cells in Shipping," 23 January 2017. [Online]. Available: http://www.emsa.europa.eu/newsroom/latest-news/item/2921-emsa-study-on-the-use-of-fuel-cells-in-shipping.html. [Accessed November 2021].

[62] Ballard, "Fuel cell solutions FCwave," [Online]. Available: https://www.ballard.com/fuel-cell-solutions/fuel-cell-power-products/marine-modules.

[63] A. Einstein, Theory of Relativity, Munich: University Press, 1905.

[64] Shell, "Decarbonising Shipping: SETTING SHELL'S COURSE," 2020. [Online]. Available: https://www.shell.com/promos/energy-and-innovation/decarbonising-

shipping-setting-shells-course/_jcr_content.stream/1601385103966/709d83f692075a4f1880104fc5cc466168e8a26a/decarbonising-shipping-setting-shells-course.pdf.

[65] Royal Institution of Naval Architects, "RINA," Royal Institution of Naval Architects, [Online]. Available: https://www.rina.org.uk/Offshore_vessel_to_be_converted_to_run_on_ammonia-powered_fuel_cell.html.