Australia's National
Science Agency

Co-design process:

Australia–Singapore initiative on low-emissions technologies for maritime and port operations

Synthesis report

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This report was authored by Rosie Dollman and Kate McMahon, with input from industry and research leaders.

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Contents

Glossary

ALARP	As low as reasonably practical
AMSA	Australian Maritime Safety Authority
B100	100% biofuel blend
BioLNG	Bio-Liquefied Natural Gas
BioLPG	Bio-Liquefied Petroleum Gas
BtL	biomass-to-liquid
CCUS	Carbon Capture, Utilisation and Storage
CH_3OH	Methanol
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DAC	Direct Air Capture
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DME	Dimethyl Ether
DMFC	Direct Methanol Fuel Cell
E-	Fuel produced from renewable electricity via electrolysis
EJ	Exajoule
FAME	Fatty Acid Methyl Ester
FC	Fuel Cell
FT	Fischer–Tropsch
GCMD	Global Centre for Maritime Decarbonisation
GHG	Greenhouse Gas
H_2	Hydrogen
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMO	International Maritime Organization

Li-ion	Lithium-ion
LNG	Liquefied Natural Gas
MCFC	Molten Carbonate Fuel Cell
MGO	Marine Gas Oil
MJ	Megajoule
MoU	Memorandum of Understanding
MPA	Maritime Port Authority
Mt	Million tonne
NG-CCUS	Natural Gas with Carbon Capture, Utilisation and Storage
NH_3	Ammonia
NO_x	Nitrogen Oxides
OCC	Onboard Carbon Capture
PPA	Pilbara Port Authority
PEM	Proton-Exchange Membrane
PBtL	Power-and-biomass-to-liquid
RoPax	Roll-on Roll-off vessel that has passenger carrying capacities
RoRo	Roll-on Roll-off
SCR	Selective Catalytic Reduction
SMR	Steam Methane Reforming
SOFC	Solid Oxide Fuel Cell
SOx	Sulphur Oxides
TRL	Technology Readiness Level
VLSFO	Very Low Sulphur Fuel Oil

Executive summary

Australia and Singapore seek to cooperate on low-emissions demonstration projects in maritime and port operations. The two countries have established an AUD 30 million initiative to reduce emissions in the maritime sector while delivering a bilateral economic benefit. The program presents a significant opportunity for both countries, given the potential for Singapore to become a global hub for green bunkering (vessel refuelling) and Australia to be a leading producer and exporter of low-emissions fuels.

The investment funds allocated under this program will aim to address some of the major challenges to adopting low-emissions fuels in the maritime sector and therefore facilitate broader ambition. By addressing specific barriers to technology adoption, this initiative will reduce the risk to firms investing in low-emissions technologies and stimulate further investment and demand. For example, developing projects that demonstrate the safe handling of fuels, such as ammonia, and support the establishment of new regulatory guidelines will be essential to achieve broad-based adoption.

This report outlines the co-design of the initiative, developed with industry stakeholders in Australia and Singapore. The approach combines desktop research, one-to-one interviews and industry workshops in both countries to develop challenge focus areas that will ultimately guide investment decisions for the program. This report also documents current practices in the maritime sector and provides an assessment of decarbonisation solutions.

Although fossil fuels still dominate the maritime and ports supply chain, the regulatory pressure to reduce emissions is increasing. In July 2023, the International Maritime Organization announced an updated greenhouse gas (GHG) emissions target to reach net-zero GHG emissions from international shipping close to 2050.[1] As a result of this pressure, a number of shipping companies, ports and port authorities in Australia and Singapore are beginning to develop strategies for adopting low-emissions fuels.

Each decarbonisation option available for maritime applications has advantages in specific contexts, which provides a case for a multi-fuel future. For example, the solutions appropriate for deep-sea vessels will be quite different to those for short-sea vessels providing port services. Table 1 summarises the main advantages and limitations of each option assessed in this study.

Table 1: Fuel/Technology assessment

FUEL/TECHNOLOGY	ADVANTAGES	LIMITATIONS
Hydrogen	• High emissions reduction potential • Fuel cells well suited to short-sea shipping	• Current cost of production is high • High storage costs due to low volumetric energy density (therefore not suitable for large vessels)
Ammonia	• High emissions reduction potential • Higher volumetric energy density (compared with hydrogen)	• Current cost of production is high • High safety risks, therefore lower acceptability • Potential for N_2O emissions
Methanol	• High emissions reduction potential • Higher volumetric energy density (compared with hydrogen) • Low safety risks	• Current cost of production is high • Difficulty in sourcing renewable CO_2 and verifying emissions impact
Biofuels	• Commercially available drop-in fuel • High emissions reduction potential (although this depends on the feedstock)	• Limited feedstock availability • Difficulty in verifying emissions impact • Low readiness of engines for B100 applications
Battery electric systems	• High emissions reduction potential • Well suited to short-sea shipping	• High capital costs, which increase with vessel size (therefore not suitable for large vessels)
Onboard carbon capture	• Reduces emissions in existing assets, which may be operating for some time	• High cost of carbon capture • Cost of offloading, transport and permanent storage • Lower emissions reduction potential (compared with alternatives)

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[1] IMO (2023) 2023 IMO Strategy on Reduction of GHG Emissions from Ships. <https://wwwcdn.imo.org/localresources/en/MediaCentre/PressBriefings/Documents/Clean%20version%20of%20Annex%201.pdf> (accessed 30 August 2023).

Although many challenges were identified in the maritime literature and during initial consultations (see Chapter 3.9), industry workshops were used to determine the highest-priority challenges, with consideration of the following criteria:

- there is a mutual benefit to Australia and Singapore
- the identified projects contribute to the physical demonstration of low-emission fuels/technologies
- there is a clear investment gap (to avoid duplication of work elsewhere)
- the projects have high relevance for maritime applications
- the challenges identified are consistent with the scale of the funding targets
- the projects focus on the most viable fuels/technologies (considering factors such as fuel cost, scalability, storage and transport costs, GHG emissions and safety).

Based on the criteria and stakeholder input, the three challenge focus areas outlined below were identified:

- mitigate safety and ecological risks associated with the use of low-emissions fuels, such as ammonia and hydrogen
- develop technology and infrastructure at ports to accommodate the adoption of low-emissions fuels
- reduce the cost of low-emissions technologies in short-sea vessels.

This program will draw on these focus areas to identify projects for co-investment. During the next stage of the process, a strategic partnership (made up of Australian and Singaporean representatives) will develop a pipeline of projects consistent with the focus areas. Projects will then be selected on an iterative basis.

The framework employed in this study is designed to strike a balance between developing the technologies and systems required for the adoption of low-emissions fuels while acknowledging the technology development that is already underway, as well as constraints on time and funding. Throughout the consultation process, other sector-wide challenges were identified, but not prioritised as a key focus area.

For example, there is a major challenge relating to the production costs of low-emissions fuels, leading to uncertainty around future fuel supply at ports. However, given many projects are already underway to support fuel production and the large costs associated with these projects, fuel supply was not identified as a focus area for the program.

Because there are many challenges that cannot be solved through this program alone, stakeholders noted that other actions are required to facilitate the adoption of low-emissions fuels. These include greater ambition on climate policy, as well as further analysis on port infrastructure requirements and the costs/emissions associated with various decarbonisation solutions.

1 Introduction

Australia and Singapore have developed a memorandum of understanding (MoU) to cooperate on developing low-emissions technologies.[2] As part of the MoU, the two countries established an AUD 30 million Australia–Singapore initiative on low-emissions technologies for maritime and port operations.

This initiative is also listed under Annex B 4.2 of the Singapore–Australia Green Economy Agreement.[3] As part of the MoU, each country will commit up to AUD 10 million to fund industry-led projects, and the program aims to raise at least a further AUD 10 million from the industry.[4] The objectives underlying the Australia–Singapore partnership are to:

- reduce emissions in shipping and port operations by accelerating deployment and reducing the cost of low-emissions fuels and technologies[5]
- deliver shared economic benefits to both Australia and Singapore.

The investments made under this program will seek to address some of the significant challenges to adopting low-emissions fuels in the maritime sector, facilitating broader ambition. There is a wide range of challenges relating to the use of low-emissions solutions in maritime applications. As a result, industry participants are hesitant to make long-term investments in the new technologies required for fuel production, port infrastructure and vessel power systems. The program therefore aims to accelerate the deployment of low-emissions fuels by co-funding projects drawing on shared infrastructure and testbeds, which will reduce the upfront capital costs associated with testing new technologies. Addressing sector challenges will also reduce the risk to firms investing in the new technologies, stimulating demand and further investment in low-emissions solutions.

The program structure includes a co-design process to guide the identification of co-investment projects. CSIRO is working with Australian and Singaporean stakeholders to support the co-design of the program. This synthesis report will summarise the work completed for this process.

1.1 Why maritime and port operations?

A partnership focusing on the maritime and ports supply chain presents an opportunity for Singapore to establish itself as a green bunkering hub and for Australia to establish itself as a leader in low-emissions fuel exports. It also offers a joint opportunity to establish a green shipping corridor between the two countries.

Australia is projected to be a leading producer and exporter of low-emissions fuels. Australia has some of the best wind and solar resources in the world and extensive available land, as well as natural gas reserves and potential CO_2 storage sites. Information on projects under development suggests that Australia will have the capacity to export around 3 Mt of low-emissions hydrogen annually by 2030.[6] These exports could be in the form of pure hydrogen, or the volumes could be used to produce derivatives such as ammonia and methanol.

As a global bunkering hub, Singapore aims to become a leading supplier of low-emissions marine fuels. The Port of Singapore supplies approximately one-fifth of the world's marine fuels (50 Mt annually), with total spending from shipping companies exceeding SGD 4.3 billion.[7]

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[2] Department of Climate Change, Energy, the Environment and Water (2020) Memorandum of understanding between the Government of Australia and the Government of Singapore for cooperation on low-emissions solutions. <https://www.dcceew.gov.au/sites/default/files/documents/australia-singapore-mou.pdf> (accessed 16 May 2023).

[3] Department of Foreign Affairs and Trade. Annex B 4.2: Green shipping cooperation. <https://www.dfat.gov.au/countries-and-regions/singapore-australia-green-economy-agreement-annexes/annex-b-42-green-shipping-cooperation> (accessed 15 May 2023).

[4] Taylor A (2021) Australia partners with Singapore on hydrogen in maritime sector. [Media release] <https://www.minister.industry.gov.au/ministers/taylor/media-releases/australia-partners-singapore-hydrogen-maritime-sector> (accessed 10 May 2023).

[5] In this study, 'emissions' refers to direct greenhouse gas (GHG) emissions such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), as well as indirect GHGs, such as nitrogen oxides (NO_x) and sulphur oxides (SO_x).

[6] IEA (2022) World Energy Outlook 2022. <https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf> (accessed 30 August 2023).

[7] MPA Singapore (2022) Maritime Singapore closes 2022 with good momentum for future growth. <https://www.mpa.gov.sg/media-centre/details/maritime-singapore-closes-2022-with-good-momentum-for-future-growth> (accessed 4 May 2023).

The greenhouse gas (GHG) emissions from fuel sales were estimated to be 148 Mt of carbon dioxide equivalent (CO_2e) in 2019, nearly three times the amount produced from Singapore's domestic economy.[8] An early transition away from emissions-intensive marine fuels could establish Singapore as a global green bunkering hub. Given that the value and volume requirements for low-emissions fuels are expected to be higher than those for conventional fuels, this could lead to a significant increase in the value of the bunker market in Singapore. In a recent study, the Global Centre for Maritime Decarbonisation (GCMD) projected in its 'realistic' scenario that ammonia bunker demand in Singapore will reach 50 Mt by 2050.[9] However, due to a lack of resources and land availability for fuel production, Singapore is looking to import low-emissions fuels. Australia is expected to supply these fuels at a low cost relative to some other exporting countries, given its potential for low-cost renewable electricity.[10]

Given the major shipping route between Australia and Singapore, establishing green corridors (defined as 'zero maritime emissions routes between two or more ports') between the two countries will advance commercial interests and accelerate the decarbonisation of the supply chain.[11] This decarbonisation will support both countries in achieving national emission reduction targets and the International Maritime Organization's (IMO) ambition for net-zero GHG emissions from international shipping close to 2050.[12]

Ports and exporters in Australia and Singapore have already begun developing green corridor plans. For example, the Silk Alliance is a developing a green corridor cluster in Asia which aims to make decarbonised fuels available in Singapore for multiple trading routes.[13] Several feasibility assessments are also underway to determine which routes would benefit from initial development due to their production and export potential.[14] Examples include the West Australia – East Asia Iron Ore Green Corridor and the Australia and New Zealand Green Corridors (still in the pre-feasibility phase).[15]

Other projects and collaborations focusing on maritime decarbonisation are also underway. In Singapore, the MPA is involved in a range of initiatives, including co-funding harbour craft electrification projects (see Chapter 2.2 for other initiatives). In addition, Shell, Penguin and Sembcorp Marine are trialling hydrogen fuel cell (FC) technology. Collaborations have also been announced in Australia, with an MoU recently signed between the Port of Melbourne, Maersk, ANL Svitzer, Stolthaven Terminals, HAMR Energy and ABEL Energy to explore the feasibility of establishing a green methanol bunkering hub at the Port of Melbourne.[16]

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[8] Mao X, Rutherford D, Osipova L, Georgeff E (2022) Exporting emissions: Marine fuel sales at the Port of Singapore. ICCT. <https://theicct.org/publication/marine-singapore-fuel-emissions-jul22/> (accessed 6 December 2022).

[9] Global Centre for Maritime Decarbonisation (2023) Ammonia bunkering pilot safety study. <https://www.gcformd.org/ammonia-bunkering-safety-study> (accessed 1 May 2023).

[10] This is supported by a study examining the cost of fuel supply for different trade routes, conducted by the Lloyd's Register Maritime Decarbonisation Hub: Lloyd's Register Maritime Decarbonisation Hub (2021) First movers in shipping's decarbonisation: A framework for getting started. <https://www.naucher.com/wp-content/uploads/2021/12/LR_First_movers_in_shipping_s_decarbonisation_A_framework_for_getting_s.pdf> (accessed 1 June 2023).

[11] Department for Transport (2022) COP 26: Clydebank Declaration for green shipping corridors. UK Government. <https://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors/cop-26-clydebank-declaration-for-green-shipping-corridors> (accessed 1 June 2023).

[12] IMO (2022) IMO's work to cut GHG emissions from ships. <https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx> (accessed 4 May 2023).

[13] Lloyd's Register Maritime Decarbonisation Hub (2022) The Silk Alliance. <https://www.lr.org/en/marine-shipping/maritime-decarbonisation-hub/the-silk-alliance/> (accessed 1 June 2023).

[14] Maersk Mc-Kinney Moller Center (2023) New Guide Provides Structured Approach to Assess Potential of Green Corridors. <https://www.zerocarbonshipping.com/news/press-release-new-guide-provides-structured-approach-to-assess-potential-of-green-corridors/> (accessed 1 June 2023).

[15] Boyland J, Beckmann M, Fahnestock J, Martins J, Meldrum M, Mingaleeva E (2023) Fuelling the decarbonisation of iron ore shipping between Western Australia and East Asia with clean ammonia. Global Maritime Forum. <https://cms.globalmaritimeforum.org/wp-content/uploads/2023/05/GMF_WA-East-Asia-Iron-Ore-Green-Corridor-Feasibility-Study.pdf> (accessed 1 June 2023); Maersk Mc-Kinney Moller Center (2022) Green Corridors: Pre-Feasibility Phase Blueprint. <http://mission-innovation.net/wp-content/uploads/2022/11/Green-Corridors-Pre-Feasibility-Blueprint-Summary.pdf> (accessed 1 June 2023).

[16] Port of Melbourne (2023) Green methanol MoU signed with Melbourne port. <https://www.portofmelbourne.com/green-methanol-mou-signed-with-melbourne-port/> (accessed 7 June 2023).

1.2 Approach

The approach for the co-design process combines desktop research and stakeholder consultation to develop challenge focus areas that will ultimately guide investment decisions for the program. The desktop research included reviewing reports and roadmaps on decarbonising the maritime and ports supply chain. Stakeholder consultations involved 50 one-on-one interviews with government, regulatory bodies, research institutions and industry participants, as well as industry workshops in Australia and Singapore. The report is structured as follows:

- **Current practices (Chapter 2)** outlines the current state of the maritime and ports supply chain in Australia and Singapore, including the fuels and technologies currently used and the relevant policies and regulations.
- **Decarbonisation solutions (Chapter 3)** assesses the low-emissions fuel and technology options for maritime and port operations, including barriers to uptake across the supply chain. A set of major challenges across fuel and technology options is identified.
- **Priority challenges (Chapter 4)** assesses the identified challenges and proposes three challenge focus areas to guide project identification.
- **Challenge focus areas (Appendix A)** outlines the three focus areas in detail.
- **Supporting information (Appendices B-D)** provides further detail on the decarbonisation solutions assessment, lower-priority challenges and a list of participating stakeholders.

2 Current practices

2.1 Conventional marine fuels

The maritime and ports supply chain is currently dominated by fossil fuels, with international shipping contributing to around 3% of global GHG emissions.[17] Most vessels draw on petroleum-based fuels; however, some are fuelled with liquefied natural gas (LNG), and a small proportion use methanol and biofuels. Both Australia and Singapore are net importers of fossil fuels for maritime use. Singapore is the third-largest oil-refining centre in the world, refining fuels for use in shipping and other sectors.[18] Although both countries have made some progress towards electrification in short-sea vessels and port operations, activities across the entire supply chain remain dependent on fossil fuels.

2.1.1 Characteristics and emissions

According to the IMO, in 2021, just under 94% of fuel used in international shipping was petroleum-based fuel.[19] These fuels are well suited to maritime applications given their high energy density, cost efficiency and ease of handling.[20] Heavy fuel oil (HFO), produced as a residual of the oil refining process, was traditionally the dominant fuel type used in deep-sea shipping due to its significantly lower cost compared with other marine fuels. HFO emits high levels of $CO_{2,}$ particulate matter, sulphur oxides (SO_x) and nitrogen oxides (NO_x).[21]

Other petroleum-based fuels with lower levels of SO_x, such as very low sulphur fuel oil (VLSFO), marine gas oil (MGO) and marine diesel oil (MDO), are now being adopted after the IMO implemented restrictions on sulphur content (see Chapter 2.2 for further details). However, the overall CO_2e intensity of these fuels is similar to that of HFO.[22]

Fuels from alternative energy sources are also being integrated into international shipping. The maritime industry has recently adopted LNG due to its lower combustion emissions (in 2021, just under 6% of all fuel used in ships was LNG).[23] According to Pavlenko et al., the use of LNG reduces tank-to-wake emissions by 30% compared with HFO; however, this study also suggests that when considering total GHG emissions on a well-to-wake basis, the emissions from LNG are much closer to (or, in some cases, can be higher than) HFO.[24] This is due, in part, to the emissions reduction from CO_2 being offset by greater emissions from upstream methane leakage and downstream methane slip (unburned methane that escapes from marine engines).[25] Despite this, there have been developments in several engines and after-treatment technologies that reduce methane slip.[26] Alternative fuels, such as LPG, biofuel and methanol, are also used to fuel vessels; however, this makes up less than 0.1% of fuel used in international shipping.[27]

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[17] IMO (2021) Fourth IMO GHG study 2020. <https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx> (accessed 4 May 2023).

[18] Energy Market Authority (2021) Energy supply chapter 1: Imports & exports of energy products. <https://www.ema.gov.sg/singapore-energy-statistics/Ch01/index1> (accessed 27 January 2023); Geoscience Australia (2021) Australia's energy commodity resources (ACER), 2021 edition. <http://pid.geoscience.gov.au/dataset/ga/130098> (accessed 30 January 2023); IEA (2020) Singapore. <https://www.iea.org/countries/singapore> (accessed 4 May 2023).

[19] IMO (2021) Energy efficiency of ships: Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (reporting year: 2021). <https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC%2079-6-1%20-%20Report%20of%20fuel%20oil%20consumption%20data%20submitted%20to%20the%20IMO%20Ship%20Fuel%20Oil%20ConsumptionDatabase...%20(Secretariat).pdf> (accessed 14 April 2023).

[20] Thepsithar P (2020) Alternative fuels for international shipping. Nanyang Technological University, Singapore.

[21] M.J. Bardley & Associates LLC (2009) Chapter 3. The fuel effect: What is being burned matters. In: The bottom of the barrel: How the dirtiest heating oil pollutes our air and harms our health. Environmental Defense Fund. <https://www.edf.org/sites/default/files/10071_EDF_BottomBarrel_Ch3.pdf> (accessed 1 June 2023).

[22] Comer B, Osipova L (2021) Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies. ICCT. <https://theicct.org/sites/default/files/publications/Well-to-wake-co2-mar2021-2.pdf> (accessed 10 May 2023); Thepsithar P (2020) Alternative fuels for international shipping. Nanyang Technological University, Singapore.

[23] IMO (2021) Energy efficiency of ships: Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2021). <https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC%2079-6-1%20-%20Report%20of%20fuel%20oil%20consumption%20data%20submitted%20to%20the%20IMO%20Ship%20Fuel%20Oil%20ConsumptionDatabase...%20(Secretariat).pdf> (accessed 14 April 2023).

[24] Pavlenko N, Comer B, Zhou Y, Clark N, Rutherford D (2020) The climate implications of using LNG as a marine fuel. ICCT. <https://theicct.org/wp-content/uploads/2021/06/LNG-as-marine-fuel-working-paper-02_FINAL_20200416.pdf> (accessed 11 January 2023).

[25] The research also points to further emissions in the production process due CO2 emissions from the energy-intensive liquification process.

[26] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (2023) Reducing methane emissions onboard vessels. <https://www.zerocarbonshipping.com/publications/reducing-methane-emissions-onboard-vessels/> (accessed 10 May 2023).

[27] IMO (2021) Energy efficiency of ships: Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (reporting year: 2021). <https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC%2079-6-1%20-%20Report%20of%20fuel%20oil%20consumption%20data%20submitted%20to%20the%20IMO%20Ship%20Fuel%20Oil%20ConsumptionDatabase...%20(Secretariat).pdf> (accessed 14 April 2023).

Although most fuel consumption comes from deep-sea vessels, including oil tankers, dry bulk carriers, container vessels and RoRo (roll-on roll-off) vessels, energy is also required to fuel short-sea vessels (including harbour craft) and port terminal operations. 'Harbour craft' refers to vessels that operate within port waters, including bunker tankers, passenger vessels, tugboats and other specialised in-port vessels.[28] Currently, most harbour craft are powered with MGO or diesel. Fuels used in ports terminals (e.g. in cranes, vehicles and conveyer belts) are typically diesel, petrol or LNG, although some port operators have electrified these operations.[29] Although the emissions from harbour craft and port terminals are minimal relative to those from international shipping,[30] the decarbonisation of these activities is of high priority for port operators.

2.1.2 Storage and bunkering

The key considerations for storing fuels in tanks at ports and onboard vessels include temperature, pressure and space requirements. The temperature and pressure vary depending on the fuel. Fuel oil is maintained as a liquid in underground or aboveground storage tanks at ambient conditions. LNG is liquid at temperatures of –162°C, so storage tanks must be well insulated. These conditions can be achieved with vacuum insulation technology. As one of the biggest and busiest ports in the world, Singapore has a large capacity for the storage and bunkering (vessel refuelling) of natural gas and petroleum-based fuels.

There are several bunkering methods; ship-to-ship bunkering is the most common process for deep-sea vessels using conventional marine fuels. This bunkering can occur at quayside, anchor or sea to avoid interrupting quayside operations. Truck-to-ship bunkering is used for smaller fuel quantities and is currently the primary process for LNG. There are also shore-to-ship transfers, where tanks connect to a bunker quay via a pipeline.

2.1.3 Use

Internal combustion engines (ICEs) power most vessels and port machinery. Vessels can be powered by two- or four-stroke engines. Two-stroke engines produce more power and are suited to the propulsion of larger, low-speed vessels. Medium- and high-speed four-stroke engines are better suited to smaller, quicker vessels, including harbour craft. In addition to the main engine, smaller auxiliary engines are used onboard vessels for electric power applications.

2.2 Regulations

The IMO regulates pollution from international shipping and has implemented restrictions for several types of emissions. Australia and Singapore are members of the IMO and signatories to the International Convention for the Prevention of Pollution from Ships (MARPOL). Annex VI of this convention regulates air pollution and includes limits for indirect GHGs, such as NO_x and SO_x.[31] The NO_x limit is 2–3.4 g/kWh for marine diesel engines depending on the power output installed, and the global sulphur limit for marine fuels is 0.5% (reduced from 3.5% in 2020).[32]

In 2023, the IMO announced revised targets for direct GHG emissions in international shipping. This includes a goal to reach net-zero GHG emissions from international shipping close to 2050, as well as interim goals to reduce GHG emissions by at least 20% by 2030 and at least 70% by 2040 (compared to 2008 levels). Specific targets have also been set for CO_2, with aims for a reduction in CO_2 intensity of at least 40% by 2030 (compared to 2008 levels).[33] As part of the GHG emission reduction strategy, IMO members must meet requirements on energy efficiency and carbon intensity. These targets are based on the Energy Efficiency Design Index for new vessels, the Energy Efficiency Existing Ship Index for existing vessels and the Carbon Intensity Indicator. These requirements vary by vessel type and are adjusted annually to align with the 2030 CO_2 intensity target.[34]

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[28] Liu M, Chiam B, Koh K, Sze Y (2020) A study on the future energy options of Singapore Harbour craft. Nanyang Technological University, Singapore.

[29] Port of Newcastle (2021) Port of Newcastle: 2021 sustainability report. <https://portofnewcastle.com.au/wp-content/uploads/2022/07/PON-2021-Sustainability-Report.pdf> (accessed 31 January 2023).

[30] MPA (2022) Decarbonisation blueprint: Working towards 2050. Maritime and Port Authority of Singapore; Port of Melbourne (2023) Port of Melbourne: 2022 sustainability report. <https://www.portofmelbourne.com/wp-content/uploads/2023-PoM-Sustainability-Report_FINAL_3.pdf> (accessed 4 May 2023).

[31] IMO (1983) International Convention for the Prevention of Pollution from Ships (MARPOL). <https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx> (accessed 9 June 2023).

[32] IMO (2021) IMO2020 fuel oil sulphur limit – cleaner air, healthier planet. <https://www.imo.org/en/MediaCentre/PressBriefings/pages/02-IMO-2020.aspx> (accessed 4 May 2023).

[33] IMO (2023) 2023 IMO Strategy on Reduction of GHG Emissions from Ships. <https://wwwcdn.imo.org/localresources/en/MediaCentre/PressBriefings/Documents/Clean%20version%20of%20Annex%201.pdf> (accessed 30 August 2023).

[34] IMO (2019) Improving the energy efficiency of ships <https://www.imo.org/en/OurWork/Environment/Pages/Improving%20the%20energy%20efficiency%20of%20ships.aspx> (accessed 4 May 2023).

In Singapore, the Maritime Port Authority (MPA) regulates port and marine services within Singaporean waters. The MPA oversees legislation, such as the employment and working conditions for seafarers and the prevention/penalties relating to sea pollution (including IMO regulations). It also promotes green maritime initiatives consistent with Singapore's international climate commitments.[35]

The MPA is involved in several strategies and pilot programs. For example, it has recently set a target that by 2030 all new harbour craft must be full electric, capable of using B100 biofuel or be compatible with net-zero fuels such as hydrogen.[36] The MPA has also entered into an MoU with the IMO and the Ministry of Climate and Environment of Norway. Together, they will work on initiatives such as NextGEN Connect, which aims to support decarbonisation through trials along existing shipping routes. The initiative has recently endorsed the Lloyd's Register Maritime Decarbonisation Hub's 'route-based action plan methodology', which draws on the Silk Alliance's green corridor cluster concept.[37] Further, the MPA has released expressions of interest for ammonia bunkering pilot projects, which, according to stakeholder consultations, will provide more certainty for future investments.[38]

In Australia, the regulatory frameworks for port and maritime operations are determined by State and Territory Governments, as well as the Federal Government through the Australian Maritime Safety Authority (AMSA). Although governments historically owned port authorities, many are now privatised. Therefore, the private sector is now largely responsible for port operations and investment. However, state and territory governments are still responsible for land use planning and controls.[39] AMSA implements international and national standards relating to ship construction, equipment, crew and vessel safety, seafarer employment and protection of the marine environment.[40] It is also responsible for enforcing Australia's international obligations, regulating emissions from all ships in Australian waters to align with IMO targets. It also sets additional emissions standards, such as sulphur use caps for cruise ships in Sydney Harbour and guidelines for 'novel vessels' (vessels that do 'not have the shape, form, function or propulsion of most vessels of a similar kind').[41]

2.3 Existing technologies for emissions reduction

2.3.1 Scrubbers

In response to the IMO's sulphur limit, many vessels are now installed with exhaust gas cleaning or 'scrubber' systems. A scrubber sprays water and chemicals in the exhaust stream, causing the sulphur dioxide to react with alkaline water, forming sulphuric acid.[42] The International Council on Clean Transportation (ICCT) estimates that sulphur scrubbers were installed on more than 4300 ships in 2021.[43] Companies such as Wärtsilä are now also developing scrubber technology to target other pollutants, including NO_x and CO_2.[44]

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[35] MPA. Maritime and Port Authority of Singapore Act. <https://www.mpa.gov.sg/regulations-advisory/maritime-legislation-of-singapore> (accessed 4 May 2023).

[36] MPA (2023) Media factsheet: Strengthening Singapore's competitiveness as a hub port and international maritime centre. <https://www.mpa.gov.sg/media-centre/details/strenghtening-singapore-s-competitveness-as-a-hub-port-and-international-maritime-centre#:~:text=MPA%20will%20set%20the%20target,2050%20national%20net%2Dzero%20target> (accessed 10 May 2023).

[37] IMO (2023) IMO, Norway and Singapore sign MOU on maritime decarbonisation. <https://www.imo.org/en/MediaCentre/PressBriefings/pages/MOU-on-maritime-decarbonization.aspx> (accessed 4 May 2023); Lloyd's Register Maritime Decarbonisation Hub (2023) LR Maritime Decarbonisation Hub wins IMO NextGEN Connect Challenge for its action plan to introduce green shipping corridors. <https://www.lr.org/en/latest-news/lr-maritime-decarbonisation-hub-wins-imo-nextgen-connect-challenge/> (accessed 1 June 2023).

[38] MPA (2022) Expression of interest (EOI) to develop an end-to-end low or zero-carbon ammonia power generation and bunkering solution ('project') in Singapore. <https://www.mpa.gov.sg/docs/mpalibraries/media-releases/older/expression-of-interest-for-ammonia-project-(final).pdf> (accessed 10 May 2023).

[39] Department of Infrastructure, Transport, Regional Development, Communications and the Arts. Ports. <https://www.infrastructure.gov.au/infrastructure-transport-vehicles/freight/ports> (accessed 4 May 2023).

[40] AMSA. Regulations and standards. <https://www.amsa.gov.au/about/regulations-and-standards#collapseArea139> (accessed 4 May 2023).

[41] AMSA. National standard for commercial vessels (NSCV). <https://www.amsa.gov.au/about/regulations-and-standards/national-standard-commercial-vessels-nscv> (accessed 4 May 2023).

[42] DNV (2018) Scrubbers at a glance. <https://www.dnv.com/expert-story/maritime-impact/Scrubbers-at-a-glance.html> (accessed 1 June 2023).

[43] Osipova L, Georgeff E, Comer B (2021) Global scrubber washwater discharges under IMO'S 2020 fuel sulfur limit. ICCT. <https://theicct.org/publication/global-scrubber-washwater-discharges-under-imos-2020-fuel-sulfur-limit/> (accessed 4 May 2023).

[44] Wärtsilä (2021) Scrubber technology to support shipping's sustainability goals. <https://www.wartsila.com/insights/article/scrubber-technology-to-support-shipping-s-sustainability-goals> (accessed 4 May 2023).

The use of scrubber technology does present some challenges. In an open-loop system, scrubbers can discharge the captured contents back into seawater without treatment, contributing to increasing water acidity and pollution.[45] However, in a closed-loop system, the captured contents can be accumulated onboard and disposed of at a port facility.[46]

2.3.2 Energy efficiency

Given that vessels typically have lifetimes of 20–30 years, fossil fuels are likely to remain in the shipping fuel mix for some time. Therefore, recent newbuilds operating on fossil fuels have developed solutions to improve energy efficiency to comply with IMO regulations and reduce emissions in the near term. Vessel operators have suggested that measures such as increased hull cleaning and using wave foils have each contributed 5–15% in fuel savings. Waste heat recovery solutions are also being implemented to reduce energy use.[47] In addition, vessel operators are considering wind propulsion technologies, which are estimated to reduce fuel consumption by up to 20%. However, this relies on optimal wind conditions.[48] Further energy efficiency solutions in development are outlined in Chapter 3.7.

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[45] Davin S (2020) The trouble with scrubbers: Shipping's emissions "solution" creates new pollution. WWF. <https://wwf.ca/stories/scrubbers-creates-new-pollution/> (accessed 4 May 2023).

[46] DNV (2018) Scrubbers at a glance <https://www.dnv.com/expert-story/maritime-impact/Scrubbers-at-a-glance.html> (accessed 1 June 2023).

[47] Climeon (2022) Waste Heat Recovery for EEXI Compliance? <https://climeon.com/waste-heat-recovery-for-eexi-compliance/> (accessed 9 June 2023).

[48] Oanh Ha K (2022) The future of shipping is Sails? Cargill. <https://www.cargill.com/the-future-of-shipping-is-sails> (accessed 16 February 2023); Telling O (2023) Shipping lines return to proven power of wind. Financial Times. <https://www.ft.com/content/50656582-8b42-47d9-9bcf-decb0f976dd3> (accessed 16 February 2023).

3 Decarbonisation solutions

This chapter outlines seven fuel/technology options available in the maritime sector for reducing emissions, namely:

- hydrogen
- ammonia
- methanol
- biofuels for maritime applications
- battery electric systems
- onboard carbon capture (OCC)
- energy efficiency solutions.

Figure 1 illustrates the relevant technologies and processes for these solutions across the supply chain.

There are challenges associated with each decarbonisation option, including technological, operational and regulatory constraints. Although this program focuses on technological and operational barriers, this report also discusses market and regulatory obstacles to provide further context. Chapter 3.9 provides a list of the major technological and operational challenges across decarbonisation solutions. This list was narrowed down to the highest-priority focus areas during workshops with key industry stakeholders in Australia and Singapore (Chapter 4 describes this process).

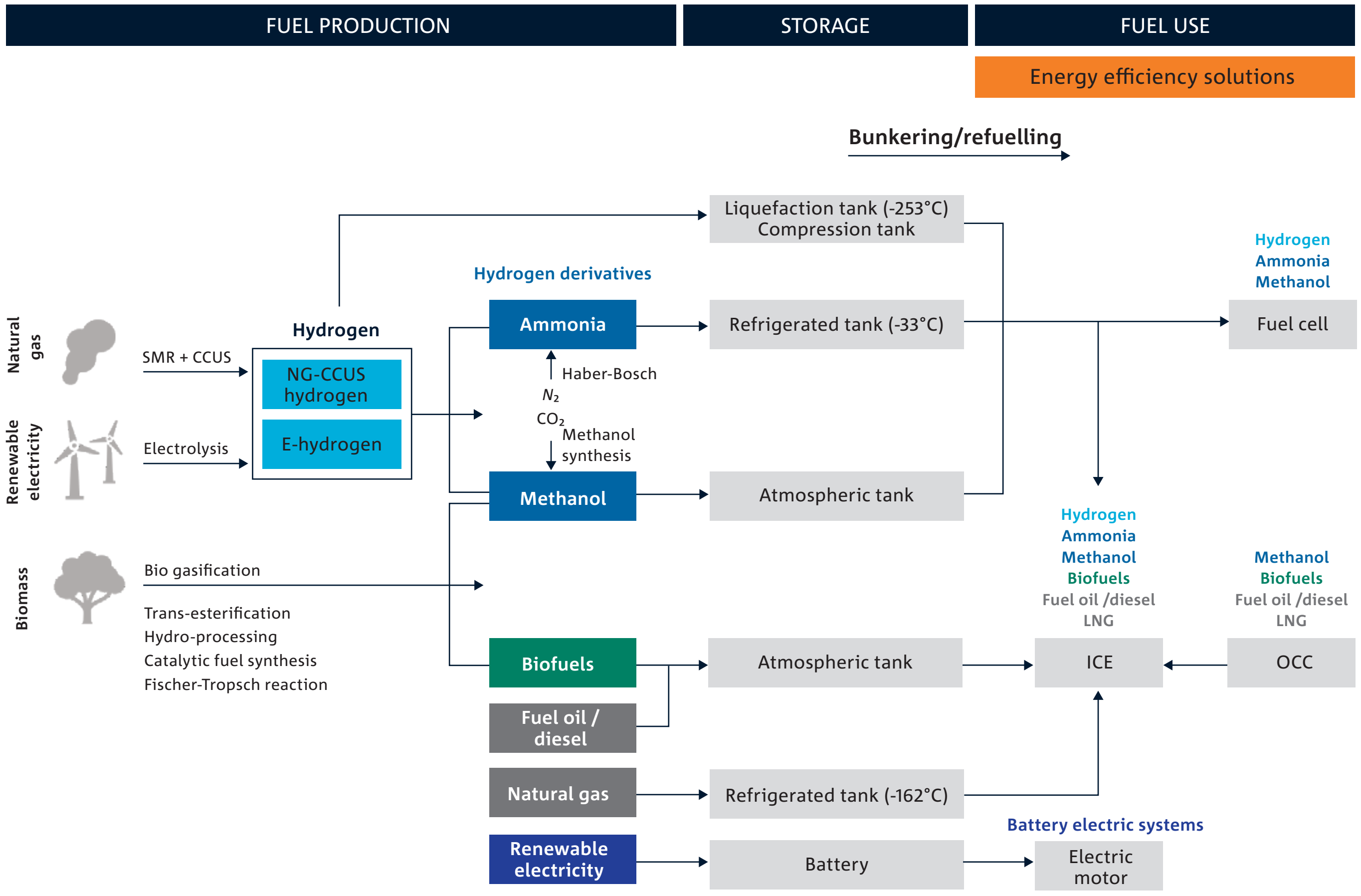

Figure 1: Supply chain for maritime and port operations

Terminology: CCUS, carbon capture, utilisation and storage; E-hydrogen, hydrogen produced from renewable electricity via electrolysis; ICE, internal combustion engine; LNG, liquefied natural gas; NG, natural gas; OCC, onboard carbon capture; SMR, steam methane reforming.

3.1 Hydrogen

Hydrogen (H_2) is one of the main options being considered to decarbonise short-sea shipping and port vehicles. The use of hydrogen in medium- to long-distance shipping will require further technological development and cost reductions. The production of renewable hydrogen (and its derivatives) also presents an economic opportunity for Australia (see Chapter 1.1).

The use of hydrogen in the maritime sector has several advantages, including its high gravimetric energy density and potential to be a zero-emissions fuel. However, there are several barriers to its uptake in the near term, with the key challenges relating to safety and the high cost of hydrogen storage.

3.1.1 Characteristics and emissions

Hydrogen is a highly flammable, colourless, odourless gas. Because of its low ignition energy, it is volatile in the air at a wide range of concentrations (4–75%). Hydrogen is also a very light gas that diffuses quickly and has a near-invisible flame when burnt.

Hydrogen emits zero direct GHG emissions from combustion, although the upstream emissions depend on the production route. These are discussed further in Chapter 3.1.2. The combustion of hydrogen will produce small amounts of other air pollutants, including NO_x and carbon monoxide.[49]

3.1.2 Production

Currently, hydrogen is primarily produced using unabated fossil-based technologies, although there is potential to be a low- or zero-emissions fuel. The main production routes are steam methane reforming (SMR) of natural gas and coal gasification. SMR of natural gas can be combined with carbon capture, utilisation and storage (CCUS) technology to reduce emissions. During industry consultations, stakeholders reported developing technologies with 60–90% capture rates. The International Energy Agency (IEA) suggests CCUS has the potential to capture 99% of CO_2 emissions.[50] However, CCUS does not address the potential for methane leakage in the production process. Hydrogen produced from renewable electricity via electrolysis (e-hydrogen) can achieve zero emissions in the production process.[51]

The high cost and lack of availability are barriers to the uptake of e-hydrogen in the maritime sector in the immediate term. Because electrolysis is an energy-intensive process, the cost of electricity is the largest driver of production costs. In addition, renewable electricity generation is currently not at the scale required to generate large quantities of e-hydrogen. An increase in the scale of renewable electricity production and improved electrolyser efficiency are necessary to lower these costs and increase hydrogen production volumes. Expenditure on capital (including electrolysers) is also a key cost driver that is expected to decrease as plant sizes increase, although the global shortage of electrolysers is another factor delaying progress.[52]

Hydrogen produced from natural gas with CCUS (NG-CCUS) is expected to be more competitive than renewable options in the near term. Although NG-CCUS hydrogen is more costly than conventional marine fuel, cost estimates are currently lower than those of hydrogen produced via electrolysis.[53] As a result, several stakeholder consultations suggested that this production route would be required in the near term to establish the hydrogen supply chain. However, there is an ongoing public concern regarding CCUS projects, stemming from an uncertainty relating to effectiveness and the potential health, safety and environmental risks from CO_2 leakage.[54] In addition, the vast majority of announced hydrogen projects in Australia are planning to produce e-hydrogen.[55]

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[49] Thepsithar P (2020) Alternative fuels for international shipping. Nanyang Technological University, Singapore; IEA (2022) Global hydrogen review 2022. <https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf> (accessed 9 January 2023).

[50] IEA (2019) The future of hydrogen: Seizing today's opportunities. <https://www.iea.org/reports/the-future-of-hydrogen> (accessed 4 June 2023).

[51] Although there are other methods of producing renewable hydrogen (including solar thermochemical, biomass gasification and methane pyrolysis with a biomass source), electrolysis has the highest level of commercial readiness, and has seen ongoing improvements in efficiency. There are also other production routes for low- or zero-emissions hydrogen (e.g. methane pyrolysis of natural gas or nuclear power); however, these processes are of lower priority and relevance to Australia. For further details on these technologies, see: KBR (2020) Study of hydrogen imports and downstream applications for Singapore. <https://www.kbr.com/en-au/insights-news/thought-leadership/study-hydrogen-imports-and-downstream-applications-singapore> (accessed 4 June 2023).

[52] Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P (2018) National hydrogen roadmap. CSIRO, Australia. IEA (2022) Electrolysers. <https://www.iea.org/reports/electrolysers> (accessed 26 June 2023).

[53] Lloyd's Register (2020) Techno-economic assessment of zero-carbon fuels. <https://www.lr.org/en/insights/global-marine-trends-2030/techno-economic-assessment-of-zero-carbon-fuels/> (accessed 10 May 2023)

[54] Greenfield C (2022) Legal and regulatory frameworks for CCUS. IEA. <https://iea.blob.core.windows.net/assets/bda8c2b2-2b9c-4010-ab56-b941dc8d0635/LegalandRegulatoryFrameworksforCCUS-AnIEACCUSHandbook.pdf> (accessed 4 May 2023).

[55] For further details, see CSIRO (2023) HyResource. <https://research.csiro.au/hyresource/> (accessed 30 August 2023).

3.1.3 Storage and refuelling

The high cost of hydrogen storage materials and the fuel's low volumetric density are significant barriers for marine applications. Hydrogen can be stored in ports and onboard vessels in tanks via compression or liquefaction (technology readiness level [TRL] 9).[56] This requires maintenance at extreme pressures or cryogenic temperatures due to hydrogen's low volumetric density of 8.5 MJ/L (Table 2). Both conditions require specific materials to maintain the necessary pressure and temperature, which have high capital costs. Liquefying hydrogen is energy intensive and requires tank materials to insulate the fuel at –253°C.[57] The compression process has a lower energy input than liquefaction, so tank materials withstand 250–700 bar pressure.

Due to the lower volumetric energy density (and insulation requirements when in liquid form), pure hydrogen requires a storage capacity that is much greater than conventional petroleum-based fuels.[58] However, the ability for frequent refuelling can reduce the requirement for storing large volumes onboard.

New infrastructure for hydrogen refuelling will need to be established to support adoption in the maritime sector. Refuelling infrastructure for hydrogen vehicles at ports is currently being explored.[59] In Singapore, PSA is working with an industry consortium on the use of hydrogen in horizontal transport at ports, including the development of a hydrogen refuel kiosk.[60] Similarly, in Australia, Coregas is developing a hydrogen refuelling station at Port Kembla for its two hydrogen FC trucks.[61]

Table 2: Fuel densities[62]

FUEL TYPE	GRAVIMETRIC ENERGY DENSITY (MJ/KG)	VOLUMETRIC ENERGY DENSITY (MJ/L)	STORAGE PRESSURE (BAR)	STORAGE TEMPERATURE (°C)
HFO	39.5	39	1	25
MGO	42.8	36.6	1	25
LNG	48.6	20.8	1	–162
Hydrogen	120	8.5	1 250–700	–253 25
Ammonia	18.9	12.7	1 10	–33 25
Methanol	20	16.2	1	25
Biodiesel	35–37	33.3	1	25

Terminology: HFO, heavy fuel oil; LNG, liquefied natural gas; MGO, marine gas oil.

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[56] Charnock S, Temminghoff M, Srinivasan V, Burke N, Munnings C, Hartley P (2019) Hydrogen research, development and demonstration: Technical repository. CSIRO, Australia.

[57] IEA (2022) Global hydrogen review 2022. <https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf> (accessed 9 January 2023).

[58] Ash N, Sikora I, Richelle B (2019) Electrofuels for shipping: How synthetic fuels from renewable electricity could unlock sustainable investment in countries like Chile. Environmental Defense Fund, London.

[59] Yang M, et al. (2022) Ammonia as a marine fuel. Nanyang Technological University, Singapore.

[60] PSA Singapore (2022) 2021: Sustainability at PSA Singapore. <https://www.singaporepsa.com/wp-content/uploads/2022/10/Sustainability-at-PSA-Singapore-2021.pdf> (accessed 13 February 2023).

[61] Coregas (2023) Port Kembla hydrogen hub. NSW. <https://portkemblahydrogenhub.com.au/app/uploads/2023/05/PKHH-Coregass-Hydrogen-Refuelling-Station.pdf> (accessed 28 June 2023); HyResource (2022) Port Kembla hydrogen refuelling facility. CSIRO. <https://research.csiro.au/hyresource/port-kembla-hydrogen-refuelling-facility/> (accessed 10 May 2023).

[62] Yang M, Ng C, Liu M (2022) Ammonia as a marine fuel. Nanyang Technological University, Singapore; Thepsithar P (2020) Alternative fuels for international shipping. Nanyang Technological University, Singapore.

Safety risks

Storing and bunkering large quantities of pure hydrogen has several safety considerations. These include its high flammability, ability to diffuse quickly, lack of odour and near-invisible flame when burnt. Therefore, when there is a hydrogen leak, it is difficult to detect, and there is an increased risk of ignition (although proper ventilation or odour additives can mitigate this risk).[63] Furthermore, hydrogen stored under pressure presents a high risk of explosion. The challenges with maintaining cryogenic temperatures or pressurised conditions and mitigating leakage risk are areas to be addressed in developing new bunkering procedures.[64]

3.1.4 Use

Vessel power systems

The two main options for hydrogen power systems onboard vessels are ICEs and fuel cells (FCs). FCs convert chemical energy from the fuel into electrical energy through an electrochemical reaction.[65] Although less suitable for large vessels compared with ICE technology, FCs are being considered for use in small- to medium-sized vessels.

Given that hydrogen storage is a challenge, there has been more development in four-stroke hydrogen-compatible engines (TRL 6–7) for short-sea vessels than two-stroke engines for deep-sea vessels.[66] MAN Energy Solutions is developing a dual-fuel four-stroke hydrogen and diesel ICE, with a goal of eventually developing a 100% hydrogen engine (although this is not expected to be commercially available until after 2030).[67]

For the short-sea shipping segment, hydrogen FC development is further advanced than four-stroke ICEs (TRL 8 for the most mature technologies). There are several FC technologies, such as proton-exchange membrane (PEMFC), solid oxide (SOFC) and molten carbonate (MCFC). These FC technologies demonstrate higher efficiencies than ICEs, potentially reaching 80% with heat recovery processes incorporated.[68] Shell, Penguin and Sembcorp Marine are trialling a hydrogen FC technology on a RoRo vessel in Singapore.[69] Similarly, in Tasmania, Incat is designing an electric and hydrogen FC RoPax vessel (a RoRo vessel that has passenger-carrying capacities).[70]

The cost of capital will remain a barrier to uptake in the near term. A study by KBR suggests that in Singapore (in the absence of carbon pricing), hydrogen-powered tugboats will not be cost competitive with conventional fuel alternatives until 2030, with other types of harbour craft remaining uncompetitive until 2050.[71]

Safety risks

The safety risks associated with the use of hydrogen also has implications for onboard operations. In particular, there is a knowledge gap regarding hydrogen fire and explosion behaviour in fuel cells onboard vessels. As a result, further understanding of dispersion scenarios, ventilation requirements and materials requirements (e.g. double piping) is needed. In addition, mitigation methods such as gas detection and emergency shutdown systems need to be put in place.[72]

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63 DNV (2022) National gas decarbonisation plan. <https://www.energynetworks.com.au/resources/reports/2022-reports-and-publications/national-gas-decarbonisation-plan-dnv-report/> (accessed 1 June 2023).

64 Tronstad T, Åstrand HH, Haugom GP, Langfeldt L (2017) Study on the use of fuel cells in shipping. EMSA. <https://www.emsa.europa.eu/publications/item/2921-emsa-study-on-the-use-of-fuel-cells-in-shipping.html> (accessed 4 May 2023).

65 Liu M, et al. (2020) A study on the future energy options of Singapore Harbour craft. Nanyang Technological University, Singapore.

66 Ovrum E, Longva T, Hammer L, Rivedal N, Endresen O, Eide M (2022) Maritime forecast to 2050. DNV. <https://www.dnv.com/maritime/publications/maritime-forecast-2022/index.html> (accessed 5 June 2023).

67 MAN Energy Solutions (2021) H2 – key player in the maritime energy transition. <https://www.man-es.com/marine/strategic-expertise/future-fuels/hydrogen> (accessed 31 January 2023).

68 Liu M, et al. (2020) A study on the future energy options of Singapore Harbour craft. Nanyang Technological University, Singapore; Ovrum E, et al. (2022) Maritime forecast to 2050. DNV. <https://www.dnv.com/maritime/publications/maritime-forecast-2022/index.html> (accessed 5 June 2023

69 Sembcorp Marine (2021) Towards a decarbonised future: Sembcorp Marine, Shell and Penguin International sign MoU for hydrogen-powered vessel. <https://www.sembmarine.com/2021/04/21/towards-a-decarbonised-future-sembcorp-marine-shell-and-penguin-international-sign-mou-for-hydrogen-powered-vessel> (accessed 16 May 2023).

70 Incat (2021) Incat electric: The back to zero revolution. <https://www.incat.com.au/wp-content/uploads/2021/08/Back-to-ZERO-Flyer.pdf> (accessed 10 May 2023).

71 KBR (2020) Study of hydrogen imports and downstream applications for Singapore. <https://www.kbr.com/en-au/insights-news/thought-leadership/study-hydrogen-imports-and-downstream-applications-singapore> (accessed 5 June 2023).

72 Tronstad T, Åstrand HH, Haugom GP, Langfeldt L (2017) Study on the use of fuel cells in shipping. EMSA. <https://www.emsa.europa.eu/publications/item/2921-emsa-study-on-the-use-of-fuel-cells-in-shipping.html> (accessed 4 May 2023).

Port operations

Hydrogen FCs are expected to be integrated into port vehicles and machinery in the medium to long term, with electrification being the leading technology in the near term (see Chapter 3.5.2).[73] As mentioned in Chapter 3.1.3, PSA Singapore and Port Kembla in Australia have plans to demonstrate hydrogen FC trucks.

Regulations

Although there are national regulations for the handling and transfer of hydrogen, further development is required on regulations or guidelines for hydrogen use in vessels and bunkering.[74] Singapore currently regulates hydrogen as a dangerous substance rather than a fuel or energy carrier.[75] *Singapore's National Hydrogen Strategy* suggests a need to work with industry to develop new standards and regulations for bunkering hydrogen (and derivatives).[76] In Australia, there has been some progress in standards development, with AMSA releasing updates to their policy on 'novel vessels' (including hydrogen vessels), which requires a risk assessment and demonstration that the system meets functional and safety requirements.[77] In addition, the Department of Climate Change, Energy, Environment and Water (DCCEEW) is undertaking a review of Australia's regulatory frameworks to support the uptake of hydrogen across sectors. This will include regulatory guidance to address barriers to investing in Australia's hydrogen industry.[78]

Further standards development for vessel power systems is required at the international level in cases where national standards do not apply. The IMO is in the process of developing interim guidelines for the use of FCs in vessels as part of amendments to the *International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels* (IGF code). Although these guidelines include installation of the FC, they do not include the fuel supply or storage. Hence, if the fuel is not already covered in the IGF code (which hydrogen currently is not), the system must undergo the alternative design approach, meaning each case must demonstrate that its design meets an equivalent level of safety.[79]

3.2 Ammonia

Ammonia is considered one of the most viable solutions to decarbonise the maritime sector. Ammonia has the potential to be a zero-emissions fuel, and, given its end uses in agriculture, the processes for its production, handling, storage and transport are well established.

However, there are several significant challenges to facilitating ammonia uptake in the maritime sector. Because ammonia has a lower volumetric energy density than conventional fuels, there is a greater storage requirement. In addition, ammonia's toxicity poses a risk to crew and marine ecosystems in the event of leakage. Further, although ammonia engines are being developed, they are not currently commercially available. As a result, onboard use and bunkering are yet to be demonstrated, which will be important for establishing social licence.

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[73] KBR (2020) Study of hydrogen imports and downstream applications for Singapore. <https://www.kbr.com/en-au/insights-news/thought-leadership/study-hydrogen-imports-and-downstream-applications-singapore> (accessed 5 June 2023).

[74] DNV (2022) Hydrogen forecast to 2050. <https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050.html> (accessed 5 June 2023); Wilson D (2020) Hydrogen in the maritime sector. Hydrogen Council. <https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Symposium%202021/Presentations/Second%20day%20-%20Blocks%203%20and%204/Block%203.4%20-%20Daryl%20Wilson_Hydrogen%20in%20the%20maritime%20sector.pdf> (accessed 10 May 2023).

[75] K&L Gates (2021) Singapore: The H2 Handbook. <https://marketingstorageragrs.blob.core.windows.net/webfiles/Hydrogen-Handbook-SINGAPORE.pdf> (accessed 8 May 2023).

[76] Ministry of Trade and Industry Singapore (2022) Singapore's National Hydrogen Strategy. <https://www.mti.gov.sg/Industries/Hydrogen> (accessed 30 August 2023).

[77] AMSA (2023) National standard for commercial vessels (NSCV). <https://www.amsa.gov.au/about/regulations-and-standards/national-standard-commercial-vessels-nscv> (accessed 10 May 2023).

[78] DCCEEW (2023) Improving Australia's hydrogen regulation. <https://www.dcceew.gov.au/energy/hydrogen#toc_6> (accessed 30 August 2023).

[79] IMO (2021) Sub-committee on carriage of cargoes and containers, 7th session (CCC 7), 6–10 September 2021. [Meeting summary] <https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/CCC-7th-session.aspx> (accessed 10 May 2023); Tronstad T, et al. (2017) Study on the use of fuel cells in shipping. EMSA. <https://www.emsa.europa.eu/publications/item/2921-emsa-study-on-the-use-of-fuel-cells-in-shipping.html> (accessed 4 May 2023).

3.2.1 Characteristics and emissions

Ammonia (NH_3) is a hydrogen derivative that is gaseous under atmospheric conditions. Ammonia is considered toxic to both human health and aquatic life following exposure (at certain concentrations and durations). It has a high ignition temperature compared with hydrogen and conventional fuels, and a lower flammability risk. Ammonia is an input into fertiliser for the agricultural sector, and therefore its production, handling, storage and transport processes are well established.

Like hydrogen, ammonia emits zero CO_2 during combustion. However, upstream emissions will depend on the production route for the hydrogen input. In addition, there is also the potential for other emissions during the combustion process, including NO_x and N_2O (a potent GHG with 300-fold the warming potential of CO_2).[80]

3.2.2 Production

Ammonia is currently produced from unabated fossil fuel-based hydrogen (mainly from SMR). However, ammonia production can also draw on NG-CCUS hydrogen or e-hydrogen, as described in Chapter 3.1.2. The challenges associated with e-hydrogen production processes also apply to the production of e-ammonia, including the limited supply and cost of renewable electricity, as well as the scarcity of electrolysers for hydrogen production. Electricity makes up a large share of the total cost of ammonia production because it is needed not only for hydrogen production, but also to power the conversion of hydrogen to ammonia (Haber–Bosch process), which is highly energy intensive. Alternative pathways, such as direct synthesis, are being developed but have a TRL of below 3 (direct synthesis only requires nitrogen and water input, thereby removing the requirement for hydrogen).[81]

Despite the challenges, various e-ammonia projects are currently in the planning phase, with current proposals estimated to eventually provide 52 Mt of annual production capacity.[82] For example, InterContinental Energy, CWP Global and Mirning Green Energy Limited have announced plans for the Western Green Energy Hub in south-east Western Australia. The hub will be developed over a 15-year period and will aim to produce 3.5 Mt of e-hydrogen, or approximately 20 Mt of e-ammonia, per year.[83]

3.2.3 Storage and bunkering

Because ammonia is already a commercial export, the storage technologies required for trading are well established. Ammonia is generally stored in its liquid state using refrigerated tanks, at around –33°C, given that this is safer and lower cost than pressurised storage.[84] Because the existing port infrastructure for LNG has refrigeration technology, this can be retrofitted to suit the storage of ammonia.[85]

Additional quantities of ammonia would need to be stored onboard and in port areas to meet the expected demand for low-emissions fuel use in shipping. Due to ammonia's lower energy density of 12.7 MJ/L (compared with 39 MJ/L for HFO; Table 2) and the insulation requirements, it is estimated that around four times the storage volume will be required for ammonia relative to MGO.[86] This presents a challenge to the Port of Singapore, which has limited land area to integrate more infrastructure. There may also be limits to the safe storage of ammonia due to safety buffer zone requirements.[87] As a result, stakeholder consultations indicated that greater certainty on future fuels is required before making large investments in storage infrastructure, which has an approximate lifetime of 25–30 years.
For onboard fuel storage, the lower energy density of ammonia could reduce cargo space, and therefore revenue. However, adjustments to vessel design or the frequency of bunkering cycles can mitigate the degree of this challenge.

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[80] Chrobak U (2021) The world's forgotten greenhouse gas. BBC. <https://www.bbc.com/future/article/20210603-nitrous-oxide-the-worlds-forgotten-greenhouse-gas> (accessed 1 June 2023).

[81] Bruce S, et al. (2018) National hydrogen roadmap. CSIRO, Australia; Yang M, et al. (2022) Ammonia as a marine fuel. Nanyang Technological University, Singapore.

[82] Boyland J, et al. (2023) Fuelling the decarbonisation of iron ore shipping between Western Australia and East Asia with clean ammonia. Global Maritime Forum. <https://cms.globalmaritimeforum.org/wp-content/uploads/2023/05/GMF_WA-East-Asia-Iron-Ore-Green-Corridor-Feasibility-Study.pdf> (accessed 1 June 2023).

[83] HyResource (2022) Western green energy hub. CSIRO. <https://research.csiro.au/hyresource/western-green-energy-hub/> (accessed 1 June 2023).

[84] Yang M, et al. (2022) Ammonia as a marine fuel. Nanyang Technological University, Singapore.

[85] Kastner L, Luo L, Maroti S, Tsai E, Zhang W (2020) Zero-carbon fuels for marine shipping. Columbia | SIPA. <https://cdn.catf.us/wp-content/uploads/2020/06/21092831/2020_SIPA_Zero-Carbon-Shipping.pdf> (accessed 5 June 2023).

[86] Ash N, Sikora I, Richelle B (2019) Electrofuels for shipping: How synthetic fuels from renewable electricity could unlock sustainable investment in countries like Chile. Environmental Defense Fund, London.

[87] Safety buffer zones consider the safe distance in a worst-case scenario without mitigation strategies. These zones vary from 84 m to 1.3 km depending on modelling conducted from different points of bunkerage. The larger distances are not possible at ports: Yang M, et al. (2022) Ammonia as a marine fuel. Nanyang Technological University, Singapore.

Ports are considering several options to facilitate the greater storage requirement associated with ammonia. Common infrastructure has been suggested to reduce the overall required area and cost for each operator. However, there could be issues with coordination and collaboration between users.[88] Offshore options, such as floating platforms with storage and recharging infrastructure, were suggested during stakeholder consultations as alternative solutions. A Japanese consortium including NYK Line, is developing such an offshore platform that can store ammonia (in addition to other functions).[89] However, during the Singapore workshop discussion, it was also noted that floating platforms would present planning and logistical challenges, given the large amount of traffic at the Port of Singapore.

Safety risks

Given the safety risks associated with ammonia, additional procedures will likely be required to prevent and mitigate the impact of leaks during the bunkering process. Research on the appropriate methods for bunkering ammonia is in the early stages and yet to be demonstrated. However, several studies are currently being conducted.

Nanyang Technological University has conducted a bunkering safety study that modelled bunkering configurations (including ship-to-ship), estimated the potential impact of ammonia release and reviewed relevant mitigation options, such as water curtains, foams, solid barriers or air curtains.[90] The SABRE project and Castor Initiative are other projects being conducted on ammonia bunkering.[91]

The GCMD released an ammonia bunkering safety study in partnership with DNV and Jurong Port that outlined suitable sites, operations and risks for bunkering pilot trials in Singapore.[92] Of the identified risks, most were classified as medium and mitigable, with none classified as high. The study estimated that a 150m-320m safety zone around bunkering trials would be required until further regulations are in place. Due to Singapore's proximity to a dense population and high water traffic movements, it is likely that these recommendations are conservative and could therefore be applied to less-crowded ports.[93]

3.2.4 Use

Vessel power systems

Ammonia ICEs do not emit CO_2 during combustion; however, there is the potential for NO_x and N_2O emissions (with the latter estimated to have around 300 times the warming potential of CO_2). Technology to minimise the NO_x and N_2O emissions from engine combustion, such as scrubbers or selective catalytic reduction (SCR) systems, will be necessary before ammonia can be rolled out commercially.[94] One recent study suggests that although small amounts of N_2O could have a large impact, N_2O levels above 0.06 g/kWh (equivalent to 2 gCO_2e/MJ or 3% of the CO_2e emissions of VLSFO) are unlikely to be accepted by manufacturers of ammonia ICEs.[95]

There will likely be ongoing CO_2 emissions from ammonia-powered vessels in the short term given another pilot fuel (such as diesel) is needed to trigger the ignition.[96] Although the first engines will include 20–30% pilot fuel in overall fuel use,[97] stakeholder consultations have suggested this share could be reduced to 1%, and draw on low-emissions fuels (such as biofuels or hydrogen) as the pilot fuel.

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[88] Cahill A, Allison J, Heck A, Lumsden L (2022) Gladstone region economic transition roadmap. The Next Economy. <https://nexteconomy.com.au/work/gladstone-regions-economic-transition-10-year-roadmap/#:~:text=The%20Gladstone%20Region%20Economic%20Transition,over%20the%20next%2010%20years.> (accessed 5 June 2023).

[89] NYK Line (2023) Parties obtain world's first AiP for ammonia floating storage and regasification barge. [Press release] <https://www.nyk.com/english/news/2023/20230105_01.html> (accessed 10 May 2023).

[90] Yang M, et al. (2022) Ammonia as a marine fuel. Nanyang Technological University, Singapore.

[91] Sumitomo (2022) Project SABRE. <https://www.sumitomocorp.com/jp/-/media/Files/hq/news/release/2022/15790/01> (accessed 10 May 2023); Lloyd's Register (2021) Unveiling the Castor Initiative. <https://www.lr.org/en/latest-news/unveiling-the-castor-initiative/> (accessed 1 December 2022).

[92] Global Centre for Maritime Decarbonisation (2023) Ammonia bunkering pilot safety study. <https://www.gcformd.org/ammonia-bunkering-safety-study> (accessed 1 May 2023).

[93] Six S (2023) Singapore moves towards ship-to-ship ammonia bunkering. Argus Media. <https://www.argusmedia.com/en/news/2443494-singapore-moves-towards-shiptoship-ammonia-bunkering> (accessed 5 May 2023).

[94] Yang M, et al. (2022) Ammonia as a marine fuel. Nanyang Technological University, Singapore; Wärtsilä (2023) Wärtsilä exhaust treatment – a futureproofed compliance solution. <https://www.wartsila.com/marine/products/exhaust-treatment> (accessed 5 June 2023).

[95] Mærsk Mc-Kinney Møller Center (2023) Managing emissions from ammonia-fuelled vessels. <https://cms.zerocarbonshipping.com/media/uploads/documents/Ammonia-emissions-reduction-position-paper_v4.pdf> (accessed 5 May 2023).

[96] Castellanos G, Roesch R, Sloan A (2021) A pathway to decarbonise the shipping sector by 2050. IRENA. <https://www.irena.org/publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050> (accessed 5 June 2023).

[97] Wärtsilä (2022) Wärtsilä coordinates EU funded project to accelerate ammonia engine development. [Press release] <https://www.wartsila.com/media/news/05-04-2022-wartsila-coordinates-eu-funded-project-to-accelerate-ammonia-engine-development-3079950#:~:text=Wärtsilä%20coordinates%20EU%20funded%20project%20to%20accelerate%20ammonia%20engine%20development,-Wärtsilä%20Corporation%2C%20Trade&text=A%20powerful%20consortium%20of%20shipping,viable%20concepts%20for%20ammonia%20fuel.> (accessed 10 May 2023).

Both two- and four-stroke ammonia ICEs are currently being developed (TRL 5–6), enabling the use of ammonia in both large, deep-sea vessels and smaller vessels.[98] Some early-stage projects are working on the development of a two-stroke ammonia ICE for deep-sea use. MAN Energy is due to release its two-stroke ammonia ICE in 2024, which will be capable of operating on several fuels.[99] WinGD and CMB.TECH are developing a two-stroke dual-fuelled diesel–ammonia engine to power a series of bulk carriers, with plans for construction in 2025 and 2026.[100] Although ammonia ICEs are expected to mature in the next decade, the current lack of commercial maturity presents a barrier to adoption.[101]

Although ammonia ICE technology may be less suited to short-sea shipping, solutions for small vessels are being developed.[102] Stakeholder consultations suggested that it may not be possible to meet the safety requirements (such as ventilation) for smaller vessels given the fuel tanks are expected to take up more space onboard. Despite this, Wärtsilä is developing a four-stroke engine capable of operating on diesel or LNG that can be upgraded to run on ammonia.[103] Ammonia FCs, which have greater efficiency, could also be a viable option for short-sea vessels.[104] Many FCs require the conversion of ammonia to hydrogen before input into the system; however, there are options for direct ammonia FCs (TRL 6).[105] In a pilot project, the Norwegian vessel *Viking Energy* is planned to be retrofitted with a direct ammonia solid oxide FC (SOFC).[106]

Safety risks

The potential for onboard ammonia leakage presents a risk to human safety and the marine environment. To ensure the safe storage and transport of ammonia, adequate detection tools and mitigation strategies need to be in place in case leakage occurs.[107] Some of this work is already underway in other countries. Lloyd's Register Maritime Decarbonisation Hub and the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping have conducted quantitative risk assessments for ammonia-fuelled vessels. The studies found that engineering officers are at highest individual risk due to their time spent in the fuel preparation and engineering control rooms. A number of measures were identified to minimise these risks, including adequate ventilation systems, reducing the period of time exposed to ammonia equipment and installing multiple types of sensors.[108] Furthermore, the NoGAPS project is designing an ammonia-powered vessel that will also be a carrier of ammonia cargo to test and establish the safety protocols and risk reduction measures required in the future.[109]

Ammonia leakages also present a risk to the marine environment. Lloyd's Register Maritime Decarbonisation Hub and the Environmental Defense Fund conducted an environmental assessment on the impacts of an onboard ammonia leak on marine life. This assessment found that although ammonia could have a similar or lesser impact on some marine life compared with oil spills, it could have a larger impact on others (particularly fish).[110]

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[98] Ovrum E, et al. (2022) Maritime forecast to 2050. DNV. <https://www.dnv.com/maritime/publications/maritime-forecast-2022/index.html> (accessed 5 June 2023).

[99] Lindstrand N. Unlocking ammonia's potential for shipping. MAN Energy Solutions. <https://www.man-es.com/discover/two-stroke-ammonia-engine> (accessed 10 May 2023).

[100] WinGD (2023) WinGD and CMB.TECH co-develop large ammonia-fuelled engines. [Press release] WinGD. <https://www.wingd.com/en/news-media/press-releases/wingd-and-cmb-tech-co-develop-large-ammonia-fuelled-engines/> (accessed 15 February 2023).

[101] A.P. Moller–Maersk (2022) ESG investor day 2022. <https://investor.maersk.com/static-files/4f208034-a546-46aa-b47b-806108bac9f3> (accessed 5 May 2023).

[102] Liu M, et al. (2020) A study on the future energy options of Singapore Harbour Craft. Nanyang Technological University, Singapore.

[103] Wärtsilä (2022) Launch of Wärtsilä 25 engine paves the way towards maritime decarbonisation. [Press release] <https://www.wartsila.com/media/news/07-09-2022-launch-of-wartsila-25-engine-paves-the-way-towards-maritime-decarbonisation-3152432> (accessed 15 February 2023).

[104] Ovrum E, et al. (2022) Maritime forecast to 2050. DNV. <https://www.dnv.com/maritime/publications/maritime-forecast-2022/index.html> (accessed 5 June 2023); Jeerh G, Zhang M, Tao S (2020) Recent progress in ammonia fuel cells and their potential applications. Journal of Materials Chemistry A 9(2), 727–752.

[105] Liu M, et al. (2020) A study on the future energy options of Singapore harbour craft. Nanyang Technological University, Singapore.

[106] Viking Energy (2020) Ship FC: Green ammonia energy system. <https://shipfc.eu/almas-marine-fuel-cell-system-awarded-approval-in-principle-by-dnv/> (accessed 6 January 2023).

[107] Yang M, et al. (2022) Ammonia as a marine fuel. Nanyang Technological University, Singapore.

[108] Franks AP, Graugaard C (2022) Quantitative risk assessment of ammonia-fuelled vessels. [Conference paper] Lloyd's Register Maritime Decarbonisation Hub. <https://www.lr.org/en/marine-shipping/maritime-decarbonisation-hub/about/our-story/research-library/conference-paper-quantitative-risk-assessment-of-ammonia-fuelled-vessels/> (accessed 5 June 2023); Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (2023) Recommendations for design and operation of ammonia-fueled vessels based on multi-disciplinary risk analysis. <https://cms.zerocarbonshipping.com/media/uploads/documents/LR-Ammonia-Report-v3.pdf> (accessed 30 June 2023).

[109] Fahnestock J, Sogaard K, Lawson E, Kilemo H (2021) NoGAPS: Nordic green ammonia powered ship: Project report. Nordic Innovation. <https://cms.zerocarbonshipping.com/media/uploads/documents/Nordic-Green-Ammonia-Powered-Ship-NoGAPS_final.pdf> (accessed 15 May 2023).

[110] Dawson L, Ware J, Vest L (2022) Ammonia at sea: studying the potential impact of ammonia as a shipping fuel on marine ecosystems. Environmental Defense Fund. <https://www.edfeurope.org/sites/euroedf/files/EDF-Europe-Ammonia-at-sea-FullReport.pdf> (accessed 23 February 2023).

Regulations

In Australia, ammonia is covered by AMSA's policy on 'novel vessels', which requires a risk assessment and demonstration that the system meets safety requirements.[111] Ammonia is also covered in the hydrogen regulatory guidelines that are currently being developed by DCCEEW.[112] Although regulations for vessels using ammonia have not been established in Singapore, these could be adopted through IMO conventions.[113]

The IMO is in the process of developing interim guidelines for ammonia use.[114] In particular, requirements may be amended in the IGF Code.[115] This will provide more clarity and certainty for investors to explore ammonia-powered vessels.

3.3 Methanol

Methanol is another hydrogen carrier that is being closely considered to reduce emissions in the maritime sector. Its handling is well established because methanol is traded globally for use in the chemical industry. Methanol can have net zero GHG emissions across its life cycle and does not have the same safety concerns associated with hydrogen or ammonia. The power systems for deep-sea vessels are also more developed than those for ammonia, with the first two-stroke ICEs due to be delivered in 2024.[116]

However, there are also barriers to the adoption of methanol. Producing e-methanol faces the critical challenge of sourcing and certifying renewable CO_2, whether from direct air capture (DAC) or biomass feedstocks. This certification is essential for ensuring that the use of e-methanol is carbon neutral in the long term. In addition, similar to ammonia, additional storage space is required for methanol onboard vessels and in ports due to its lower volumetric energy density than conventional fuels.

3.3.1 Characteristics and emissions

Methanol (CH_3OH) is a hydrogen derivative that exists in liquid form at ambient conditions. Methanol has a low flashpoint of 11°C–12°C, making it a more flammable fuel than MGO and ammonia, but less flammable than hydrogen. It can be corrosive to certain materials, such as carbon steel.[117] It is also toxic if inhaled or swallowed, but buffer zones are not mandated for mitigation.[118]

Methanol produces CO_2 and NO_x emissions when combusted. While it has the potential to be a net zero-emissions fuel, given that methanol production requires a CO_2 input, there are arguments that the process can only be truly carbon neutral if it draws on renewable CO_2 (defined below).

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[111] AMSA (2023) National standard for commercial vessels (NSCV). <https://www.amsa.gov.au/about/regulations-and-standards/national-standard-commercial-vessels-nscv> (accessed 10 May 2023).

[112] DCCEEW (2023) Improving Australia's hydrogen regulation. <https://www.dcceew.gov.au/energy/hydrogen#toc_6> (accessed 30 August 2023).

[113] Yang M, et al. (2022) Ammonia as a marine fuel. Nanyang Technological University, Singapore.

[114] Bakhsh N (2022) IMO to develop safety guidelines for ammonia and hydrogen. Lloyd's List. <https://lloydslist.maritimeintelligence.informa.com/LL1142303/IMO-to-develop-safety-guidelines-for-ammonia-and-hydrogen> (accessed 5 May 2023).

[115] IMO. International code of safety for ship using gases or other low-flashpoint fuels (IGF Code). <https://www.imo.org/en/OurWork/Safety/Pages/IGF-Code.aspx> (accessed 10 May 2023).

[116] A.P. Moller–Maersk (2022) Sustainability report 2022. Maersk. <https://www.maersk.com/sustainability/our-approach/strategy> (accessed 25 February 2023); Ovrum E, et al. (2022) Maritime forecast to 2050. DNV. <https://www.dnv.com/maritime/publications/maritime-forecast-2022/index.html> (accessed 5 June 2023).

[117] Thepsithar P (2020) Alternative fuels for international shipping. Nanyang Technological University, Singapore.

[118] DNV (2022) Alternative fuels for containerships: Methanol and LNG. DNV. <https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-methanol-download.html> (accessed 10 May 2023).

3.3.2 Production

Methanol requires a source of hydrogen and CO_2. Commercial methods for methanol synthesis use unabated fossil fuels (natural gas and coal) to produce hydrogen and carbon.[119] CCUS technologies can be integrated into the hydrogen production process, but this does not lead to a material reduction in CO_2 emissions.[120] Methanol must be produced using renewable resources to achieve large emissions reductions in the long term. There are two key renewable production routes:

- E-methanol: Using hydrogen produced with renewable electricity and renewable CO_2, this has the potential to be carbon neutral. The CO_2 could be sourced via DAC or bioenergy with carbon capture (with the latter referred to as 'power-and biomass-to-liquid' [PBtL]).
- Bio-methanol: Using biomass gasification or biogas conversion. Biomass feedstocks include forest residues, agricultural waste and by-products and municipal solid waste.

DAC (TRL 6) is a more costly and earlier stage technology than biomass with carbon capture, but is likely to have higher scalability. DAC is more energy intensive than traditional carbon capture at point sources and is therefore more expensive.[121] Heat recovery (potentially from methanol synthesis) to power DAC can reduce power requirements and cost.[122] Further technological improvements are necessary for DAC to increase capture efficiency and become commercially operational.

Although bioenergy with carbon capture is lower cost than DAC, there are challenges relating to limited biomass feedstock availability.[123] Despite this, stakeholder consultations indicated that using biomass in the short term could be beneficial in developing methanol supply chains. ABEL Energy in Tasmania, Australia, is developing an e-methanol production plant as part of an MoU collaboration with the Port of Melbourne.[124] ABEL Energy plans to use established renewable electricity resources for hydrogen production and second-generation biomass to produce CO_2 while DAC technology is still being developed. This plant is expected to produce 226 t of e-methanol per day.[125]

Another method for producing e-methanol, which could lead to emissions reductions in the short term, involves drawing on e-hydrogen and carbon capture from an industrial point source. For example, Vast Solar has announced plans to develop a solar methanol production facility, drawing on concentrated solar thermal to produce hydrogen and a co-located lime plant for the supply of captured CO_2 (from unavoidable process emissions).[126]

3.3.3 Storage and bunkering

Like ammonia, a larger footprint is required for methanol than for conventional fuels to store the same energy content. Methanol has a relatively low volumetric energy density of 16.2 MJ/L, which is less than half that of MGO (Table 2). As a result, methanol requires a storage footprint of at least two times that of MGO.[127] This has the potential to reduce the space available for cargo unless there are adjustments to vessel design or bunkering cycles.

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[119] IRENA, Methanol Institute (2021) Innovation outlook: Renewable methanol. IRENA. <https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol> (accessed 5 June 2023).

[120] Martin A (2021) A step forward for 'green' methanol and its potential to deliver deep GHG reductions in maritime shipping. ICCT. <https://theicct.org/a-step-forward-for-green-methanol-and-its-potential-to-deliver-deep-ghg-reductions-in-maritime-shipping%E2%80%AF/> (accessed 1 June 2023).

[121] Budinis S (2022) Direct air capture. IEA. <https://www.iea.org/reports/direct-air-capture> (accessed 11 January 2023); Baylin-Stern A, Berghout N (2021) Is carbon capture too expensive? IEA. <https://www.iea.org/commentaries/is-carbon-capture-too-expensive> (accessed 11 January 2023).

[122] IEA (2022) Direct air capture. <https://iea.blob.core.windows.net/assets/78633715-15c0-44e1-81df-41123c556d57/DirectAirCapture_Akeytechnologyfornetzero.pdf> (accessed 1 June 2023).

[123] IRENA, Methanol Institute (2021) Innovation outlook: Renewable methanol. IRENA. <https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol> (accessed 5 June 2023).

[124] Port of Melbourne (2023) Green methanol MoU signed with Melbourne port. [Media Release] <https://www.portofmelbourne.com/green-methanol-mou-signed-with-melbourne-port/> (accessed 9 June 2023).

[125] ABEL Energy (2022) Knowledge-sharing report. <https://abelenergy.com.au/knowledge-sharing-report> (accessed 10 May 2023).

[126] HyResource (2023) SM1. CSIRO. <https://research.csiro.au/hyresource/sm1/> (accessed 1 June 2023).

[127] Ash N, Sikora I, Richelle B (2019) Electrofuels for shipping: How synthetic fuels from renewable electricity could unlock sustainable investment in countries like Chile. Environmental Defense Fund, London; KBR (2020) Study of hydrogen imports and downstream applications for Singapore. <https://www.kbr.com/en-au/insights-news/thought-leadership/study-hydrogen-imports-and-downstream-applications-singapore> (accessed 5 June 2023).

Because methanol exists in liquid form under ambient conditions, there are no significant challenges to storing and bunkering this fuel. As an exported commodity, the storage solutions are well established. In addition, for use as a marine fuel, operating LNG and diesel tanks can safely use methanol fuel without major upgrades required.[128] This compatibility with existing infrastructure will also allow the bunkering of methanol to have similar processes to conventional marine fuels and increase the ease of multi-fuel adoption in ports. However, there does need to be a consideration when choosing materials for tanks and bunker hoses because methanol can corrode carbon steel over time.[129]

3.3.4 Use

Vessel power systems

Methanol two-stroke engines are commercially available, making methanol a suitable option for deep-sea shipping in the near term. To power ships, dual-fuel ICEs, running partially on methanol, are becoming increasingly popular in newbuilds. These engines allow for a continuation of fossil fuel use before renewable fuel becomes more widely available. A.P. Moller–Maersk has ordered a total of 19 two-stroke dual-fuelled methanol-enabled vessels, set to be delivered in 2024 and 2025.[130] The order from such a large company has signalled the demand for renewable methanol to the industry more broadly, enabling the upstream investment in production processes with more confidence. For the short-sea shipping segment, methanol four-stroke ICEs are expected to be available in 2024.[131] However, with less cargo space available for fuel tanks, the issues with storage space requirements onboard vessels are greater for small vessels.

Methanol-powered FCs have a lower readiness level (TRL 5) than ICEs and are not expected to be commercially available until at least 2030.[132] Direct methanol fuel cells (DMFCs) currently have low efficiencies of around 20%.[133] However, there are FCs available which can convert methanol to hydrogen and achieve higher efficiency (SOFCs and MCFCs have an estimated efficiency of around 50–60%, and can achieve up to 85% with heat recovery). These FC systems are relatively large and costly, and so may be better suited to larger vessels with lower capacity constraints.[134]

Onboard operations

Safety considerations for the onboard handling and use of methanol will have similar guidelines and processes to existing fuels, which will need to be integrated into bunkering protocols and training procedures. Given that methanol is toxic if inhaled or swallowed, proper ventilation and mitigation measures need to be in place onboard to minimise this risk.[135]

Regulations

The recent development of maritime regulations for methanol use are facilitating its adoption in shipping. The IMO released interim international guidelines for the safe use of methanol as a fuel in ships that include considerations for equipment, bunkering, monitoring systems and fire safety control measures.[136] This provides the enabling regulatory landscape for vessel designers, builders and operators to invest in methanol-fuelled ships.

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[128] Castellanos G, et al. (2021) A pathway to decarbonise the shipping sector by 2050. IRENA. <https://www.irena.org/publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050> (accessed 5 June 2023).

[129] Liu M, Li C (2021) Methanol as a marine fuel. Nanyang Technological University, Singapore.

[130] A.P. Moller–Maersk (2022) 2022 Sustainability report. Maersk. <https://www.maersk.com/sustainability/our-approach/strategy> (accessed 25 February 2023).

[131] MAN Energy Solutions (2021) MAN Energy solutions upgrading four-stroke engines for green future-fuels. <https://www.man-es.com/company/press-releases/press-details/2021/11/29/man-energy-solutions-upgrading-four-stroke-engines-for-green-future-fuels> (accessed 1 June 2023).

[132] Ovrum E, et al. (2022) Maritime forecast to 2050. DNV. <https://www.dnv.com/maritime/publications/maritime-forecast-2022/index.html> (accessed 5 June 2023).

[133] IMO (2021) Sub-committee on carriage of cargoes and containers, 7th session (CCC 7), 6–10 September 2021. [Meeting summary] <https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/CCC-7th-session.aspx> (accessed 10 May 2023); Tronstad T, et al. (2017) Study on the use of fuel cells in shipping. EMSA. <https://www.emsa.europa.eu/publications/item/2921-emsa-study-on-the-use-of-fuel-cells-in-shipping.html> (accessed 4 May 2023).

[134] Tronstad T, et al. (2017) Study on the use of fuel cells in shipping. EMSA. <https://www.emsa.europa.eu/publications/item/2921-emsa-study-on-the-use-of-fuel-cells-in-shipping.html> (accessed 4 May 2023).

[135] CCS (2022) Guidelines for ships using methanol/ethanol fuel 2022. <https://www.ccs.org.cn/ccswzen/specialDetail?id=202211300573121166> (accessed 10 May 2023); Liu M, Li C (2021) Methanol as a marine fuel. Nanyang Technological University, Singapore.

[136] IMO (2020) Interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel. <https://wwwcdn.imo.org/localresources/en/MediaCentre/MeetingSummaries/Documents/MSC.1-Circ.1621%20-%20Interim%20Guidelines%20For%20The%20Safety%20Of%20ShipsUsing%20MethylEthyl%20Alcohol%20As%20Fuel%20%28Secretariat%29%20%282%29.pdf> (accessed 10 May 2023).

3.4 Biofuels for maritime applications

Biofuels are being considered in the short to medium term as a decarbonisation solution for the maritime sector. Some biofuels can be used in existing engines for vessels and port vehicles with little to no modifications and are easily integrated into the existing infrastructure. However, in the long term, there are challenges that will likely limit the scale of biofuel use in the maritime sector. There is limited sustainable feedstock (i.e. those that do not compete with food production or contribute to land use change) available for fuel production and strong competition from other sectors, such as mining and aviation. There are also regulatory challenges associated with monitoring production processes to ensure that the feedstock is sustainable. As a result, the bilateral economic opportunity for Australia and Singapore associated with drop-in biofuels in the maritime sector is expected to be limited.[137]

3.4.1 Characteristics and emissions

'Biofuel' refers to liquid or gaseous fuels derived primarily from biomass feedstock. A wide range of fuel types can be derived from biomass and used in maritime applications, with varying characteristics and emissions. All biofuels emit GHG emissions during combustion, and although these fuels can be considered carbon neutral within the carbon cycle, broader emissions impacts must also be considered, such as those from fuel production and land use change.

3.4.2 Production

First-generation feedstocks from the human food chain (such as palm oil or canola oil) or second-generation feedstocks that are non-food sources (such as waste cooking oil or forest residues) can be used to produce biofuel.[138] There are also investigations into third-generation feedstocks (algae) and fourth-generation feedstocks (waste and genetically modified algae).[139] First-generation feedstocks are considered less sustainable than second-, third- and fourth-generation feedstocks due to the direct competition with food crops, which could lead to either further emissions from land use change or higher food prices.

Several forms of biofuel can be dropped into existing diesel or LNG engines in vessels, whereas others would require different engine technology.[140] The main drop-in biofuels currently considered for use in shipping include biodiesel (also known as fatty acid methyl ester [FAME]) and renewable diesel (hydrotreated vegetable oil [HVO]). These fuels draw on feedstocks from plant oils or animal fats. Fischer–Tropsch (FT) diesel is another type being considered, which can be produced using lignocellulosic biomass or a combination of hydrogen and biomass. Bio-methane or bio-liquefied natural gas (bioLNG), which draws on biogas feedstock (generated from manure, agricultural waste and food waste), can also be used in existing LNG engines and infrastructure.[141] Other biofuels require new engine technologies, such as bio-methanol (covered in Chapter 3.3.2), bio-liquefied petroleum gas (bioLPG) and dimethyl ether (DME).[142] Table 3 summarises these various fuel types and production processes.

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[137] Australia does process large quantities of animal fat that are sold to Singapore for refining. However, these feedstocks mainly feed into the production of sustainable aviation fuel.

[138] ARENA, CEFC (2019) Biofuels and transport: An Australian opportunity. CEFC. <https://www.cefc.com.au/media/4f2dctmf/biofuels-and-transport-an-australian-opportunity-november-2019.pdf> (accessed 10 May 2023); Castellanos G, et al. (2021) A pathway to decarbonise the shipping sector by 2050. IRENA. <https://www.irena.org/publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050> (accessed 5 June 2023).

[139] Thepsithar P (2020) Alternative fuels for international shipping. Nanyang Technological University, Singapore.

[140] Hsieh CC, Felby C (2017) Biofuels for the marine shipping sector. IEA Bioenergy. <https://www.ieabioenergy.com/wp-content/uploads/2018/02/Marine-biofuel-report-final-Oct-2017.pdf> (accessed 1 June 2023).

[141] Mærsk Mc-Kinney Møller Center (2022) Fuel pathway maturity map. <https://www.zerocarbonshipping.com/fuel-pathways > (accessed 1 June 2023).

[142] BioLPG can be produced from a range of feedstocks (including fats and oils, woody biomass and municipal waste) but is usually a by-product of HVO and FT production. DME is produced using methanol or syngas (TRL 8–9) and can be used in a blend to replace the propane component of LPG. DME has a lower energy density compared with other biofuels, and the infrastructure for commercial production is not available.

Table 3: Biofuels considered for maritime applications[143]

FUEL	FEEDSTOCKS	PRODUCTION PROCESS	COMPATIBILITY WITH EXISTING ENGINES
FAME Biodiesel	Animal fats, vegetable oils	Transesterification	Diesel engine: 20% blend drop-in or requires modifications
HVO renewable diesel	Animal fats + hydrogen Vegetable oils + hydrogen	Hydrotreating	Diesel engine: 100% drop-in
FT Diesel	Lignocellulosic biomass E-hydrogen + biomass	BtL FT process PBtL FT process	Diesel engine: 100% drop-in
BioLPG	Vegetable oils, lignocellulosic biomass	The by-product of HVO or the FT process	LPG engines: 100% drop-in
DME	Lignocellulosic biomass, natural gas	Gasification + fuel synthesis	LPG engine: 20% blend drop-in or requires modifications
	Renewable electricity + CO_2	Electrolysis + fuel synthesis	Diesel engine: blend or requires modifications
BioLNG	Lignocellulosic biogas	Anaerobic digestion + cooling	LNG engine: 100% drop in

Terminology: BioLNG, bio-liquefied natural gas; bioLPG, bio-liquefied petroleum gas; BtL, biomass to liquid; DME, dimethyl ether; FAME, fatty acid methyl ester; FT, Fischer–Tropsch; HVO, hydrotreated vegetable oil; LNG, liquefied natural gas; LPG, liquefied petroleum gas; PBtL, power and biomass to liquid.

The life cycle emissions intensity of biofuels varies based on the feedstock. Emission reduction estimates can range from net zero to comparable emissions with MGO (e.g. the reductions for HVO and FAME compared with MGO have been estimated to be between 70% and 85% if second-generation feedstocks are used).[144] Biofuels generally have lower emissions of other air pollutants, such as SO_x and particulate matter. However, depending on the type of feedstock, the blend of fuel and engine load, biofuels can produce greater NO_x than conventional fuels.[145]

The major challenge for the use of biofuels in the maritime industry is sustainable feedstock availability. Globally, there is some consensus that the global supply of sustainable bioenergy is around 100 EJ/year.[146] Existing projections suggest that the total demand for biomass feedstocks could be around four times this level (430 EJ).[147] Similar trends are expected in Australia. *Australia's Bioenergy Roadmap* suggests that even with a focused effort by government and industry on deploying biofuels in hard-to-abate sectors, feedstock constraints will still be a limiting factor for use.[148]

If demand for biofuels does far outstrip supply at the current price, this will lead to shortages and ultimately large price rises in the long term. There is already evidence of a supply crunch in some areas, with stakeholder consultations reporting that certain biofuel products are unavailable. Consultations also suggested that the maritime industry will face strong competition from sectors with a higher willingness to pay, such as aviation and mining, driven by ambitious company-level targets, government mandates/incentives and limited decarbonisation alternatives. As a result, although biofuels are the most cost-competitive low-emissions fuel currently, they could be one of the least competitive options in the long term.

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[143] Castellanos G, et al. (2021) A pathway to decarbonise the shipping sector by 2050. IRENA. <https://www.irena.org/publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050> (accessed 5 June 2023); Frontier Economics (2023) Pathway to zero emissions for LPG. <https://www.gasenergyaus.au/read/2008/pathway-zero-emission-for-lpg.html#:~:text=The%20supply%20of%20conventional%20LPG,supply%20still%20in%20the%20market.> (accessed 5 June 2023).; Zhou Y, et al. (2020) The potential of liquid biofuels in reducing ship emissions. ICCT. <https://theicct.org/wp-content/uploads/2021/06/Marine-biofuels-sept2020.pdf> (accessed 1 June 2023).

[144] Zhou Y, et al. (2020) The potential of liquid biofuels in reducing ship emissions. ICCT. <https://theicct.org/wp-content/uploads/2021/06/Marine-biofuels-sept2020.pdf> (accessed 1 June 2023).

[145] Zhou Y, Pavlenko N, Rutherford D, Osipova L, Comer B (2020) The potential of liquid biofuels in reducing ship emissions. ICCT. <https://theicct.org/wp-content/uploads/2021/06/Marine-biofuels-sept2020.pdf> (accessed 1 June 2023).

[146] IPCC (2018) Global warming of 1.5°C: An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press. doi:10.1017/9781009157940

[147] Mærsk Mc-Kinney Møller Center (2022) Maritime decarbonization strategy 2022. <https://www.zerocarbonshipping.com/publications/maritime-decarbonization-strategy/> (accessed 25 January 2023).

[148] ENEA Australia, Deloitte Financial Advisory (2021) Australia's bioenergy roadmap report. ARENA. <https://arena.gov.au/knowledge-bank/australias-bioenergy-roadmap-report/> (accessed 1 June 2023).

In addition to feedstock availability challenges, there is still debate over which feedstocks are sustainable, leading to difficulty in estimating the emissions impact associated with biofuels. For example, certifying waste cooking oil is difficult and can be subject to fraud.[149] There are also concerns that burning forest biomass could lead to net positive emissions and risk promoting the wood harvesting industry.[150]
In response to these concerns, the GCMD is aiming to establish a framework for the supply chain integrity of biofuels.[151]

3.4.3 Storage and bunkering

Biofuels are liquid at ambient conditions and can thus be stored in existing fuel storage and bunkering infrastructure. However, biodiesel can dissolve or have an oxidation reaction with some tank materials, causing the degradation of storage tanks. Metals that are not susceptible to this reaction will be required for biodiesel storage and bunkering.

3.4.4 Use

Power systems

Drop-in biofuels are already being used to power vessels and port machinery, with ICEs for biofuels commercially available.[152] Demonstrations to date suggest that FAME can only be dropped-in into existing engines in a 20% blend with petroleum diesel (Table 3). Otherwise, it requires modifications to the engine to support a 100% ratio (B100). This is due to its high cold flow plugging point, which can lead to engine damage. Also, given biodiesel can degrade over time and dissolve certain materials, the fuel must be of a particular grade to be used for marine applications.[153] However, HVO can be dropped-in without any significant modifications to the engine.

Other biofuels are considered less suitable for broad-based maritime applications than FAME and HVO. These are therefore less of a focus in this report. FT diesel is higher quality (and higher cost) compared with other marine fuel options, and is therefore better suited to the aviation market.[154] DME is less relevant for maritime use because the technology for directly combusting methanol is readily available, reducing the value in converting methanol to DME. Although bioLPG appears to be a viable option to reduce emissions, the use of LPG in shipping is still in early stages and is currently only adopted in LPG carriers.[155] BioLPG could be potential bridging fuel for ammonia use due to the established storage terminals and bunkering infrastructure, with the requirement for new materials and safety standards relevant for both fuels.[156]

There are many commercial examples of the use of biofuels in the maritime sector. Oldendorff, in partnership with BHP and the MPA, conducted a biofuel bunkering trial for a dry bulk carrier vessel.[157] ANL partnered with Woolworths Group to complete their trial vessel voyage from Brisbane to other Australian ports via South-east Asia, running on a B20 biofuel blend.[158] Wärtsilä has conducted a test with a Holland America Line cruise ship operating on 100% biofuels, to determine the impact on engine performance and emissions.[159]

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[149] Carvalho F, et al. (2023) Key issues in LCA methodology for marine fuels. ICCT. <https://theicct.org/wp-content/uploads/2023/04/Marine-fuels-LCA_final.pdf> (accessed 10 May 2023).

[150] Mackey B, et al. (2022) Burning forest biomass for energy: not a source of clean energy and harmful to forest ecosystem integrity. Griffith University 22(2), 1–8. doi:10.25904/1912/4547.

[151] GCMD (2022) Drop-in biofuels. <https://www.gcformd.org/drop-in-biofuels> (accessed 8 June 2023).

[152] Castellanos G, et al. (2021) A pathway to decarbonise the shipping sector by 2050. IRENA. <https://www.irena.org/publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050> (accessed 5 June 2023).

[153] Thepsithar P (2020) Alternative fuels for international shipping. Nanyang Technological University, Singapore.

[154] Hsieh CC, Felby C (2017) Biofuels for the marine shipping sector. IEA Bioenergy. > (accessed 1 June 2023); Castellanos G, et al. (2021) A pathway to decarbonise the shipping sector by 2050. IRENA. <https://www.irena.org/publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050> (accessed 5 June 2023).

[155] Wärtsilä (2020) Retrofit highlights use of LPG as a marine fuel. <https://www.wartsila.com/insights/article/retrofit-highlights-use-of-lpg-as-a-marine-fuel#:~:text=The%20world%27s%20first%20LPG%2Dfuelled,ways%20to%20reduce%20marine%20emissions.> (accessed 27 June 2023).

[156] DNV (2019) Making LPG fuel an option for the shipping industry. DNV. <https://www.dnv.com/expert-story/maritime-impact/Making-LPG-fuel-an-option-for-the-shipping-industry.html#:~:text=The%20new%20DNV%20GL%20rules%20for%20ships%20using,LPG%20is%20a%20mixture%20of%20propane%20and%20butane> (accessed 1 June 2023); Hellenic Shipping News (2020) Make room for LPG as a marine fuel. <https://www.hellenicshippingnews.com/make-room-for-lpg-as-a-marine-fuel/> (accessed 1 June 2023).

[157] BHP (2021) BHP, Oldendorff and GoodFuels successfully complete first trial with sustainable biofuel supplied in Singapore. [Media release] <https://www.bhp.com/news/media-centre/releases/2021/04/bhp-oldendorff-and-goodfuels-successfully-complete-first-trial-with-sustainable-biofuel-supplied-in-singapore#:~:text=Global%20resources%20company%20BHP%2C%20German,Singapore%20on%204%20April%202021.> (accessed 1 June 2023).

[158] ANL (2022) ANL: Completes biofuel powered voyage in oceania. <https://www.anl.com.au/news/1835/anl-completes-biofuel-powered-voyage-in-oceania> (accessed 10 May 2023).

[159] Wärtsilä (2022) Wärtsilä, Carnival Corporation and GoodFuels partner in 100% biofuel tests. <https://www.wartsila.com/media/news/20-10-2022-Wartsila-carnival-corporation-and-goodfuels-partner-in-100-biofuel-tests-3172387> (accessed 10 May 2023).

Maersk and Svitzer are integrating second-generation biofuel blends into their vessel network at the purchase of their customers.[160] Jurong Port is moving towards using biodiesel in their forklift fleet by 2026, which is estimated to reduce emissions by 15–20%.[161]

Regulations

Although standards for biofuels are generally well established, there are some barriers to adoption. In Singapore, standards have been introduced to support biofuel bunkering trials.[162] There is also existing legislation in Australia, including the *Fuel Quality Standards Act 2000* and the *Fuel Quality Standards Regulations 2019*, which incorporates density standards for the use of biodiesel. However, HVO does not meet the density threshold requirements,[163] therefore creating a regulatory hurdle for the use of HVO in vessels in Australia.

3.5 Battery electric systems

Electric propulsion of vessels and port vehicles/machinery is another option for reducing emissions if the electricity is generated from renewable sources. Electricity can be stored in batteries in ports and onboard vessels. Battery electric systems can be used in combination with full electric or hybrid power systems in short-sea vessels.

Although the technology for batteries and electric motors is advanced and continues to be developed, there are barriers to its use onboard vessels. Battery electric systems are heavy, have short lifespans and are very costly compared with ICEs. Given the cost of a battery increases with the size of the vessel and journey distance, battery electric systems are better suited to short-sea vessels, such as harbour craft. In addition, there are challenges relating to recharging infrastructure and logistics. Despite this, the use of battery electric technologies in smaller vessels could provide a bilateral economic benefit as Singapore will be seeking to import low emissions fuels, not only for direct maritime applications, but also for the generation of electricity.

3.5.1 Characteristics, emissions and production

Batteries can store electricity and be used to energise equipment and systems directly in port and maritime operations. Batteries present some safety issues due to fire risks from electrical faults; however, these have been incorporated into mitigation strategies and regulations for onboard use.

If produced from fossil fuels, material upstream emissions are associated with generating electricity. In contrast, if produced from renewable sources, such as wind, solar and hydro, there are zero emissions from generation.

There are currently a number of collaborations between port operators and electricity generators to reduce emissions. PSA and Jurong Port are actively collaborating with industry partners and power generators to reduce the emissions intensity of electricity use.[164] In addition, the Port of Newcastle has achieved 100% renewable electricity use due to a contract deal with Bodangora Wind Farm.[165]

3.5.2 Storage, charging and use

Storage and power systems

Batteries store electricity and can be used alongside electric motors in small vessels. The two main types of batteries are lithium-ion (Li-ion) batteries and redox flow batteries. Although less developed than Li-ion batteries and generally larger, redox flow batteries have several advantages given they are non-flammable, at 25 years have nearly twice the lifespan of Li-ion batteries and can be easily scaled to suit the vessel by altering tank capacity.[166]

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[160] Maersk (2023) Maersk ECO delivery. <https://www.maersk.com/transportation-services/eco-delivery> (accessed 12 June 2023); Svitzer (2023) Svitzer Ecotow <https://svitzer.com/services/ecotow/> (accessed 12 June 2023).

[161] MPA (2022) Decarbonisation blueprint: Working towards 2050. Maritime and Port Authority of Singapore.

[162] These standards are being revised to incorporate blends of distillate and residual fuel oils with fatty acid methyl ester(s): MPA (2023) Supply of biofuel within the Port of Singapore to vessels. <https://www.mpa.gov.sg/port-marine-ops/marine-services/bunkering/biofuel-bunkering> (accessed 10 May 2023).

[163] Yournrg. HVO fuel specifications. <https://yournrg.co.uk/advice-hub/hvo/hvo-fuel-specifications#:~:text=At%2015%C2%B0C%2C%20HVO%20has%20a%20density%20of%20778kg,allows%20it%20to%20blend%20with%20conventional%20fossil%20diesel> (accessed 10 May 2023).

[164] MPA (2022) Decarbonisation blueprint: Working towards 2050. Maritime and Port Authority of Singapore.

[165] Port of Newcastle (2023) Port of Newcastle: 2022 sustainability report. <https://www.portofnewcastle.com.au/wp-content/uploads/2023/04/2022-Sustainability-Report.pdf> (accessed 2 May 2023).

[166] The Maritime Executive (2023) Vanadium redox flow battery gets closer to maritime use. <https://maritime-executive.com/article/vanadium-redox-flow-battery-gets-closer-to-maritime-use> (accessed 1 June 2023).

A full electric vessel uses an electric motor and batteries. These systems are currently better suited to smaller vessels and short routes due to their weight, size and energy density. Although full electric systems operate at a higher energy efficiency (50–80%) than diesel propulsion systems (32–36%), they have a much lower energy capacity than MGO. Therefore, battery electric vessels require more frequent recharging (7–19 times per day).[167] In addition, there is a high capital expenditure required for new full electric vessels. One case study suggests that electric vessels were up to 40% more expensive than a conventional new passenger ferry.[168] However, the lower fuel cost can lead to long-term savings overall.[169]

There are a number of initiatives aimed at full electrification. The MPA and the Singapore Maritime Institute have started investing SGD9 million of funding towards harbour craft electrification.[170] In addition, the Australian company Incat is aiming to deliver a full electric RoPax ferry by 2025 to operate in South America.[171]

Hybrid systems contain electric motors with either an ICE or a FC, and, as a result, the size requirement of the battery is smaller.[172] These systems are suited for peak-shaving, where the battery powers the electric motor to reduce the load of the main engine, or to power auxiliary engines. Hybrid systems will be favoured in the short to medium term over full electric systems due to energy density constraints.[173] Many vessel operators are already implementing hybrid systems in short-sea vessels to reduce emissions. Siem Offshore has begun installing hybrid battery systems into their platform supply vessel fleet, with the first vessel achieving a 10% fuel saving.[174]

Charging

Charging infrastructure will need to be installed for ports to adopt battery electric vessels. These vessels will require more regular and longer-duration refuelling (charging) than conventional vessels. This refuelling results in greater non-operating time during charging or requires battery-swapping systems (which would increase capital expenditure).[175] Integrating these systems into existing port infrastructure may also present logistical challenges.

Vessel operators and ports are also interested in shore power infrastructure to reduce the emissions from deep-sea vessels in the short term. Shore power is currently used to power the auxiliary engine of deep-sea vessels at berth. Wärtsilä estimates this can reduce fuel consumption by up to 10%.[176] The challenge with developing shore power is ensuring consistency across ports to allow international vessels easy access to plug-in regardless of the location.

Regulations

Regulations for batteries are well established. The DNV GL handbook outlines the rules required for newbuild vessels, including battery fabrication, installation, operation and maintenance.[177] The guidelines consider the use of batteries both as a source of propulsion power during operations and as a source of auxiliary power.[178]

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[167] Sza Y, et al. (2020) Electrification of Singapore Harbour craft. Nanyang Technological University, Singapore; Liu M, Chiam B, Koh K, Sze Y (2020) A study on the future energy options of Singapore Harbour craft. Nanyang Technological University, Singapore.

[168] Murray A (2020) Plug-in and sail: Meet the electric ferry pioneers. BBC. <https://www.bbc.com/news/business-50233206> (accessed 10 May 2023).

[169] Sza Y, et al. (2020) Electrification of Singapore Harbour craft. Nanyang Technological University, Singapore.

[170] MPA (2022) Decarbonisation blueprint: Working towards 2050. Maritime and Port Authority of Singapore.

[171] The Maritime Executive (2023) Incat Plans to Deliver World's First Large, Lightweight Electric Ferry. <https://maritime-executive.com/article/incat-plans-to-deliver-world-s-first> (accessed 10 May 2023).

[172] Liu M, et al. (2020) A study on the future energy options of Singapore Harbour Craft. Nanyang Technological University, Singapore.

[173] Sza Y, et al. (2020) Electrification of Singapore Harbour craft. Nanyang Technological University, Singapore.

[174] SIEM Offshore (2021) ESG report. <https://www.siemoffshore.com/news/esg-report-2021> (accessed 15 December 2022).

[175] Sza Y, et al. (2020) Electrification of Singapore Harbour craft. Nanyang Technological University, Singapore.

[176] Bussow T, Zabel J (2022) Plug and play – cutting vessel fuel consumption with shore-power. Wärtsilä. <https://www.wartsila.com/insights/article/plug-and-play-cutting-vessel-fuel-consumption-and-emissions-with-shore-power> (accessed 15 February 2023).

[177] DNV (2016) DNV GL handbook for maritime and offshore battery systems. <https://www.dnv.com/maritime/publications/maritime-and-offshore-battery-systems-download.html> (accessed 5 June 2023).

[178] EMSA (2017) EMSA study on the use of fuel cells in shipping. <https://www.emsa.europa.eu/publications/item/2921-emsa-study-on-the-use-of-fuel-cells-in-shipping.html> (accessed 5 June 2023).

3.6 Onboard carbon capture

Given that fossil fuels are expected to remain in the vessel fleet for decades, onboard carbon capture (OCC) is a potential solution to reduce emissions in existing vessel assets. There are several capture technologies, such as membrane separation, adsorption separation, liquid absorption separation and solid absorption separation.[179] The captured CO_2 could be offloaded to a port and used to produce fuels such as methanol or transported to geological sites for permanent storage. Doing so could translate into a bilateral economic opportunity, with the potential for Singapore to transport its CO_2 to permanent storage locations offshore Australia.[180]

Characteristics and emissions

Although land-based carbon capture technologies are relatively mature, OCC has a low readiness level (TRL 6) and faces several barriers to uptake. Studies by DNV and the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping suggest OCC technology will not be available until 2030 due to several obstacles for onboard use.[181] These include the loss of cargo due to the space required for the carbon capture systems and carbon storage tanks, as well as the energy intensity of the capture process.[182] The energy intensity is also higher when high-purity CO_2 is required for other end uses. In addition, although it has been suggested that onboard CO_2 capture rates of 82% are achievable,[183] achieving capture rates above 30–50% may not be economically feasible.[184]

Even with higher capture rates, the emissions mitigation is still lower compared with other solutions. The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping estimated that an 82% capture rate would lead to life cycle emissions reductions of 55–60% due to greater well-to-tank emissions and onboard energy consumption (and this does not include the emissions from CO_2 transport and long-term storage).[185]

Despite the challenges, several initiatives are trialling OCC technology. Kawasaki Kisen Kaisha, Ltd. and partners have been trialling an OCC system on a coal carrier vessel since mid-2021, successfully capturing high-purity CO_2.[186] GCMD is also currently designing an OCC solution, which will be piloted on a tanker vessel.[187]

Offloading, transport and storage

The development of technologies for onboard CO_2 storage, offloading and transport is still in early stages (TRL 5).[188] Technologies include 'CO_2 batteries', a storage system being developed by Value Maritime which can charge and discharge CO_2. These systems use the captured CO_2 to charge the battery, which can then be offloaded at ports and transported to end users. Once the CO_2 is discharged, the battery is returned the to the vessel to be recharged.[189] Solutions for CO_2 pipelines and shipping are also under development for longer distance transport of CO_2 to end users or storage sites.[190]

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[179] Mærsk Mc-Kinney Møller Center (2022) The role of onboard carbon capture in maritime decarbonization. <https://cms.zerocarbonshipping.com/media/uploads/publications/The-role-of-onboard-carbon-capture-in-martime-decarbonization.pdf> (accessed 10 May 2023).

[180] This is supported by a joint study to explore the feasibility of transporting CO2 from Singapore to Australia: Chevron (2022) chevron and MOL to study CO_2 shipping from Singapore to Australia. <https://www.chevron.com/newsroom/2022/q4/chevron-and-mol-to-study-co2-shipping-from-singapore-to-australia> (accessed 27 June 2023).

[181] Ovrum E, et al. (2022) Maritime forecast to 2050. DNV. <https://www.dnv.com/maritime/publications/maritime-forecast-2022/index.html> (accessed 5 June 2023); Mærsk Mc-Kinney Møller Center (2022) The role of onboard carbon capture in maritime decarbonization. <https://cms.zerocarbonshipping.com/media/uploads/publications/The-role-of-onboard-carbon-capture-in-martime-decarbonization.pdf> (accessed 10 May 2023).

[182] Lloyd's Register Maritime Decarbonisation Hub (2023) Onboard carbon capture utilisation and storage. <https://storage.pardot.com/941163/1681265725z3Fr6oRT/LR_ZCFM_CCS_Report_FINAL.pdf> (accessed 10 May 2023); Mærsk Mc-Kinney Møller Center (2022) The role of onboard carbon capture in maritime decarbonization. <https://cms.zerocarbonshipping.com/media/uploads/publications/The-role-of-onboard-carbon-capture-in-martime-decarbonization.pdf> (accessed 10 May 2023).

[183] Mærsk Mc-Kinney Møller Center (2022) The role of onboard carbon capture in maritime decarbonization. <https://cms.zerocarbonshipping.com/media/uploads/publications/The-role-of-onboard-carbon-capture-in-martime-decarbonization.pdf> (accessed 10 May 2023).

[184] Lloyd's Register Maritime Decarbonisation Hub (2023) Onboard carbon capture utilisation and storage. <https://storage.pardot.com/941163/1681265725z3Fr6oRT/LR_ZCFM_CCS_Report_FINAL.pdf> (accessed 10 May 2023).

[185] Mærsk Mc-Kinney Møller Center (2022) The role of onboard carbon capture in maritime decarbonization. <https://cms.zerocarbonshipping.com/media/uploads/publications/The-role-of-onboard-carbon-capture-in-martime-decarbonization.pdf> (accessed 10 May 2023).

[186] Kawasaki Kisen Kaisha Ltd (2021) "K" LINE successfully separated and captured CO2 from exhaust gas in world's first CO_2 capture plant on vessel. K-Line. <https://www.kline.co.jp/en/news/csr/csr818532238088767329/main/0/link/211020EN.pdf> (accessed 10 May 2023).

[187] GCMD (2022) Project REMARCCABLE. <https://www.gcformd.org/project-remarccable> (Accessed 15 February 2023).

[188] Mærsk Mc-Kinney Møller Center (2022) The role of onboard carbon capture in maritime decarbonization. <https://cms.zerocarbonshipping.com/media/uploads/publications/The-role-of-onboard-carbon-capture-in-martime-decarbonization.pdf> (accessed 10 May 2023).

[189] Value Maritime (2020) Value Maritime announces installation of the world's first onboard CO_2 capture and storage unit on an operational vessel! <https://valuemaritime.com/news/value-maritime-announces-co2-capture-unit-2/> (accessed 30 June 2023).

[190] Mærsk Mc-Kinney Møller Center (2022) The role of onboard carbon capture in maritime decarbonization. <https://cms.zerocarbonshipping.com/media/uploads/publications/The-role-of-onboard-carbon-capture-in-martime-decarbonization.pdf> (accessed 10 May 2023).

OCC technology will likely need to be combined with permanent storage solutions to achieve long-term emissions reductions. Although storage solutions are commercially operating today (TRL 8), operational storage capacity is only estimated to be 42 Mt CO_2/year (for reference, the shipping industry alone is responsible for around 1050 Mt CO_2 per year).[191] There are also challenges associated with the transnational movement of CO_2 for offshore storage because the rules are still being developed under the London Protocol.[192] Given the lack of offshore storage sites within its jurisdiction, this challenge is significant for Singapore.

Recycling and utilisation

Another solution to support long-term emissions reductions (in addition to permanent storage) is the ongoing recycling of CO_2. For example, if OCC systems were combined with e-methanol-powered vessels, the CO_2 could be captured, offloaded to the port and used to produce additional e-methanol. If these systems can achieve high CO_2 capture rates, this could lead to significant emissions reductions relative to the baseline. For example, OCC was recently demonstrated alongside a hydrogen–methanol propulsion system as part of the HyMethShip project in Europe, achieving large emissions reductions compared with conventional fuel.[193] However, this solution would rely on renewable electricity and e-methanol production close to port, which is unlikely to be viable in countries like Singapore.

3.7 Energy efficiency solutions

Energy efficiency solutions have a role in minimising GHG emissions in existing vessels operating on fossil fuels and reducing fuel usage in low-emissions vessels. This is because fuels with low volumetric energy densities compared with conventional fuels (see Chapters 3.1–3.3 for further information) are estimated to require more frequent bunkering and greater storage. Increasing the efficiency of vessels will decrease the volume of fuel used and therefore the requirements for bunkering or onboard storage.

Vessel operators have already developed measures to reduce fuel usage (see Chapter 2.3.2) and are exploring additional measures to improve efficiency. For example, Blue Visby is developing a solution to address the typical approach of 'Sail fast, then wait'. That is, due to the lack of coordination for the speed and route of vessels, there is greater traffic and longer waiting periods at ports than is necessary. This traffic contributes to higher fuel usage. Improving the efficiency with a coordinated approach to shipping is estimated to reduce emissions of the current fleet by around 20%.[194]

Port operators and authorities are also developing solutions to improve efficiency. For example, the MPA has adopted the following strategies:

- Digitalisation: a platform to improve the scheduling of port calls, and delivery of services such as cargo handling, bunkering and ship resupply, repair, and maintenance. This will allow ships to reduce waiting time and therefore fuel use.
- Automation: integrating autonomous prime movers and cranes to reduce energy use.[195]

Energy efficiency solutions are less of a focus for this program compared with other decarbonisation solutions. These solutions are essential for reducing emissions in the short and long term. However, these measures are being embraced by industry already and have not been flagged as a significant challenge preventing the decarbonisation of the maritime sector.

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[191] IEA (2022) CO_2 transport and storage. <https://www.iea.org/reports/CO2-transport-and-storage> (accessed 10 May 2023).

[192] IEA (2022) CO_2 transport and storage. <https://www.iea.org/reports/CO2-transport-and-storage> (accessed 10 May 2023); Lloyd's Register Maritime Decarbonisation Hub (2023) Onboard carbon capture utilisation and storage. <https://storage.pardot.com/941163/1681265725z3Fr6oRT/LR_ZCFM_CCS_Report_FINAL.pdf> (accessed 10 May 2023).

[193] Cordis (2022) Hydrogen–methanol ship propulsion system using on-board pre-combustion carbon capture. European Commission. <https://cordis.europa.eu/project/id/768945> (accessed 1 June 2023).

[194] Harwood S, Oy N (2022) Submission to the environmental audit committee of the UK parliament on eradicating an operational inefficiency in ocean cargo transport, so as to reduce GHG emissions. Blue Visby. <https://committees.parliament.uk/writtenevidence/106792/html/> (accessed 5 June 2023); Ralston W (2023) Why the global shipping industry can't clean up its act. Bloomberg News. <https://www.bloomberg.com/news/articles/2023-03-14/why-the-global-container-shipping-industry-can-t-clean-up-its-act> (accessed 29 May 2023).

[195] MPA (2022) Decarbonisation blueprint: Working towards 2050. Maritime and Port Authority of Singapore.

3.8 Comparison of decarbonisation solutions

This chapter assesses each decarbonisation option against a range of criteria to provide an overall view of each solution relative to the alternatives. Current and projected fuel prices reflect the production cost and availability of low-emissions fuels in the short and long term. Costs relating to onshore storage and transport, and onboard capital requirements are also key drivers of total costs. The GHG emissions mitigation associated with each option will vary and heavily depend on the feedstock used to produce the fuel. Finally, safety risks will greatly impact the acceptability of a low-emissions technology. Note that energy efficiency solutions can apply across all options, so these have not been included in the comparison.

This assessment highlights that the most viable solution for reducing emissions will depend on factors such as time horizon and the specific marine application. For example, some options that are currently low cost but have constraints on scalability (e.g. battery electric systems, biofuels) could still have an impact on near-term decarbonisation, whereas options that are currently higher-cost but more scalable (e.g. ammonia, methanol) may have little effect in the near term but could have a significant impact on long-term decarbonisation. The assessment will also vary when considering vessels of different types and sizes, as well as journey distance. Given that there is a broad spectrum of vessel and journey types, for simplicity, we assess the suitability of two broad applications below.[196]

- deep-sea shipping involving large vessels
- short-sea shipping involving small vessels (e.g. harbour craft).

Table 4 summarises the assessment of each decarbonisation option, with further detail relating to the scoring against each criterion in Appendix B.

Table 4: Assessment of fuel/technology characteristics

OPTION	CURRENT FUEL PRICE	PROJECTED FUEL PRICE (2050)	ONSHORE STORAGE AND TRANSPORT COST	ONBOARD CAPITAL COST	GHG EMISSIONS	SAFETY RISK	SUITABILITY FOR DEEP-SEA SHIPPING	SUITABILITY FOR SHORT-SEA SHIPPING
Hydrogen	◐	◕	◔	◔	◓	◑	☒	☑
Ammonia	◐	◕	◕	◕	◓	◔	☑	☑
Methanol	◍	◑	◕	◕	◓	◕	☑	☑
Biofuels	◕	◔	●	●	◉	●	☑	☑
Battery electric	●	●	◕	○	●	◕	☒	☑
OCC	●	●	◑	◑	◔	●	☑	☒

● Very low ◕ Low ◑ Moderate ◔ High ○ Very high | ◐ Range (i.e. scores 2–3)

Notes: Each criteria receives a score of 0-4. The grey shading reflects a wide range of scores within a fuel, depending on the production route.

Assumptions: The fuel price assessment does not incorporate the explicit costs associated with carbon pricing. Onboard capital costs include the cost of storage (e.g. batteries, tanks), power systems (e.g. engines, fuel cells) and other equipment, such as carbon capture systems. Hydrogen and ammonia routes include NG-CCUS and electrolysis, while methanol routes include bio-methanol, e-methanol (biogenic CO_2) and e-methanol (DAC).

Terminology: GHG, greenhouse gas; OCC, onboard carbon capture.

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196 Vessel size and journey distance will not capture the variation across all vessel types. For example, cruise ships will have a higher safety threshold than cargo vessels. In addition, container ships tend to travel on fixed routes, whereas tankers tend to vary routes, leading to different bunkering practices and therefore different requirements for low-emissions fuels.

The most viable decarbonisation solutions for deep and short-sea shipping differ based on the criteria assessed.

For deep-sea shipping, ammonia appears to be the most viable solution in the long term due to its GHG mitigation potential, the expectations for a more competitive fuel supply in the future and the lower capital costs relative to other options. However, the safety risks associated with ammonia remain a concern. Fuels derived from biomass, such as FAME, HVO and bio-methanol, are likely the most appropriate solutions for near-term decarbonisation given that they are currently more cost competitive than hydrogen and ammonia, and the required engines have a high TRL.[197] Despite this, the emissions reduction associated these fuels will vary depending on the feedstock, and they are unlikely to be a scalable solution for long-term decarbonisation due to feedstock availability constraints. OCC solutions could also be incorporated into deep-sea vessels; however, this appears to be a less viable option due to the challenges associated with achieving high CO_2 capture rates, as well as the transport and permanent storage of $CO_{2.}$

Battery electric and hydrogen solutions are viable options for short-sea shipping in the near term. Although these solutions are not well suited to deep-sea shipping due to high onboard capital costs, this is less of an issue with shorter distances due to the capacity for regular refuelling/recharging. In addition, the high efficiency of these power systems compared with ICEs can lead to fuel cost savings that can offset the higher capital costs.

Each decarbonisation option has advantages and challenges, which supports the case for a multi-fuel future. A recent survey of industry participants suggests a need to prepare vessel fleets to operate on three or more fuel types.[198] However, there is still much uncertainty over the future uptake of different fuel types.

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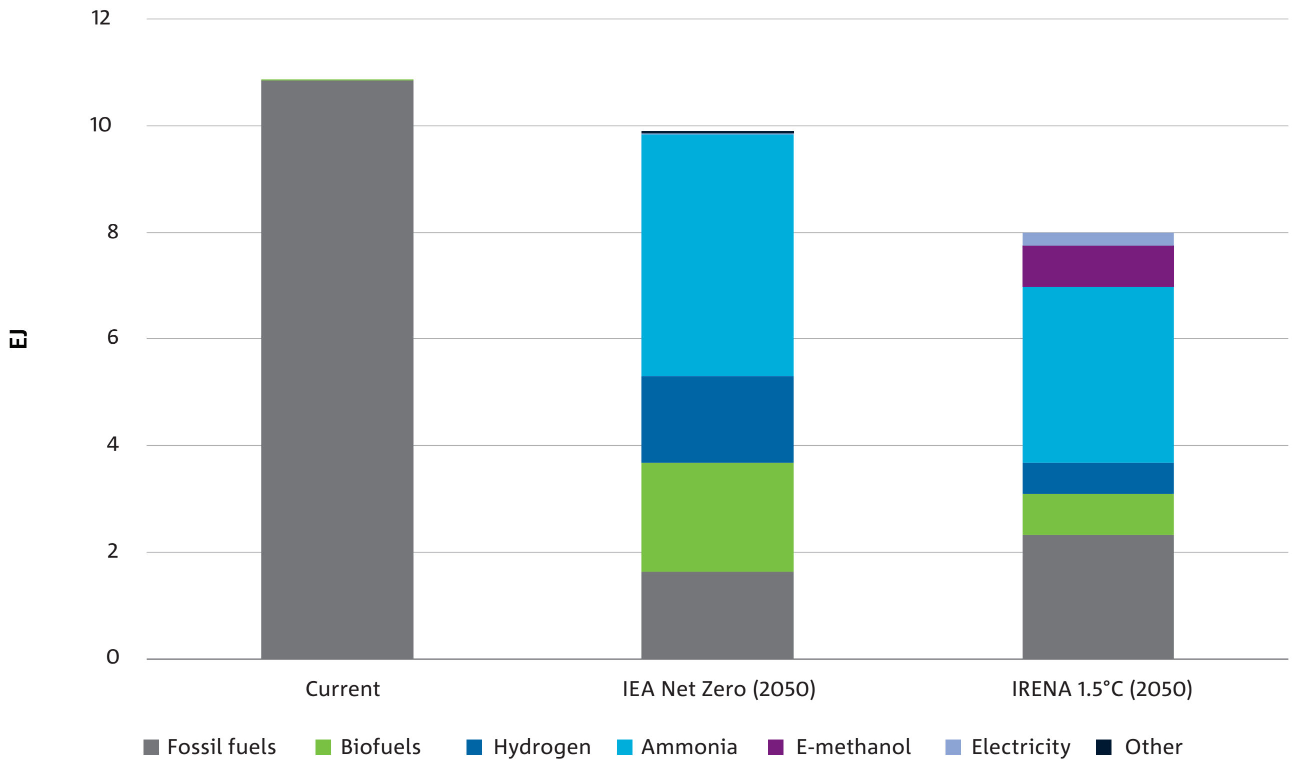
[197] Currently, e-methanol is estimated to be significantly more expensive than bio-methanol.

[198] GCMD (2023) Survey suggests a multi-fuel future for the shipping industry on the path to zero emissions. <https://www.gcformd.org/post/survey-suggests-a-multi-fuel-future-for-the-shipping-industry-on-the-path-to-zero-emissions-1> (accessed 9 June 2023).

Global fuel mix projections developed by the IEA and IRENA under a 1.5°C scenario present some guide on potential pathways (Figure 2).[199] Ammonia is expected to see the largest uptake in both scenarios, because this is expected to be the lowest-cost option for deep-sea shipping. The IEA projects that under its Net Zero Emissions scenario, energy demand in shipping will be approximately 10 EJ, including 4.6 EJ from ammonia, 2.1 EJ from biofuels and 1.6 EJ from hydrogen. IRENA estimates that energy demand in shipping will fall to around 8 EJ by 2050 due to energy efficiency improvements, with 3.3 EJ from ammonia and around 2.4 EJ from other low-emissions fuels. Both scenarios suggest an ongoing role for fossil fuels in 2050.

A range of scenarios has also been developed by DNV, including pathways consistent with IMO ambitions (from the 2018 strategy) and projections for full decarbonisation by 2050.[200] One of the 'IMO ambitions' pathways was chosen for DNV's broader Energy Transition Outlook. Under this scenario, energy demand is projected to reach 12.9 EJ by 2050, with ammonia contributing 4.6 EJ, biofuels 2.3 EJ, e-fuels 1.9 EJ and electricity 0.3 EJ, with the remaining energy demand (3.9 EJ) met by fossil fuels.[201]

Figure 2: Energy consumption by fuel in shipping, 2050



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[199] IEA (2021) Net Zero by 2050. A Roadmap for the Global Energy Sector. <https://www.iea.org/reports/net-zero-by-2050> (accessed 13 June 2023); Castellanos G, Roesch R, Sloan A (2021) A pathway to decarbonise the shipping sector by 2050. IRENA. <https://www.irena.org/publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050> (accessed 5 June 2023).

[200] Ovrum E, et al. (2022) Maritime forecast to 2050. DNV. <https://www.dnv.com/maritime/publications/maritime-forecast-2022/index.html> (accessed 5 June 2023).

[201] DNV (2022) Energy Transition Outlook 2022: A global and regional forecast to 2050. <https://www.dnv.com/energy-transition-outlook/about.html> (accessed 5 June 2023).

3.9 Major challenges across decarbonisation solutions

Table 5 summarises the significant challenges relating to technology and operations identified across decarbonisation solutions. Chapter 4 outlines a prioritisation framework to reduce this list to the three challenge focus areas that are closely aligned to the program objectives.

Table 5: Summary of major challenges

SUPPLY CHAIN	FUEL/TECHNOLOGY	CHALLENGES
Production	E-hydrogen E-ammonia E-methanol	Reduce cost of renewable electricity and improve electrolyser efficiency
		Reduce the cost of capital
	NG-CCUS hydrogen NG-CCUS ammonia	Reduce upstream methane leakage
	E-methanol	Reduce the cost of DAC
Storage, transport and refuelling	Hydrogen Ammonia Methanol Battery electric	Develop port infrastructure/technology to accommodate bunkering, recharging and storage
	Hydrogen Ammonia	Mitigate safety and ecological risks associated with storage and bunkering
	Hydrogen	Reduce the cost of storage
	OCC	Improve technological maturity of CO_2 offloading and transport
Use	Hydrogen Ammonia	Mitigate safety and ecological risks associated with use in vessels
	Hydrogen Ammonia Methanol Battery electric	Improve onboard storage solutions due to greater volume requirements
		Improve technological maturity of power systems in deep-sea vessels
		Reduce the cost of power systems in short-sea vessels
	Ammonia	Reduce N_2O and NO_x emissions from ICEs
	Biofuels	Improve technological maturity of engines for B100 applications
	OCC	Improve CO_2 purity to meet requirements for end uses
		Improve economic viability of higher capture rates

Terminology: B100, 100% biofuel blend; CCUS, carbon capture, utilisation and storage; CO_2, carbon dioxide; DAC, direct air capture; E-, fuel produced from renewable electricity via electrolysis; ICE, internal combustion engine; N_2O, nitrous oxide; NO_x, nitrogen oxides; OCC, onboard carbon capture.

4 Priority challenges

The analysis of decarbonisation solutions in the maritime sector identified a broad range of major challenges (summarised in Chapter 3.9). This illustrates the need for public investment and policy to support the transition.

Although many of the challenges identified will need to be addressed to facilitate decarbonisation in the maritime sector, a framework was developed to identify three focus areas that are proposed as a guide for project identification.

The focus areas have been presented as challenge statements to support the investment process. Presenting investment priorities in this format clearly defines problems that need to be solved, and therefore helps identify appropriate solutions. Such an approach provides a clear investment case and is commonly used by companies and government entities for the development of innovation strategies.

4.1 Prioritisation framework

A framework was developed to prioritise the challenges to decarbonisation that this program can address. This was drawn upon by the project team and industry stakeholders in Australia and Singapore during the workshops to identify a set of focus areas. The considerations for the projects funded are as follows:

- **Mutual benefit to Australia and Singapore**: Prioritise projects that benefit both countries.
- **Demonstrations (TRL 4–6; TRL 7–9; commercial)**: Fund or contribute to demonstration projects that advance low-emissions fuel use in maritime and port operations.
- **Investment gap**: Avoid duplicating other work addressing the relevant challenge, given various projects are already being developed in this space.
- **Maritime sector relevance**: Focus on most critical challenges for downstream maritime applications rather than challenges that apply to multiple sectors.
- **Within funding targets**: Within the initial investment target (an AUD 30 million industry co-investment initiative) or contribute to a broader initiative.
- **Fuel/technology suitability**: Focus on the most viable fuels/technologies for decarbonising the sector (as discussed in Chapter 3.8). To assess viability, the criteria include:
  - **Current and projected fuel price**: The production of fuels/technologies should be cost competitive and scale to support projected demand
  - **Onshore storage and transport costs**: The storage and transport costs of fuels/technologies at ports are not expected to be a barrier to supply
  - **Onboard capital cost**: The onboard capital costs (such as storage and propulsion systems) of the fuels/technologies are not expected to be a barrier to uptake (considering both short-sea and deep-sea shipping)
  - **GHG emissions**: The well-to-wake GHG emissions of the fuels/technologies are significantly reduced compared with conventional fuels
  - **Safety risks**: The safety risks to humans or other ecosystems from the use of fuels/technologies in vessels are as low as reasonably practical (ALARP).

4.2 Prioritisation of challenges

The broad list of challenges outlined in Chapter 3.9 was reduced to a set of challenge focus areas using the prioritisation framework. Table 6 summarises the assessment of each challenge against the identified criteria.

Table 6: Major challenges across decarbonisation options

SUPPLY CHAIN	FUEL/ TECHNOLOGY	CHALLENGES STATEMENTS	MUTUAL BENEFIT TO AU/SG	DEMONSTRATIONS	INVESTMENT GAP	MARITIME SECTOR RELEVANCE	WITHIN FUNDING TARGETS	FUEL/TECHNOLOGY SUITABILITY
Production	E-hydrogen E-ammonia E-methanol	Reduce cost of renewable electricity and improve electrolyser efficiency	🟦	⬜	⬜	⬜	⬜	🟦
		Reduce cost of capital	🟦	⬜	⬜	⬜	⬜	🟦
	NG-CCUS hydrogen NG-CCUS ammonia	Reduce upstream methane leakage	🟦	🟦	⬜	⬜	🟦	🟦
	E-methanol	Reduce cost of DAC	🟦	🟦	🟦	⬜	⬜	🟦
Storage, transport and refuelling	Hydrogen Ammonia Methanol Battery electric	Develop port infrastructure/technology to accommodate bunkering, recharging and storage	🟦	🟦	🟦	🟦	🟦	🟦
	Hydrogen Ammonia	Mitigate safety and ecological risks associated with storage and bunkering	🟦	🟦	🟦	🟦	🟦	🟦
	Hydrogen	Reduce cost of storage	🟦	⬜	⬜	⬜	🟦	⬜
	OCC	Improve technological maturity of CO_2 offloading and transport	🟦	🟦	🟦	🟦	🟦	⬜
Use	Hydrogen Ammonia	Mitigate safety and ecological risks associated with use in vessels	🟦	🟦	🟦	🟦	🟦	🟦
	Hydrogen Ammonia Methanol	Improve onboard storage solutions due to greater volume requirements	🟦	🟦	⬜	🟦	🟦	🟦
		Improve technological maturity of power systems in deep-sea vessels	🟦	🟦	⬜	🟦	🟦	🟦
	Hydrogen Ammonia Methanol Battery electric	Reduce the cost of power systems in short-sea vessels	🟦	🟦	🟦	🟦	🟦	🟦
	Ammonia	Reduce N_2O and NO_x emissions from ICEs	🟦	🟦	⬜	🟦	🟦	🟦
	Biofuels	Improve technological maturity of engines for B100 applications	⬜	🟦	⬜	🟦	🟦	🟦
	OCC	Improve CO_2 purity to meet requirements for end uses	🟦	🟦	🟦	🟦	🟦	⬜
		Improve economic viability of higher capture rates	🟦	🟦	🟦	🟦	🟦	⬜

⬜ Does not meet criteria

🟦 Meets criteria

Terminology: AU, Australia; B100, 100% biofuel blend; CCUS, carbon capture, utilisation and storage; CO_2, carbon dioxide; DAC, direct air capture; E-, fuel produced from renewable electricity via electrolysis; ICE, internal combustion engine; NG, natural gas; N_2O, nitrous oxide; NO_x, nitrogen oxides; OCC, onboard carbon capture; SG, Singapore.

4.2.1 Challenge focus areas

The challenge focus areas identified are summarised below and outlined in more detail in Appendix A.

CHALLENGE 1	**Mitigate safety and ecological risks associated with the use of low-emissions fuels, such as ammonia and hydrogen** Establish social licence by demonstrating that the risks to human safety and the broader marine environment from the bunkering, handling and onboard use of low-emissions fuels (such as hydrogen and ammonia) are as low as reasonably practical (ALARP).
CHALLENGE 2	**Develop technology and infrastructure at ports to accommodate the adoption of low-emissions fuels** Develop port technology and infrastructure (e.g. bunkering, charging systems and storage facilities) to accommodate low-emissions solutions such as hydrogen, ammonia, methanol and electrification.
CHALLENGE 3	**Reduce the cost of low-emissions technologies in short-sea vessels** Facilitate a shift in low-emissions vessel technology designed for shorter journeys (e.g. battery electric, FCs) from proof-of-concept to demonstration across the entire port value chain.

The framework used in this study is designed to strike a balance between developing the technologies and systems required for the adoption of low-emissions fuels while acknowledging the technology development that is already underway, as well as constraints on time and funding. Throughout the consultation process, other sector-wide challenges were identified, but not prioritised as a key focus area due to program constraints (see Appendix C for further detail).

For example, improving technological maturity for deep-sea vessels is not a focus as stakeholder feedback suggested there is no clear investment gap in this area. Despite this, Challenges 1 and 2 will facilitate the adoption of low-emissions fuels in all vessel types by addressing the barriers to storing, transporting and using these fuels in a marine environment. Although Challenge 3 focuses on short-sea shipping, there is potential for learnings that could apply to deep sea vessels.

In addition, there is a major challenge relating to the production costs of low-emissions fuels, leading to uncertainty around future fuel supply at ports. Because vessel operators require guaranteed supply of low-emission fuels at different bunkering locations, many are waiting for supply chains to be established before making investments in new fuel technology. This is complicated by the fact that ports may supply different fuel types in the future, depending on production capabilities in a given location and other port characteristics. However, there are many large-scale production projects that are already underway in proximity to Australian ports (see Appendix C for further detail). As a result, stakeholders suggested such projects are of lower relevance to this program.

Although full supply chain challenges are not directly included in the focus areas, these should be considered when assessing projects for downstream applications. Investment bodies can draw on green corridor frameworks to identify upstream barriers facing a project, including assessments of low-emissions fuels supply, port readiness levels, trade routes, cargo characteristics and the regulatory landscape.[202] For example, the development of testbed facilities should focus on port locations that will likely be large adopters of low-emissions fuels.

4.2.2 Other actions

Stakeholder consultations suggested that there are other actions, alongside project funding, that are required to accelerate the uptake of low-emissions fuels in Australia and Singapore. This reflected two key areas: regulation and incentives; and further analysis.

Regulation and incentives

Stakeholder consultations in Australia suggested that more ambitious emissions reduction policies are required. For example, broad-based policy incentives, such as taxes, rewards schemes and public–private partnerships, are needed to level the playing field and stimulate investment across the entire supply chain. The recently announced Hydrogen Headstart program, which will allocate AUD2 billion for green hydrogen production credits in Australia, is an example of progress in this area.[203] Relatedly, in the absence of an entirely level playing field, it was noted that financial support for first movers and green corridor initiatives is needed to reduce the risks associated with new investments.

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[202] Maersk Mc-Kinney Moller Center (2022) Green Corridors: Pre-Feasibility Phase Blueprint. <http://mission-innovation.net/wp-content/uploads/2022/11/Green-Corridors-Pre-Feasibility-Blueprint-Summary.pdf> (accessed 1 June 2023).

[203] ARENA (2023) Hydrogen headstart. <https://arena.gov.au/funding/hydrogen-headstart/> (accessed 1 June 2023).

Decarbonising the shipping corridor between Singapore and Australia will also require a clear strategy for the sector that is incorporated into national energy strategies and reflects market requirements in both countries. For example, the recently announced *Maritime Emissions Reduction National Action Plan* in Australia and the Maritime Decarbonisation Blueprint in Singapore are aimed at reducing emissions locally and in international shipping.[204] This is particularly important in Australia given the dispersed and private nature of Australian ports and their diverse export capabilities. A collective approach involving government, ports and fuel producers will be required to accelerate the adoption of low-emissions fuels.

There was also feedback that further development was required for industry standards on fuel handling and verification schemes. In particular, the development of onboard safety and training standards is needed, with consistency across ports in Singapore and Australia to support the development of green corridors between the two countries. In addition, consistency between fuel standards and verification schemes, such as the Guarantee of Origin scheme being developed in Australia, will be critical to supporting investments in low-emissions technologies.[205]

Further analysis

As well as policy gaps, stakeholder workshops highlighted gaps in industry analysis. Representatives in both Australia and Singapore communicated that further study was required in the two countries, including estimation of the life cycle emissions intensities and levelised costs for various decarbonisation solutions. Examples of relevant analysis include the ‘First Movers’ study by Lloyd’s Register Maritime Decarbonisation Hub, which compared the levelised costs of low-emissions fuels across various trade routes, including Australia–Singapore routes.[206] In addition, feedback suggested there is still uncertainty regarding port infrastructure requirements. This is particularly the case in Australia, where the characteristics of ports vary, with city ports likely having different restrictions to remote ports. Further analysis in this area could be supported by CSIRO’s Hydrogen Ports Tool and Geoscience Australia’s Hydrogen Opportunities Tool.[207]

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[204] King C (2023) Charting course towards zero maritime emissions for Australia. [Media release] <https://minister.infrastructure.gov.au/c-king/media-release/charting-course-towards-zero-maritime-emissions-australia> (accessed 1 June 2023); MPA (2022) Decarbonisation blueprint: Working towards 2050. Maritime and Port Authority of Singapore.

[205] Department of Climate Change, Energy, the Environment and Water (2022) Australia’s Guarantee of Origin Scheme. <https://storage.googleapis.com/files-au-climate/climate-au/p/prj232e2205fdfa8b85770e8/public_assets/Policy%20position%20paper%20%20-%20%20Australia’s%20Guarantee%20of%20Origin%20Scheme.pdf> (accessed 8 June 2023).

[206] Lloyd’s Register Maritime Decarbonisation Hub (2021) First movers in shipping’s decarbonisation: A framework for getting started. <https://www.naucher.com/wp-content/uploads/2021/12/LR_First_movers_in_shipping_s_decarbonisation_A_framework_for_getting_s.pdf> (accessed 1 June 2023).

[207] Hayward J, Palfreyman D (2021) Model: Hydrogen Ports. v1. CSIRO. Data Collection. csiro:50387. <https://shiny.csiro.au/hydrogen-knowledge-centre/H2Ports/> (accessed 9 June 2023); Geoscience Australia (2019) AusH2 – Australia’s hydrogen opportunities tool. <https://portal.ga.gov.au/persona/hydrogen> (accessed 9 June 2023).

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Appendix A: Challenge focus areas

Challenge 1: Mitigate safety and ecological risks associated with the use of low-emissions fuels, such as ammonia and hydrogen

The use of hydrogen and ammonia as marine fuels presents new challenges in establishing social licence, due to safety and ecological risks. Hydrogen is flammable and presents an explosion risk. Ammonia is highly toxic, presenting a risk to both human health and aquatic life. Therefore, public acceptability is important to facilitate the uptake of these fuels. In particular, it must be established that the risks associated with the handling, bunkering and onboard use of these low-emissions fuels are as low as reasonably practical (ALARP). As a result, there is a need to demonstrate relevant processes, train personnel at ports and onboard vessels, and establish mitigation strategies to minimise risks.

The opportunity for Australia and Singapore

Mitigating the risks associated with hydrogen and ammonia will support industry participants in both Australia and Singapore in achieving the IMO's GHG emissions targets for international shipping. Addressing this challenge will also promote economic growth in both countries. Australia is projected to become a leading exporter of low-emissions hydrogen and ammonia, given its extensive renewable energy resources, as well as its natural gas reserves and potential CO_2 storage sites. Furthermore, Singapore is looking to position itself as a green bunkering hub, which will require importing hydrogen and ammonia from countries like Australia. In a recent study, the Global Centre for Maritime Decarbonisation (GCMD) projected in its 'realistic' scenario that ammonia bunker demand in Singapore will reach 50 Mt by 2050.[208]

Supporting information

Ammonia is considered toxic to both human health and aquatic life following exposure at certain concentrations and durations. Given ammonia is already a widely traded commodity, there are comprehensive assessments relating to the safety of ammonia handling, storage and transportation on land. However, safety analysis relating to ammonia as a marine fuel is still in early stages.[209] Therefore, physical demonstrations of ammonia bunkering and use on vessels are still required to validate the safety of these processes and establish the appropriate standards (including training requirements).

The safety concerns for hydrogen relate to the explosion risk. Hydrogen has high flammability, lacks an odour, can diffuse quickly and has a near-invisible flame when burnt. Therefore, leakages are difficult to detect and have an increased risk of ignition. Hydrogen also has a high risk of explosion when stored under pressure. As a result, demonstrations of hydrogen bunkering and use onboard vessels are required to inform explosion risk mitigation measures (e.g. odour additives, ventilation requirements).

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[208] GCMD (2023) Ammonia bunkering pilot safety study. <https://www.gcformd.org/ammonia-bunkering-safety-study> (accessed 1 May 2023).

[209] Yang M, et al. (2022) Ammonia as a marine fuel. Nanyang Technological University, Singapore.

Existing projects

PROJECT/STUDY NAME	PARTNERS	DESCRIPTION
Ammonia bunkering pilot safety study[210]	Global Centre for Maritime Decarbonisation	A study that outlines suitable sites, operations and risks for bunkering pilot trials in Singapore to enable safe demonstrations
Ammonia as a marine fuel – bunkering, safety and release simulations[211]	Nanyang Technological University, Singapore Maritime Institute	A study that simulates the dispersion pattern of ammonia in the event of a hose rupture scenario during bunkering. It draws on these simulations to make recommendations for bunkering configurations and a review of mitigation measures
Expression of interest to develop an end-to-end low- or zero-carbon ammonia power generation and bunkering solution ('project') in Singapore[212]	Energy Market Authority and Maritime Port Authority Singapore	Projects that enable the verification, demonstration and build-up of capabilities for ammonia use in Singapore, with end use in both power generation and bunkering
Ammonia at sea[213]	Environmental Defense Fund, Lloyd's Register, Ricardo PLC	An environmental assessment report on the impacts an ammonia spill may have on marine life and ecosystems
Yara/PPA ammonia bunkering study[214]	Yara Clean Ammonia, Pilbara Ports Authority (PPA)	A study to identify the required bunkering infrastructure to meet estimated demand, and ensure safe operations and guidelines for ammonia handling/use
Ammonia-powered bulk carrier: Pilot Report[215]	Green shipping Programme, Grieg star	A study to determine the risks and suitability of retrofitting a bulk carrier to operate on ammonia
Ammonia as a marine fuel: Safety handbook[216]	Green shipping Programme, Grieg star, Norwegian Maritime Authority	An outline of safety recommendations for ammonia-powered ship design

Potential projects

PROJECT	DESCRIPTION
Early detection warning systems	Test onboard early detection warning systems in the case of an ammonia leak
Ship-to-ship bunkering pilot	Demonstrate successful ship-to-ship bunkering procedures
Water curtains	Test mitigation impact of water curtains in the case of a leak

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[210] GCMD (2023) Ammonia bunkering pilot safety study. <https://www.gcformd.org/ammonia-bunkering-safety-study> (accessed 1 May 2023).

[211] Yang M, et al. (2022) Ammonia as a marine fuel. Nanyang Technological University, Singapore; Dawson L, et al. (2022) Ammonia at sea: Studying the potential impact of ammonia as a shipping fuel on marine ecosystems. Environmental Defense Fund. <https://www.edfeurope.org/sites/euroedf/files/EDF-Europe-Ammonia-at-sea-FullReport.pdf> (accessed 23 February 2023).

[212] MPA (2022) Expression of interest (EOI) to develop an end-to-end low or zero-carbon ammonia power generation and bunkering solution ('project') in Singapore. <https://www.mpa.gov.sg/docs/mpalibraries/media-releases/older/expression-of-interest-for-ammonia-project-(final).pdf> (accessed 10 May 2023).

[213] Dawson L, et al. (2022) Ammonia at sea: studying the potential impact of ammonia as a shipping fuel on marine ecosystems. Environmental Defense Fund. <https://www.edfeurope.org/sites/euroedf/files/EDF-Europe-Ammonia-at-sea-FullReport.pdf> (accessed 23 February 2023).

[214] Yara (2022) Yara Clean Ammonia and Pilbara Ports Authority team up to assess ammonia as a shipping fuel. <https://www.yara.com/news-and-media/news/archive/news-2022/yara-clean-ammonia-and-pilbara-ports-authority-team-up-to-assess-ammonia-as-a-shipping-fuel/> (accessed 10 May 2023).

[215] Green Shipping Programme (2023) Ammonia powered bulk carrier pilot report. <https://greenshippingprogramme.com/wp-content/uploads/2023/06/Ammonia-powered-bulk-carrier.-Pilot-report.pdf> (accessed 19 June 2023).

[216] Green Shipping Programme (2023) Ammonia as a marine fuel: Safety handbook. <https://greenshippingprogramme.com/wp-content/uploads/2021/03/Ammonia-as-a-Marine-Fuel-Safety-Handbook-Rev.02.pdf> (accessed 22 June 2023).

Challenge 2: Develop technology and infrastructure at ports to accommodate the adoption of low-emissions fuels

As port and vessel operators in Australia and Singapore transition to using low-emissions fuels, new port technologies and infrastructure will be required, including bunkering, charging and storage facilities. These developments will provide assurance to investors in new vessels that ports will be able to supply low-emissions fuels once they become available.

With the expectation of a multi-fuel future to meet maritime decarbonisation demands, ports face increasing pressure to ensure compatibility with various fuel options (e.g., hydrogen, ammonia, methanol, and electricity). In addition, given that the volume requirements for low-emission fuels will be significantly greater than those for conventional fuels (due to the lower volumetric energy density), more infrastructure and land area are required to store and transfer these fuels. Limited space creates a challenge for port operators to improve existing processes and expand operations to meet user demands while maintaining cost competitiveness.

The opportunity for Australia and Singapore

With many ports in Australia, each specialising in specific vessel types and cargo, there is an opportunity to supply a range of fuel types. The shift to low-emissions fuels will likely lead to bunkering more frequently (due to the lower volumetric energy density than conventional fuels). Although Australian ports are not typically used for bunkering, the added demand could enable several locations to provide this service in support of green corridors.

As a global bunkering hub, Singapore has an opportunity to make use of innovative solutions to optimise storage and bunkering. The limited space available in Singapore means these solutions will be essential for the port to supply low-emissions fuels. There is also an opportunity for shared infrastructure across sectors given that some low-emissions fuels (e.g., ammonia) are viable solutions to decarbonise other sectors (e.g., power generation).

Supporting information

The compatibility of bunkering and recharging infrastructure across ports will be required to support a multi-fuel future. Because fuels such as methanol, ammonia and hydrogen have different material requirements to ensure safety and prevent corrosion or leakage, this creates an extra complexity for ports to coordinate.

To minimise upfront investment costs, establishing retrofit options for existing (and future) storage and refuelling infrastructure will provide greater confidence for investors in the short term. For example, LPG and LNG infrastructure could be retrofitted for the use of ammonia, which will reduce the need for new infrastructure investment as ammonia becomes available.

Battery electric vessels present additional challenges. Full battery electric vessels require more frequent recharging for longer periods of time (compared with refuelling), which presents the logistical difficulty of navigating other port traffic. The development of charging technology and infrastructure will also be required. This will be the case not only for short-sea vessels, but also deep-sea shipping, because drawing on shore power while in port can reduce emissions in the short term (assuming renewable electricity is supplied).

To address the space constraints and upfront costs associated with new storage and refuelling infrastructure, ports could consider common user facilities. Before fuel production plants reach large scale, it is likely that multiple producers will be supplying small volumes to ports. As a result, the infrastructure costs pose a large cost barrier to an individual producer. The integration of storage between operators or industries (e.g. power generation and maritime) would reduce the cost of newbuild infrastructure, particularly while the volume of fuel supplied is small. However, this is a rare practice in ports and would require business model development to consider the most cost-effective use of infrastructure for multiple suppliers and users. A pilot trial would likely be needed to demonstrate the feasibility of such a model.

Offshore storage and refuelling options can also address the barrier of limited land availability and potential safety concerns. However, this can present challenges with navigating vessel routes. Because the structure of waterways at each port is unique, feasibility studies for each port to determine the most viable offshore locations would likely be required. Demonstrations that the technology is successful without increasing safety risks would also be needed.

Existing projects

PROJECT/STUDY NAME	PARTNERS	DESCRIPTION
Ammonia floating storage and regasification barge[217]	NYK Line, IHI Corporation, Nihon Shipyard Co., Ltd	Developing an offshore floating facility to store, degasify and send onshore when needed. (The risk-identification portion of the project has been completed)
Charging Infrastructure implementation masterplan[218]	MPA	Conducting a study on locations for electric recharging facilities to support the electric harbour craft
Keppel Offshore & Marine Ltd Consortium[219]	Keppel Offshore & Marine Ltd, Eng Hup Shipping, The Energy Research Institute @ NTU, Envision Digital, Surbana Jurong and DNV	Use Keppel Offshore & Marine's Floating Living Lab as a testbed for electric charging infrastructure
Green Port[220]	Port of Risavika, DNV, Kystverket, Kystrederiene, Kongsberg, ABB, Equinor	A pilot project to identify the feasibility of and technical needs for the electrification of cranes, trucks, shore-power, hybrid vessels etc

Potential projects

PROJECT	DESCRIPTION
Floating storage and refuelling options	A demonstration of floating storage or refuelling kiosks at ports to determine the impact on port traffic and vessel logistics
Common user infrastructure	A feasibility study on the economic benefit of installing common use pipelines
Retrofitting LPG infrastructure to ammonia	Investigating the technological and economic requirements to retrofit LPG infrastructure to ammonia

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[217] NYK Line (2023) Parties obtain world's first AiP for ammonia floating storage and regasification barge. [Press release] <https://www.nyk.com/english/news/2023/20230105_01.html> (accessed 10 May 2023).

[218] MPA (2023) Media Factsheet: Strengthening Singapore's Competitiveness as a Hub Port and International Maritime Centre. <https://www.mpa.gov.sg/media-centre/details/strenghtening-singapore-s-competitveness-as-a-hub-port-and-international-maritime-centre> (accessed 6 June 2023).

[219] MPA (2023) Media Factsheet: Strengthening Singapore's Competitiveness as a Hub Port and International Maritime Centre. <https://www.mpa.gov.sg/media-centre/details/strenghtening-singapore-s-competitveness-as-a-hub-port-and-international-maritime-centre> (accessed 6 June 2023).

[220] Green Shipping Programme (2020) Green Port. <https://greenshippingprogramme.com/pilot/green-port/> (accessed 19 June 2023).

Challenge 3: Reduce the cost of low-emissions technologies in short-sea vessels

Many large shipping companies are investing in newbuild deep-sea vessels operating on low-emission fuels; however, the cost to smaller firms investing in short-sea vessels can be a larger hurdle. Reducing the initial capital cost barrier for small low-emissions vessels will be the main enabling factor to uptake. Given the capital outlay for these vessel types will be relatively small from an overall funding perspective, investing in these projects presents low-hanging fruit towards decarbonising port operations.

The opportunity for Australia and Singapore

Although not the main contributor to emissions in the maritime sector, short-sea vessels such as tugboats, bunker vessels and ferries will also need to be powered by low-emission fuels to fully decarbonise maritime operations. Introducing low-emissions technologies into the large number of short-sea vessels operating in Australia and Singapore will also give investors confidence that the supply chain is actively working towards full decarbonisation.

Trialling low emissions technologies in short-sea shipping may also provide learnings that can be transferred to other applications. For example, hydrogen fuels cells (FCs) could potentially be adopted for medium-distance journeys on routes where frequent bunkering is possible. Furthermore, incorporating technologies such as methanol or ammonia FCs (direct or indirect) into short-sea vessels may also provide insights that can be applied to deep-sea vessels.

Although each port will have its own combination of short-sea vessels, learnings can be shared across ports and countries. This can provide more certainty on the viability of low-emissions technology in short-sea vessels and reduce costs for later adopters. In Singapore, investments are already being made in this area to support the MPA target for new harbour craft (these vessels must be full electric, capable of using B100 biofuel or compatible with net-zero fuels such as hydrogen by 2030).[221] Learnings from these initiatives could guide Australian ports as to the viable options for decarbonising and ensure that the corridor between the two countries has compatible infrastructure. With 106 ports located around Australia, there is also an opportunity to trial technologies and share those learnings with other ports in Australia.

Supporting information

Battery electric technology is further developed than other low-emission options, making it a favourable short-term solution for short-sea shipping. These systems are currently better suited to smaller vessels and short routes due to the weight and cost of battery technology. Although the high capital cost is still a barrier to adoption for these vessels, this can be offset by the lower fuel costs in the long term.

FCs are being favoured for longer-term adoption in short-sea shipping. There are several types of FCs, such as proton-exchange membrane fuel cells (PEMFC), direct methanol fuel cells (DMFCs), solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC). Currently PEMFC systems that run off pure hydrogen are the most mature (TRL 8). The development of DMFCs (designed to have methanol as the only input) is underway (at TRL 5), but these have much lower efficiencies of around 20%.[222] Finally, SOFCs and MCFCs are higher cost and larger systems that operate at high enough temperatures to allow input from multiple fuels, including methanol.[223]

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[221] MPA (2023) Media factsheet: Strengthening Singapore's competitiveness as a hub port and international maritime centre. <https://www.mpa.gov.sg/media-centre/details/strenghtening-singapore-s-competitveness-as-a-hub-port-and-international-maritime-centre#:~:text=MPA%20will%20set%20the%20target,2050%20national%20net%2Dzero%20target> (accessed 10 May 2023); MPA (2022) Maritime Singapore decarbonisation blueprint: Working towards 2050. Maritime and Port Authority of Singapore.

[222] Ovrum E, et al. (2022) Maritime forecast to 2050. DNV. <https://www.dnv.com/maritime/publications/maritime-forecast-2022/index.html> (accessed 5 June 2023); Tronstad T, et al. (2017) Study on the use of fuel cells in shipping. EMSA. <https://www.emsa.europa.eu/publications/item/2921-emsa-study-on-the-use-of-fuel-cells-in-shipping.html> (accessed 4 May).

[223] Tronstad T, et al. (2017) Study on the use of fuel cells in shipping. EMSA. <https://www.emsa.europa.eu/publications/item/2921-emsa-study-on-the-use-of-fuel-cells-in-shipping.html> (accessed 4 May).

Existing projects

PROJECT/STUDY NAME	PARTNERS	DESCRIPTION
Elektra[224]	Behala, Ballard Power Systems, Anleg	Developed a push boat driven by an electric FC hybrid system
Future of the Fjords[225]	Brodrene Aa	Operating an all-electric passenger catamaran with two electric engines, as well as a floating dock for recharging
Incat Electric[226]	Incat	Integrating an electric and hydrogen FC into a RoPax ferry
Largest lightweight battery electric ship[227]	Incat	Constructing the world's largest 100% battery-electric Ro-Pax ferry, with over 40MWh battery storage
Electric Dream[228]	Incat Crowther	Design and development of full electric passenger ferry to carry passengers between mainland Singapore and the island of Bukom
Sea Change[229]	Incat Crowther	Launch of hydrogen fuel cell-powered electric-drive high speed passenger ferry to operate in California
High-speed hydrogen-powered passenger vessels[230]	Kinn Kommune, DNV, Norwedgian Maritime Authority, Kongsberg, Corvus Energy, ABB, Equinor	A project to pilot a high-speed hydrogen fuel cell-powered passenger vessel (100–150 passenger capacity), and to analyse feasibility, investment and operating costs, payback time and environmental benefits

Potential projects

PROJECT	DESCRIPTION
Trial of FCs	Demonstrate FC propulsion on alternative fuels (hydrogen, ammonia or methanol) using a common use or 'lease style' business model for vessel trials to reduce upfront capital expenditure

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[224] Habibic A (2021) Germany welcomes 1st emission-free hydrogen-fueled push boat. Offshore Energy. <https://www.offshore-energy.biz/germany-welcomes-1st-emission-free-hydrigen-fueled-push-boat> (accessed 4 May).

[225] Brodrene AA (2018) The Fjords takes delivery of groundbreaking 'Future of The Fjords'. <https://www.braa.no/news/future-of-the-fjords> (accessed 4 May 2023)

[226] Incat (2021) Incat electric: The back to zero revolution. <https://www.incat.com.au/wp-content/uploads/2021/08/Back-to-ZERO-Flyer.pdf> (accessed 10 May 2023).

[227] Incat (2023) Australian shipbuilder incat Tasmania to deliver the world's largest battery electric ship. <https://incat.com.au/australian-shipbuilder-incat-tasmania-to-deliver-the-worlds-largest-battery-electric-ship/> (accessed 30 August 2023).

[228] Incat Crowther (2021) Electric dream coming to Singapore. <https://www.incatcrowther.com/news/news-feed/posts/2021/sep/electric-dream-coming-to-singapore/> (accessed 30 August 2023).

[229] Incat Crowther (2021) Zero-emission hydrogen fuel cell ferry hits the water. <https://www.incatcrowther.com/news/news-feed/posts/2021/sep/zero-emission-hydrogen-fuel-cell-ferry-hits-the-water/> (accessed 30 August 2023).

[230] Green shipping programme (2020) High-speed hydrogen-powered passenger vessels. <https://greenshippingprogramme.com/pilot/high-speed-hydrogen-powered-passanger-vessels/> (accessed 19 June 2023).

Appendix B: Decarbonisation solutions assessment

The below provides the rationale for the scores provided in Table 4.

Current fuel price

Currently, the fuel options that are most competitive with conventional fuels are battery electric systems, OCC (assuming this is used alongside conventional fuel) and biomass-derived fuels, such as HVO, FAME and bio-methanol. This is primarily due to these options existing at a commercial scale. E-methanol is currently higher cost than bio-methanol due to the high cost of e-hydrogen and renewable CO_2 (produced using bioenergy with carbon capture or DAC technology). The cost of hydrogen and ammonia produced using NG-CCUS is currently more competitive than renewable alternatives.[231] As a result, stakeholder consultations suggested that these production routes should be considered in the transition while renewable alternatives become cost competitive.

Projected fuel price

Fuel costs are expected to remain the lowest for battery electric and OCC technologies. The costs for e-hydrogen and its derivatives (e-methanol and e-ammonia) are projected to decrease as the scale of renewable electricity production increases; however, the development will take time. The challenges associated with scalability are less severe for hydrogen production and derivatives compared to biofuels. Biomass-derived fuels are expected to face scalability constraints in the long term due to limited supply and the anticipated increase in demand across multiple sectors.[232] This will likely increase the price of these fuels, leading to lower competitiveness in the future.

Onshore storage and transport cost

The lower energy density of hydrogen (and, to a lesser extent, derivatives such as ammonia and methanol) compared with biofuels and conventional fuels will lead to higher onshore storage and transport costs. Charging infrastructure and connections to electricity generation infrastructure will contribute to costs for battery electric systems. OCC systems will incur additional costs from offloading infrastructure and onshore storage, as well as long-distance transport to permanent storage sites.

Onboard capital costs

The onboard capital cost for vessels will depend on the power system, onboard storage requirements and other systems, such as carbon capture.

Of the options considered, biofuels have the lowest capital costs for vessel power systems and onboard storage. These fuels have a similar energy density to conventional fuels and can be dropped into existing diesel or LNG ICEs (although, in some cases, engine modifications are required for blends above 20%).[233]

The technology for methanol two-stroke engines is well developed (TRL 9), with the equivalent for ammonia (TRL 6) due to be piloted in 2024. These solutions will therefore be appropriate for deep-sea shipping because two-stroke ICEs are required to achieve high propulsion power. However, ammonia and methanol have higher power system and onboard storage costs than biofuels.

Current estimates suggest that OCC systems contribute to higher onboard capital costs compared with ammonia and methanol systems.[234] Although OCC systems are still a viable option for larger vessels, they are not suited to short-distance vessels due to large storage requirements.

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[231] Lloyd's Register (2020) Techno-economic assessment of zero-carbon fuels. <https://www.lr.org/en/insights/global-marine-trends-2030/techno-economic-assessment-of-zero-carbon-fuels/> (accessed 10 May 2023); Castellanos G, et al. (2021) A pathway to decarbonise the shipping sector by 2050. IRENA. <https://www.irena.org/publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050> (accessed 5 June 2023).

[232] Lloyd's Register (2020) Techno-economic assessment of zero-carbon fuels. <https://www.lr.org/en/insights/global-marine-trends-2030/techno-economic-assessment-of-zero-carbon-fuels/> (accessed 10 May 2023).

[233] Thepsithar P (2020) Alternative fuels for international shipping. Nanyang Technological University, Singapore; Energy Efficiency and Renewable Energy. Biodiesel blends. U.S. Department of Energy. <https://afdc.energy.gov/fuels/biodiesel_blends.html> (accessed 1 June 2023).

[234] Lloyd's Register (2020) Techno-economic assessment of zero-carbon fuels. <https://www.lr.org/en/insights/global-marine-trends-2030/techno-economic-assessment-of-zero-carbon-fuels/> (accessed 10 May 2023); Mærsk Mc-Kinney Møller Center (2022) The role of onboard carbon capture in maritime decarbonization. <https://cms.zerocarbonshipping.com/media/uploads/publications/The-role-of-onboard-carbon-capture-in-martime-decarbonization.pdf> (accessed 10 May 2023).

The capital costs for hydrogen and battery electric systems are significantly higher than other low-emission solutions. For hydrogen, the challenges relate to its lower energy density, and the high cost of maintaining pressurised or cryogenic conditions. The cost of hydrogen FCs is also significantly higher than the cost for of ICEs, although they are more cost competitive than methanol or ammonia FCs.[235] Similarly, there is a high cost of capital associated with batteries (which are larger and heavier than fuel storage tanks). Due to these high storage costs, these systems are unsuitable for large vessels undertaking long-distance journeys. However, this is not a limitation for smaller vessels travelling shorter distances, where regular refuelling and recharging can reduce the requirement for onboard fuel storage.

GHG emissions

Multiple solutions have the potential to achieve net zero emissions on a well-to-wake basis. However, the impact can vary depending on the production route, highlighting the need for Guarantee of Origin schemes.

The use of hydrogen and derivatives such are ammonia and methanol can be considered carbon neutral across the life-cycle. The combustion of hydrogen and ammonia does not produce CO_2 emissions. Other GHGs may be produced in hydrogen and ammonia ICEs; however, solutions are being developed to reduce these emissions (see Chapter 3.2.4 for further details). When these fuels are used in FCs, there are minimal to no combustion GHG emissions. Although methanol emits CO_2 emissions during combustion, drawing on bioenergy with carbon capture or DAC during production can be used to offset these emissions. The production of hydrogen and derivatives from renewable electricity via electrolysis can achieve zero emissions in the production process. The use of NG-CCUS to produce these fuels will also lead to a considerable reduction in emissions, although, unless capture rates reach 100%, these will not be net zero.

Other solutions can also achieve carbon neutrality. The well-to-wake emissions for drop-in biofuels and bio-methanol will depend on the feedstock and volume blend, with emission reduction potentials ranging from net zero to comparable emissions with MGO. In addition, battery electric systems can achieve net zero if the electricity is generated from renewable sources, given there are minimal to no combustion GHG emissions associated with electricity use.

In contrast to the decarbonisation options above, the emissions reduction potential associated with OCC will be limited. Current evidence suggests that OCC systems will be highly energy intensive and there will be difficulty exceeding capture rates of 30–50% while remaining economically viable.

Safety risk

Hydrogen and ammonia decarbonisation solutions present higher risks to human safety and the environment than other fuel options. Ammonia is classified as high risk because it can be toxic to human health following exposure (depending on the exposure period and concentration) and it can harm marine ecosystems when leakage occurs. Hydrogen safety is classified as moderate in this framework due to its high flammability. Both fuels have regulations and mitigation strategies for onshore handling. However, strategies are yet to be established for onboard use in engines. As a result, there is a lack of acceptability which presents a significant barrier to deploying these fuels.

There are risks with other fuel options, although these have been classified as low or very low in this framework. Batteries present some dangers due to fire risks from electrical faults. These have been incorporated into mitigation strategies and regulations for onboard use. Although methanol has flammability and toxicity risks, these risks are lower relative to those for hydrogen and ammonia. In addition, interim regulations are in place for the onboard use and bunkering of methanol. For biofuels, although there is a slight flammability risk, the risk is lower than for conventional fuels such as MGO.[236] Regulations for the onboard use and bunkering of biofuels have been established.

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[235] This is due to pure hydrogen FCs having favourable properties (lower cost, small system size and moderate–high system power).

[236] Thepsithar P (2020) Alternative fuels for international shipping. Nanyang Technological University, Singapore.

Appendix C: Lower-priority challenges

Although some of the initial challenges identified did not meet all the criteria for this program, these are still significant barriers to adopting low-emissions fuels. The rationale for regarding some challenges as a lower priority for this program is outlined below.

- **Production of hydrogen and derivatives**: The production and export of hydrogen (and derivatives such as ammonia and methanol) present a clear opportunity for Australia. Despite the significant challenges relating to scale, there are already many projects underway in Australia to set up hydrogen production facilities, including the Australian Renewable Energy Hub, the Gladstone Hydrogen Hub, H2Perth and the Tiwi Islands Project.[237] In addition, the types of projects required to lower the cost and increase the supply of fuel are large scale and cannot be addressed with the funding targets of this program.
- **Biofuels**: Drop-in biofuels, such as FAME and HVO, are an effective solution for reducing vessel emissions in the near term. However, these solutions have reached commercial scale, suggesting a minimal investment gap. Furthermore, current evidence indicates that the limited supply of sustainable feedstocks will restrict scalability as a bunker fuel and potentially lead to high prices. Given the likelihood of supply constraints, the biofuels opportunity for Australia and Singapore is expected to be limited.
- **Hydrogen storage solutions**: The cost of hydrogen storage remains a challenge due to lower volumetric energy density. Investing in storage technologies can enable both countries to decarbonise multiple sectors. However, stakeholder workshops suggested that pure hydrogen storage should not be a focus for investment given that other fuel options (e.g. ammonia and methanol) are expected to be more economically viable for deep-sea shipping in the future.
- **Power systems in deep-sea vessels**: Establishing the effective use of low-emissions power systems in deep-sea shipping is important for unlocking opportunities in Australia and Singapore. The most viable fuel options for these vessels (methanol and ammonia ICEs) are being rolled out or will soon be trialled in other parts of the world (where expertise in vessel engine development is already established). As a result, stakeholder workshops suggested that there is already sufficient investment and that these technologies could be adopted in Australia and Singapore once they are commercially available.
- **OCC**: Decarbonisation solutions involving the continued use of fossil fuels presents an opportunity for both countries to reduce emissions in the near term while avoiding the creation of stranded assets. There may also be an economic opportunity associated with these technologies, with the potential for Singapore to transport its CO_2 to permanent storage locations offshore Australia. However, OCC emissions mitigation is lower than other solutions. In addition, the transport and permanent storage of CO_2 could be costly and there may be difficulty in assigning ownership of the CO_2 once it has crossed national borders. Consequently, stakeholder consultations and workshops viewed OCC as a lower priority for this program.

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[237] HyResource (n.d.) Projects. CSIRO. <https://research.csiro.au/hyresource/category/projects/> (accessed 10 May 2023).

Appendix D:
List of participating stakeholders

ORGANISATION	REGIONAL FOCUS
A*STAR Institute of Sustainability	SNG
ABEL Energy	AUS
AMOG Consulting	AUS
Ampol	AUS
ANL	AUS
Australian Hydrogen Council	AUS
Australian Maritime College	AUS
Australian Maritime Safety Authority	AUS
Bell Bay Advanced Manufacturing Zone (BBAMZ)	AUS
BP	AUS; SNG
CWP Global	AUS
DNV	Global
Enterprise Singapore	SNG
Exxon Mobil-Singapore Energy Centre	SNG
Fortescue Future Industries (FFI)	AUS; SNG
Future Energy Exports Cooperative Research Centre (FenEx)	AUS
Gladstone port	AUS
Global Centre for Maritime Decarbonisation (GCMD)	SNG
HAMR Energy	AUS
Iwatani Singapore	SNG
Jurong Port	SNG
Keppel Infrastructure; **Keppel Offshore & Marine**	SNG
Lloyd’s Register Maritime Decarbonisation Hub	Global
Maersk	AUS; Global
Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping	Global
Maritime Industry Australia Ltd (MIAL)	AUS
Maritime Port Authority of Singapore (MPA)	SNG
MMA Offshore	AUS
Ministry of Manpower	SNG
Nanyang Technological University – Maritime Energy and Sustainable Development Centre of Excellence	SNG
Ocean Network Express (ONE)	SNG
Pilbara Port Authority	AUS
Port of Melbourne	AUS
Port of Newcastle	AUS
PSA Singapore	SNG
Provaris	AUS
Sembcorp Marine	SNG
SIEM Offshore	AUS; Global
Singapore Maritime Institute	SNG
Singapore Chemical Industry Council Limited (SCIC)	SNG
Stolt-Nielsen/Stolthaven	AUS; SNG
Sumitomo	AUS; global
Svitzer	AUS
TasPorts	SNG
Temasek/GenZero	SNG
Wärtsilä	SNG; global
Woodside	AUS
Yara	AUS; global

Terminology: AUS, Australia; SNG, Singapore.

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Strategic Partnerships I Growth
Carmel O'Brien, Senior Program Manager, Global
carmel.obrien@csiro.au

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