BLUE ECONOMY
COOPERATIVE RESEARCH CENTRE

HYDROGEN POWERING OF VESSELS

PHASE I REPORT

A REVIEW OF THE FEASIBILITY OF UTILISING HYDROGEN AS A MARINE FUEL IN AUSTRALIA | NOVEMBER 2023

Australian Government
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| ABBREVIATIONS

AC	Alternating current
AFC	Alkaline fuel cell
AIP	Approval in principle
AMSA	The Australian Maritime Safety Authority
AUD	Australian dollars
BoP	Balance-of-Plant
CAPEX	Capital expenditure
COFs	Covalent organic frameworks
CTV	Crew transfer vessel
DBT	Dibenzyl toluene
DC	Direct current
DOE	Department of energy
ETS	Emission trade system
EU	European Union
FAME	Fatty Acid Methyl Ester
FC	Fuel cell
GHG	Greenhouse gas
HT-PEMFC	High-temperature PEMFC
HVO	Hydrotreated Vegetable Oil
H2	Hydrogen
ICE	Internal combustion engine
IEC	The International Electrotechnical Commission
IGF Code	The International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels
IMO	The International Maritime Organization
ISO	The International Organization for Standardization
LHV	Lower heating value
LNG	Liquified natural gas
LOHC	Liquid organic hydrogen carrier
MCFC	Molten carbonate fuel cell
MCH	Methylcyclohexane
MEPC	The IMO's Marine Environment Protection Committee
MOFs	Metal-organic frameworks
Mt	Million tonnes
OPEX	Operational expenditure
PAFC	Phosphoric acid fuel cell
PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cell
PIMs	Polymers of intrinsic microporosity
SGMF	The Society for Gas as a Marine Fuel
SOFC	Solid oxide fuel cell
SOLAS	The International Convention for the Safety of Life at Sea
STCW	The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
TCO	Total cost of ownership
US	United states
USD	US dollars

| EXECUTIVE SUMMARY

This study examined the viability of utilising hydrogen as a power source for domestic vessels in Australia. It delved into the motivating factors driving the acceptance of hydrogen as a marine fuel, explored the existing and anticipated advancements in hydrogen-powered vessels, analysed the technological and economic considerations involved, evaluated the readiness of regulations and standards, and assessed the need for training. Additionally, the study identified specific vessel types that are well-suited for hydrogen adoption and provided a comprehensive overview of the safety design principles applicable to hydrogen-powered vessels.

The study revealed the below key findings:

- Australia's domestic maritime fleet predominantly consists of small vessels. Currently, hydrogen energy solutions are better suited for these smaller vessels, aligning perfectly with the imperative for Australia's domestic maritime sector to attain net zero emissions by 2050.

NET ZERO EMISSIONS BY 2050

The existing hydrogen-powered vessels worldwide, which are mainly of smaller size, serve as valuable examples for the adoption of hydrogen technology in Australian waters.

- Hydrogen fuel cell (FC) systems, already well-established in the automotive sector, can be utilised on ships considering the marine environment.
- Compressed hydrogen and cryogenic liquid hydrogen storage methods are feasible in the short term. Metal hydrides offer safety advantages and high storage efficiency, making them suitable for maritime applications in the future. The potential of liquid chemical hydrogen carriers is limited due to the complexity and high energy consumption associated with the dehydrogenation process.

- Hydrogen bunkering operations have been carried out globally. The high-pressure refuelling technologies in the automotive industry provide valuable references for compressed hydrogen bunkering. Cryogenic liquid hydrogen bunkering has also been successfully demonstrated. In the case of smaller vessels, the portable tank swap mode using ISO tank containers can be a convenient option for both compressed and liquid hydrogen.
- The total cost of ownership (TCO) of a hydrogen FC-powered vessel can be evaluated using available data. The estimated 2022 constant cost range for 700 bar Type IV tanks for maritime use is AUD1490-2210 per kgH2, while for 350 bar Type IV tanks, the estimated 2022 constant cost range is AUD1192-1768 per kg of hydrogen. For PEMFC systems with a power output of 100-250 kW, the projected 2022 constant cost range is between AUD3486 and 7499 per kW, depending on the production scale.

  The estimated 2022 constant cost range for PEMFC stacks is between AUD504 and 812 per kW, depending on the production scale. The 2022 constant cost of a lithium-ion battery pack for maritime use is estimated to be AUD331/kWh. The estimated levelised cost of hydrogen dispensed by refuelling stations in Australia could range from AUD6.78-15.60/kg according to CSIRO. The FC stack and battery are anticipated to be replaced several times throughout the ship's lifespan.
- The regulatory, normative, and standard framework for hydrogen-powered ships is steadily taking shape, with obstacles in this regard gradually being overcome.
- Training programmes related to hydrogen-powered vessels have not yet been built and conducted in Australia. It is imperative to promptly initiate training programs for the operation and bunkering of hydrogen-powered ships.

In the initial stages, the implementation of feasible hydrogen-powered ships should primarily target small-sized vessels operating on fixed routes. This approach ensures the practicality of fuel bunkering and the availability of hydrogen power systems.

- The design process of a hydrogen-powered vessel incorporates both the regulatory established design method and the alternative risk-based design methods, considering the safety risks associated with hydrogen and the current insufficiency of regulations and standards.

To address the identified gaps and accelerate the adoption of hydrogen on vessels in Australia, the following recommendations were proposed:

- Developing or adopting regulations and standards for designing, building, and certifying hydrogen-powered vessels in Australia.
- Establishing risk assessment methods for designing and assessing hydrogen-powered vessels.
- Establishing and implementing comprehensive training programmes for ship crew and bunkering workers to facilitate the adoption of hydrogen on vessels.

To expedite the use of hydrogen on vessels in Australian waters to meet the country's net zero emission target, the study recommends the following actions:

- Conducting conceptual hydrogen powertrain design for selected target vessels in Australia.
- Evaluating and comparing TCO of potential hydrogen-powered vessels with other zero-emission solutions.
- Assessing and comparing the lifecycle GHG emissions of potential hydrogen-powered vessels with other zero-emission solutions from a lifecycle perspective.
- Building or retrofitting hydrogen-powered vessels and gathering relevant data to lay the foundation for the widespread adoption of hydrogen-powered vessels on a large scale in Australia.

By implementing these recommendations, Australia can take substantial steps towards establishing a sustainable and zero-emission maritime industry, harnessing the potential of hydrogen as an environmentally friendly and efficient marine fuel.

1. BACKGROUND

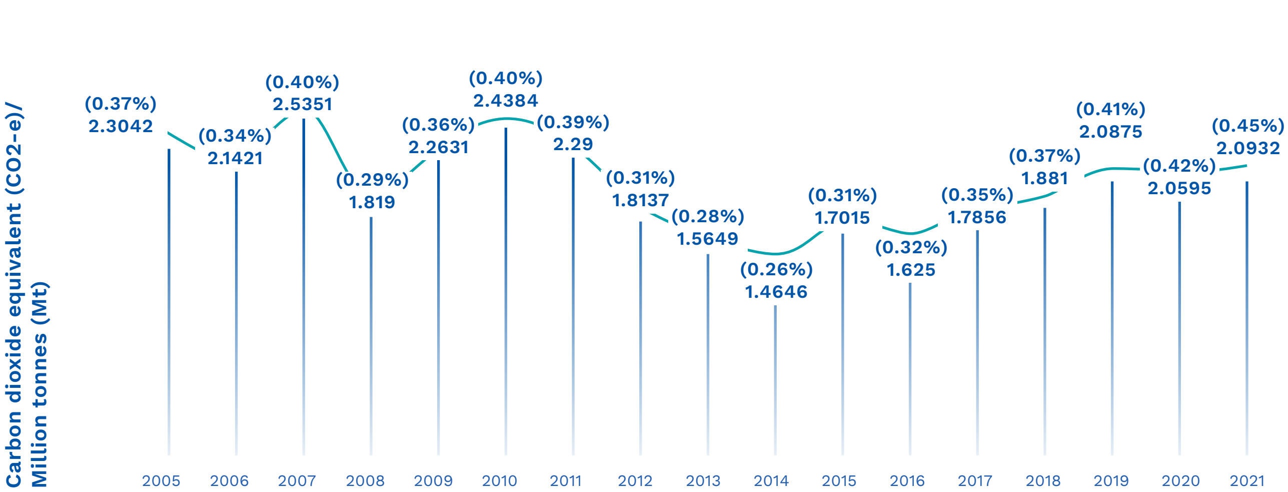
Decarbonising Australia's maritime fleet requires coordinated efforts from both Australian-flagged international ships and domestic vessels. As a signatory country to the International Maritime Organization (IMO), Australian-flagged international navigation ships must follow the IMO's decarbonisation roadmap (IMO, 2023). Meanwhile, Australia's domestic maritime sector must align the country's emission reduction timeline. This report is specifically dedicated to the decarbonisation of Australia's domestic maritime sector using hydrogen as an energy source.

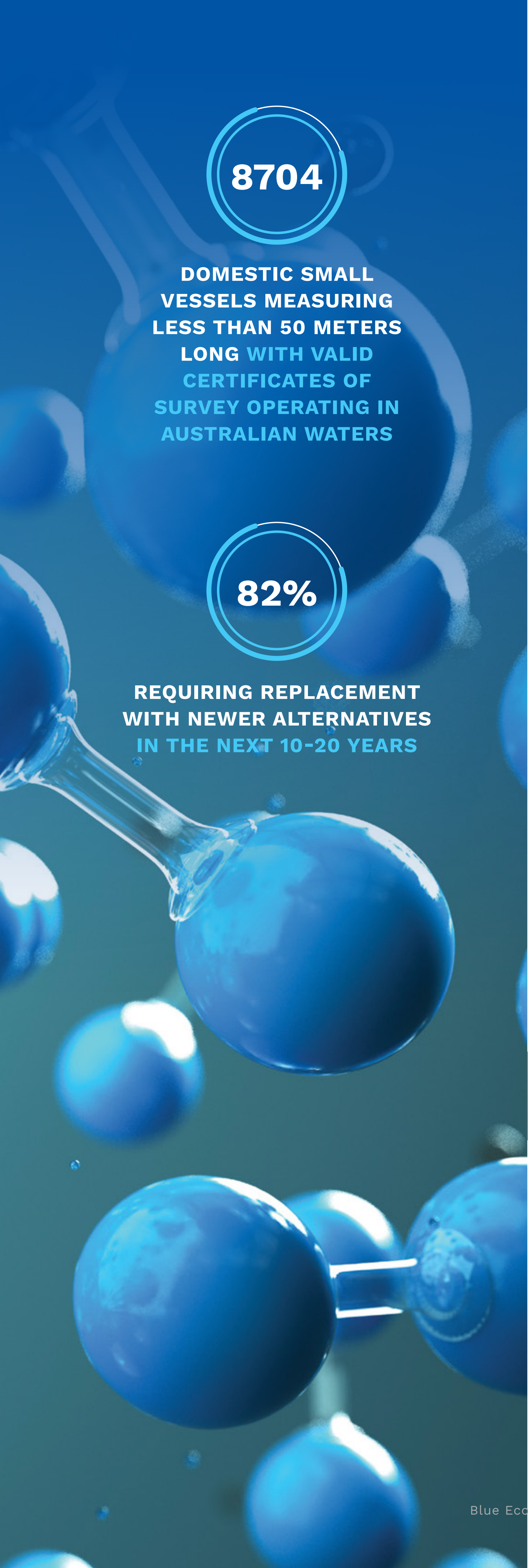
1.1. DECARBONISATION GOALS

Australia has announced to achieve net zero greenhouse gas (GHG) emissions by 2050, and cut emissions by 43% from 2005 levels by 2030 (Australian government, 2022; Reese, 2021). Therefore, the emission reduction timeline for Australia's domestic vessels should align with this overarching goal.

Based on the data submitted by the Australian Government to the United Nations Framework Convention on Climate Change (Australian government, 2023), Figure 1 illustrates Australia's domestic maritime navigation carbon dioxide equivalent (CO2-e) emissions from 2005 to 2021. In recent years, domestic maritime emissions have consistently hovered around 2 million tonnes per year, constituting approximately 0.4% of the nation's total annual emissions. To achieve the decarbonisation targets, these emissions should be reduced by 43% from 2005 levels, reaching 1.31 million tonnes annually by 2030, and ultimately reach zero emissions by 2050.

Figure 1. Australian domestic maritime GHG emissions.





1.2. DECARBONISATION PATHWAYS AND HYDROGEN'S ROLE

To mitigate GHG emissions from vessels, various operational and technical measures, and market-based mechanism (carbon tax and subsidies) have been identified, as shown in Figure 2.

Operational measures comprise a range of strategies, including voyage optimisation methods, such as optimising speed, port logistics, vessel capacity, and on-board energy management, and digitalisation of shipping using technologies such as the Internet of Things (IoT) and autonomous shipping. Technical methods focus on implementing energy-saving measures, exploring alternative fuels or energies, and using the carbon capture technology. Energy-saving measures may include optimising vessel design, improving engine technologies, utilising improved propulsion technologies, and adopting power assistance methods. Alternative fuels and energy sources include using low emission fuels such as liquefied natural gas (LNG) and adopting zero or near zero emission fuels or energy. Using operational measures, low emission fuels, and carbon capture method may prove effective in achieving medium decarbonisation targets; however, to achieve zero emission target, utilising zero emission fuels or energy is the sole viable option.

Zero emission fuels or energy compromises biofuels and green electricity. Viable biofuels include Fatty Acid Methyl Ester (FAME), Hydrotreated Vegetable Oil (HVO), Bio-LNG, and Bio-methanol. The green electricity can be stored in batteries or e-fuels (or so-called "Power-to-X"), which include hydrogen, e-ammonia, e-methanol, and e-LNG. Each fuel or energy form has a role to play in achieving the zero-emission target.

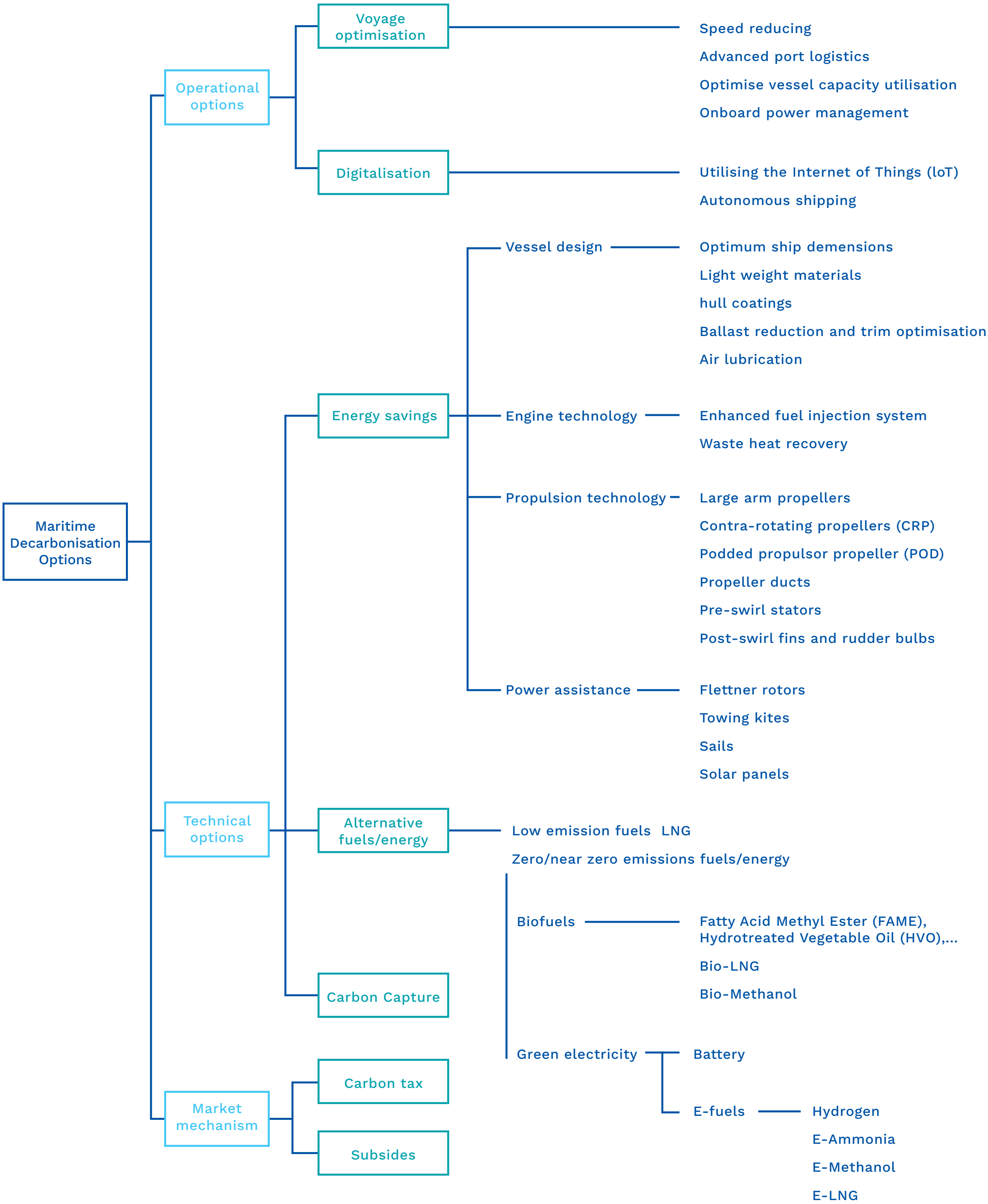
In Australia, small vessels are responsible for major portion of GHG emissions from the domestic navigation sector.

According to the Australian Maritime Safety Authority (AMSA), as of July 2023, there are 8704 domestic small vessels, measuring less than 50 meters long, operating within Australian waters with valid certificates of survey. Among these vessels, 7114 (82%) are already over a decade old, necessitating their replacement with newer alternatives within the next 10-20 years. Vessels have long lifespans (25-30 years). This means that the new vessels will remain in operation through 2050. Therefore, it becomes crucial to explore energy sources capable of facilitating zero emissions for these upcoming replacements.

This study focuses on utilising hydrogen on Australian domestic vessels. This is primarily because:

- Hydrogen serves as an excellent carrier of renewable energies such as wind, solar, and hydropower, which can be released as heat through combustion or as electricity through fuel cells (FCs), and the only additional input required is oxygen, and the sole by-product produced is water. Not only GHG emissions but also air pollutants, such as sulphur oxides, nitrogen oxides, and particulate matter, could be well addressed using hydrogen as a fuel.
- Current hydrogen solutions are better suited for small vessels.

Figure 2. Decarbonisation pathways for vessels.



2. CURRENT STATUS OF HYDROGEN APPLICATIONS IN THE MARITIME SECTOR

The first hydrogen-powered boat, called "Hydra," made its debut in Germany in 2000. Designed as a passenger boat, it featured a metal-hydride hydrogen storage tank capable of storing 3kg of hydrogen, along with a 6.8kW alkaline FC serving as its primary power source. The refuelling process for Hydra took approximately thirty minutes. With a cruising speed of 4.8 knots, the boat could travel for 16 hours on a full tank. Unfortunately, the ship owner went into liquidation in September 2001. However, before its untimely demise, this ground-breaking creation transported over 1600 passengers (Butler, 2019).

Since then, the maritime industry has witnessed a growing number of hydrogen-powered ships being constructed or retrofitted to explore their feasibility and demonstrate their potential. Currently, more and more hydrogen-powered vessels are under construction, on order, or under development. This section provides an overview of these hydrogen-powered vessels and discusses the prospects of future advancements in this field.

2.1. EXISTING HYDROGEN-POWERED VESSELS

As of June 2023, a total of 41 hydrogen-powered vessels have undergone testing and most of them are currently operational.

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The information of these vessels can be found in Appendix Table A1. Figure 3 shows the number of vessels categorised by their respective delivery year. As the maritime industry prioritises the decarbonisation of its operations, the emergence of hydrogen-powered vessels has been on the rise since 2021, and 19 out of the existing ships (46%) were delivered after 2021. Figure 4 presents a breakdown of the number of ships based on the countries. It is evident that a considerable proportion of these vessels are in Europe, while the United States (US), East Asian countries such as China, Japan, and South Korea, as well as New Zealand, have also some hydrogen-powered vessels.

Figure 3. Hydrogen-powered vessels by delivery years.

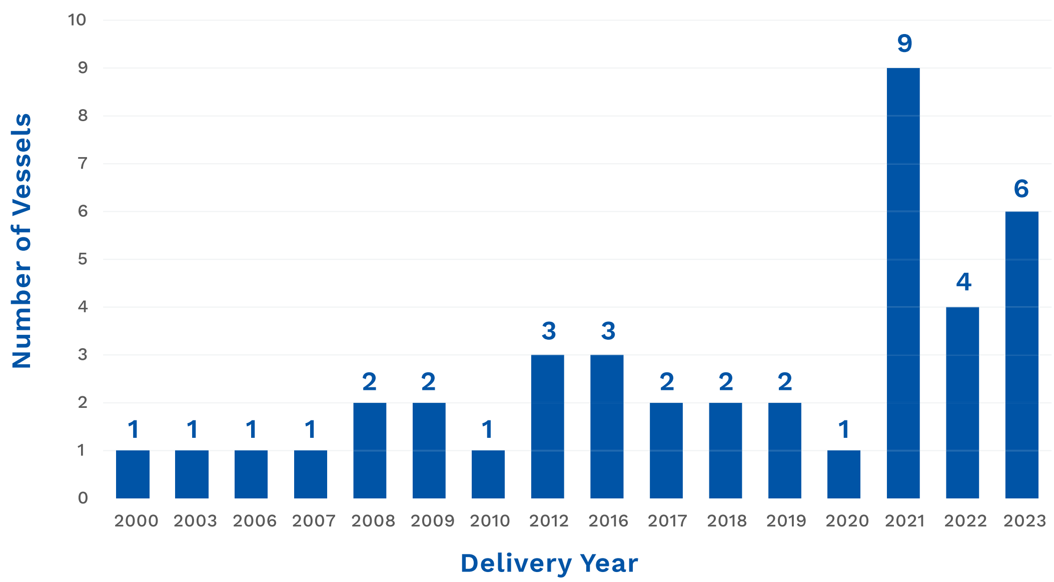
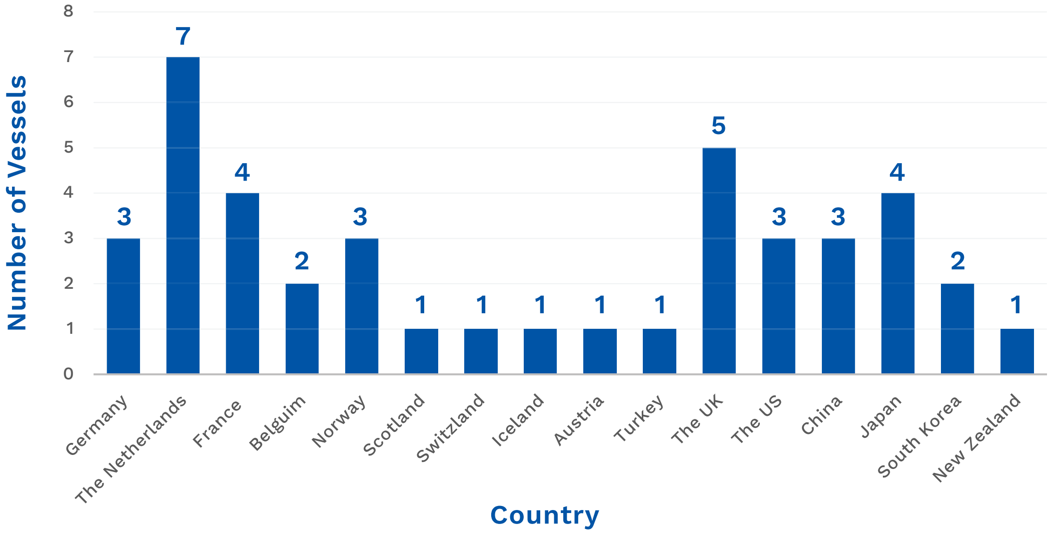


Figure 4. Hydrogen-powered vessels by countries.



The fleet of existing hydrogen-powered vessels comprises a diverse range of ship types, encompassing passenger ships, cargo ships, tugboats, sailing boats, and race boats.

The distribution of these ship types is presented in Figure 5, highlighting the versatility and feasibility of utilising hydrogen across various vessel categories. Figure 6 shows that most of these vessels use hydrogen as main power source.

Figure 7 shows photos of the selected vessels. Most the existing hydrogen-powered vessels are classified as small-sized vessels, as illustrated in Figure 8. A significant majority of these vessels, specifically 34 (83%) out of the total have a length of less than 50 meters. This indicates that the existing cases of small-sized vessels utilising hydrogen can be crucial references for achieving the zero-emission target for Australia's domestic maritime sector.

Figure 5. Hydrogen-powered vessels by ship types.

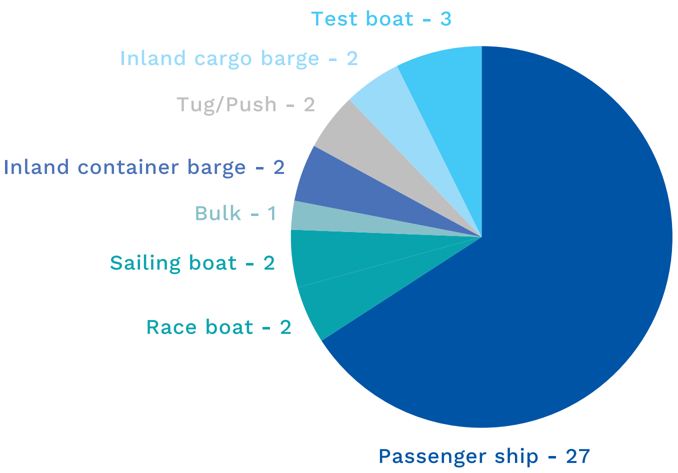


Figure 6. Hydrogen-powered vessels by power source type.

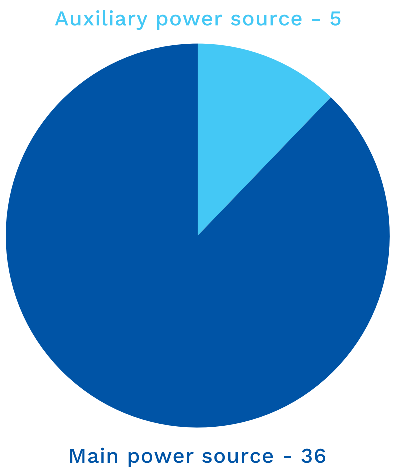


Figure 7. Selected typical hydrogen-powered vessels.

2023, Inland cargo barge, "Antonie", The Netherlands

2023, Inland container barge, "H2 Barge 1", The Netherlands

2023, Tugboat, "Hydrotug 1", Belgium

2023, Passenger ship, "San Xia Qing Zhou 1", China

2022, Race boat, "Chase Zero", New Zealand

2022, Offshore crew transfer vessel (CTV), "Hydrocat 48", The UK

2021, Ferry, "Sea Change", The US

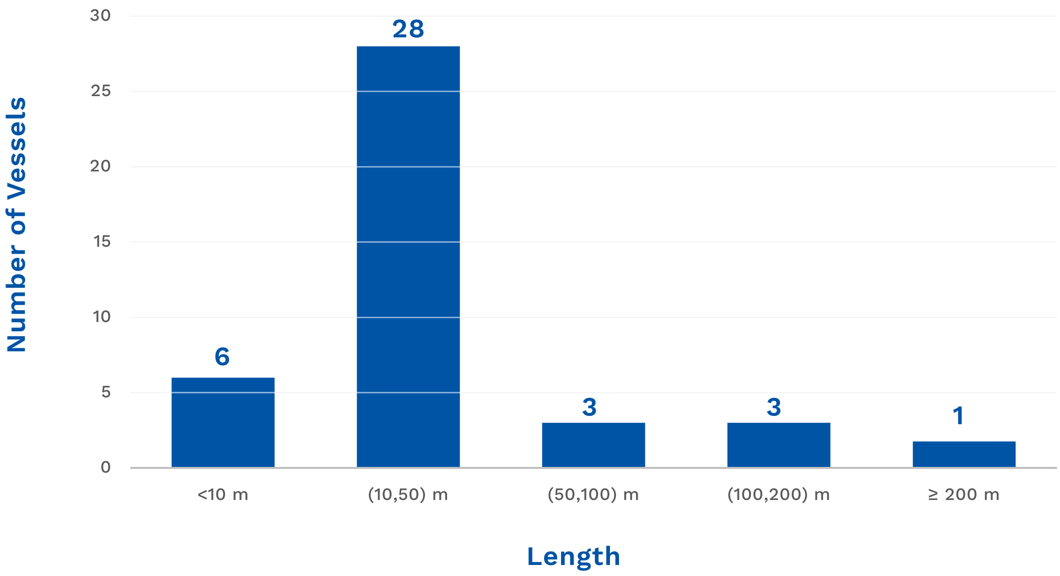
2021, Ferry, "MF Hydra", Norway

2021, Passenger ship, "Hydro BINGO", Japan

2021, Inland pusher tug, "Elektra", Germany

Note: see appendix table A1 for the sources of the pictures

Figure 8. Hydrogen-powered vessels by ship lengths.



Regarding newbuilding vessels, designers have the flexibility to incorporate hydrogen systems by adapting traditional designs.

Retrofitting existing vessels, on the other hand, presents some complexities, as it involves replacing diesel systems with hydrogen systems and complying with safety requirements outlined in class rules.

Figure 9 provides an overview of the distribution of new build vessels and retrofitted vessels, illustrating the efforts in adopting hydrogen technologies in both newbuilding and retrofitting sectors.

A variety of technologies have been explored and tested on the vessels. Among the existing vessels, 36 of them utilise hydrogen as their primary power source, while 5 vessels employ hydrogen as an auxiliary power source.

Compressed hydrogen storage is the prevailing method adopted for onboard fuel storage, as indicated in Figure 10. However, other storage methods such as cryogenic liquid hydrogen and material-based method (hydride) have also been utilised.

Figure 11 provides an overview of the distribution of FC and internal combustion engine (ICE) technologies used on these vessels.

A significant majority of the vessels utilise proton exchange membrane (PEM) FCs. It is worth noting that the existing hydrogen-powered vessels typically have lower FC power capacities, with a significant number of them falling below 200 kW. Only one ship's FC power is greater than 1 MW reaching 1.2 MW.

Figure 12 and Figure 13 present the distributions of the power of individual FC modules and the total FC power per ship respectively, providing insights into the power capacities of these vessels.

Figure 9. Hydrogen-powered vessels by new-build or retrofit.

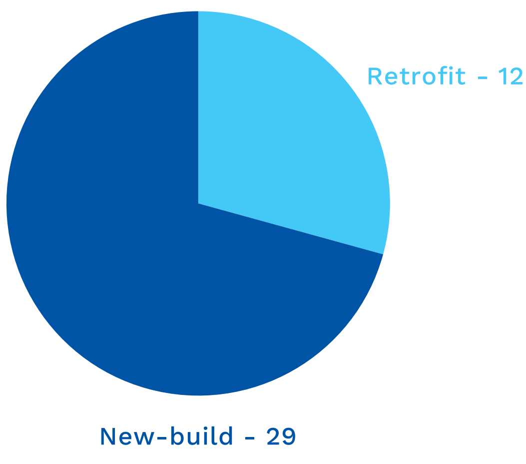


Figure 10. Hydrogen-powered vessels by hydrogen storage methods.

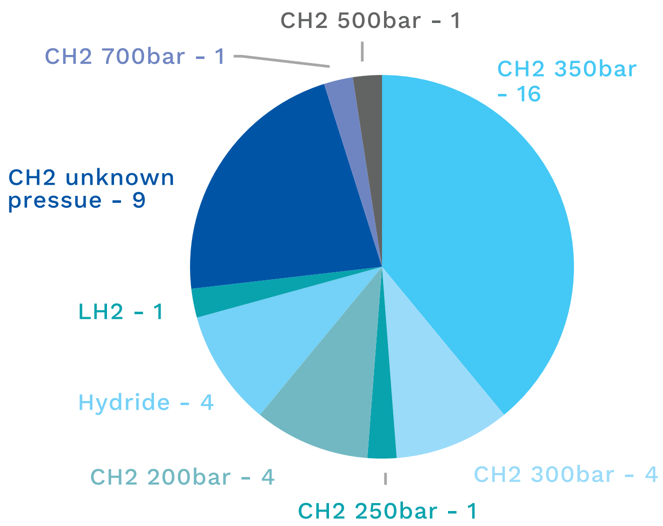


Figure 11. Hydrogen-powered vessels by energy conversion methods.

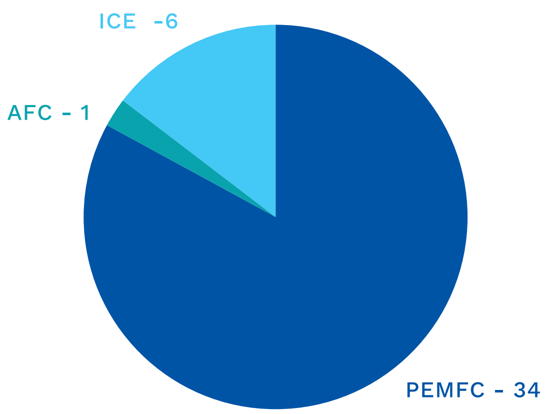


Figure 12. Hydrogen-powered vessels by fuel cell single module power.

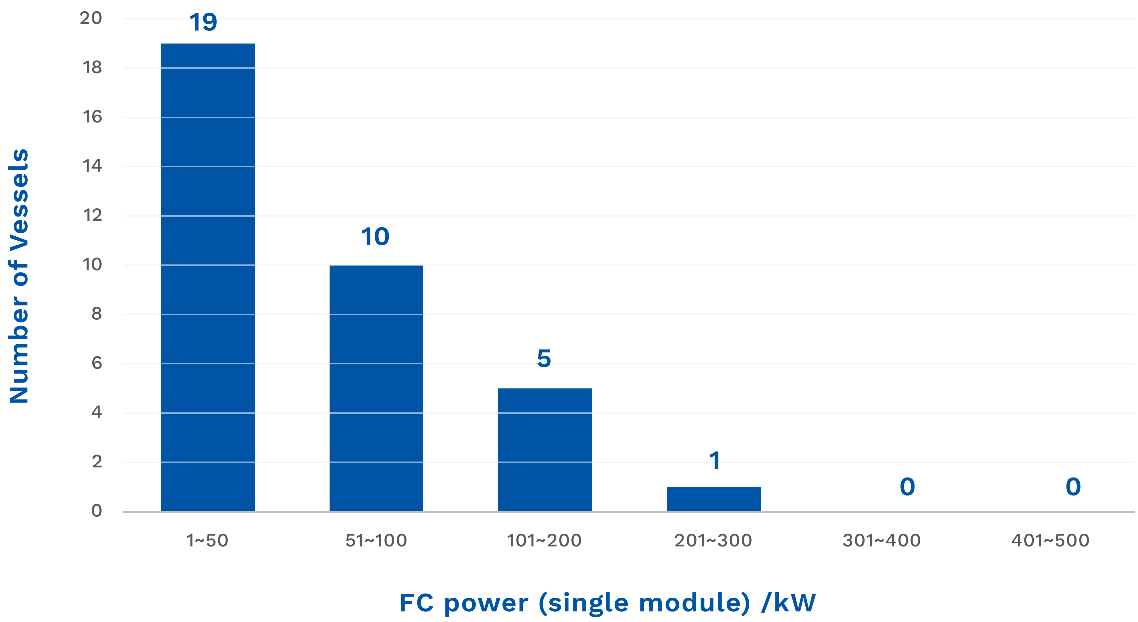


Figure 13. Hydrogen-powered vessels by fuel cell power.

2.2. FUTURE HYDROGEN-POWERED VESSELS

With the maturing of hydrogen-related technologies, the maritime industry is venturing into the exploration of larger and more advanced hydrogen-powered vessels.

Several countries have set ambitious targets in this regard. Notably, the California Air Resources Board in the US has established a goal to ensure that at least 25% of ships operating in California waters will be powered by hydrogen FCs by 2045 (Mandra, 2022).

According to the currently available information, by 2030, at least 35 hydrogen-powered vessels are expected to be delivered around the world. Most of these vessels will utilise PEMFCs as their primary propulsion power source. Among them, certain vessels will have FC power ranging 2-6 MW, with the largest vessel reaching a maximum power of 23 MW, which is equivalent to the maximum power levels of existing fossil fuel powered ships. Detailed information about the future hydrogen-powered vessels can be found in Appendix Table A2.

3. TECHNOLOGIES

The core technologies for utilising hydrogen as an energy source in maritime applications include energy conversion technologies (FCs or ICEs), hydrogen storage technologies, and hydrogen bunkering technologies. This section discusses the characteristics and maturity levels of the technologies.

3.1. ENERGY CONVERSION

The technologies of using hydrogen as a power source on vessels can be primarily divided into two types: using hydrogen as a feedstock to generate electricity in FCs and using hydrogen as a fuel in ICEs, where it reacts directly with oxygen to produce thermal energy.

3.1.1. Fuel Cells

Hydrogen FCs facilitate the direct conversion of chemical energy inherent in the fuel into electrical energy via chemical reactions.

These electrochemical devices can serve as a reliable power source for vessels. Comprising positive and negative electrodes and an electrolyte, FCs operate through oxidation and reduction reactions that transpire on opposing sides of the electrolyte membrane. As the liberated electrons move through an external circuit, they generate a continuous flow of electrical energy. By sustaining a steady inflow of fuel and oxidant, FCs maintain an uninterrupted generation of electrical energy.

Hydrogen FCs can be classified into various types based on the type of electrolyte they employ, including Alkaline Fuel Cell (AFC), Proton Exchange Membrane Fuel Cell (PEMFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC), and Solid Oxide Fuel Cell (SOFC). PEMFC can be further subdivided into Low-Temperature PEMFC (typically represented as PEMFC) and High-Temperature PEMFC (HT-PEMFC). The comparison of these technologies can be found in the literature (ENERGY.GOV, 2023).

It appears that there is a preference for PEMFC when regarding maritime applications due to its high technology readiness level. PEMFC operates at relatively low temperatures, which enhances its flexibility, safety, and quick start-up.

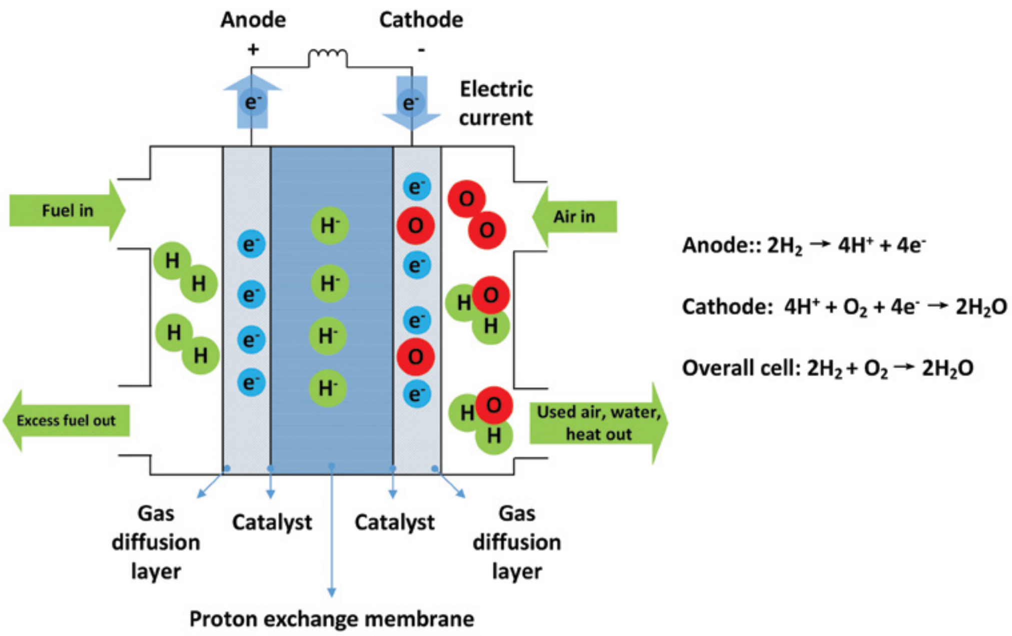
Figure 14 shows a schematic of a typical PEMFC. It consists of anode and cathode, sandwiched around a PEM. Hydrogen is fed to the anode, and air is fed to the cathode. A catalyst separates hydrogen atoms into protons and electrons, which take different paths to the cathode.

The electrons go through an external circuit, creating a flow of electricity. The protons migrate through the electrolyte to the cathode, where they reunite with oxygen and the electrons to produce water and heat.

When PEMFC is employed to provide power for vessels, it is commonly achieved by arranging multiple identical FC units in series or parallel to form a FC module. Multiple FC modules are then connected in series or parallel to create a FC stack.

The PEMFC system comprises the FC stack and its balance-of-plant (BoP) systems including hydrogen supply system, air supply system, and cooling system, as shown in Figure 15.

Figure 14. Schematic of a PEM fuel cell.



As FCs do not deliver mechanical energy as needed for propulsion, they must be combined with electric motors. Figure 16 presents a simplified powertrain of a vessel.

As hydrogen FCs produce direct current (DC) electricity, vessels typically employ a DC distribution system. The FC system is connected to the DC bus via a DC-DC converter, which stabilises the variable amplitude DC electricity generated by the FC system. The DC bus is then connected to an inverter, converting the DC electricity on the bus into alternating current (AC) electricity to power propulsion motors and the onboard electrical grid for daily loads. The motors drive the rotation of the main propulsion propeller or azimuth thrusters.

Figure 15. Schematic of the fuel cell power system.

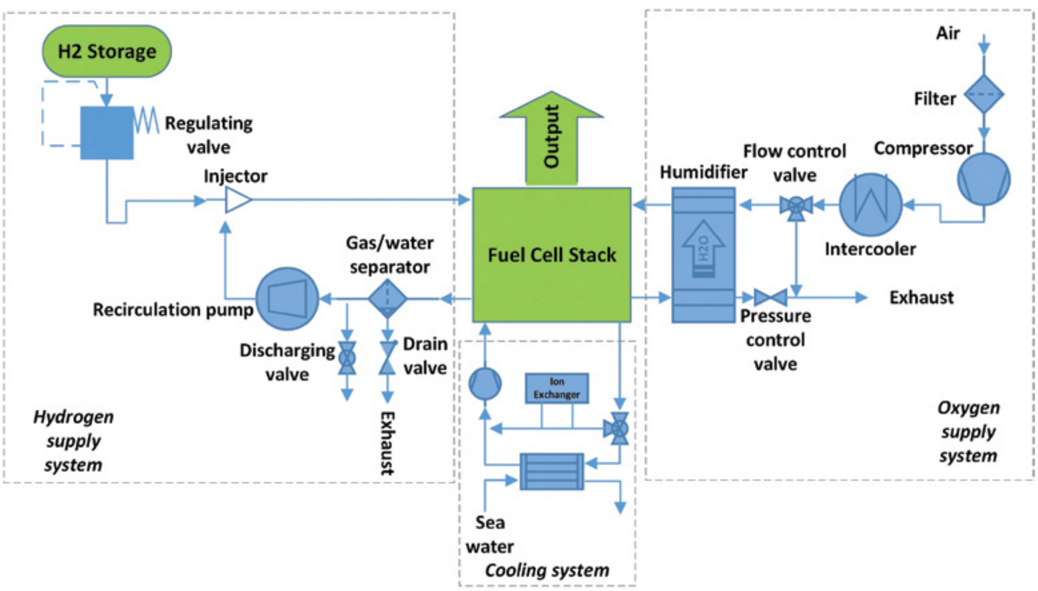
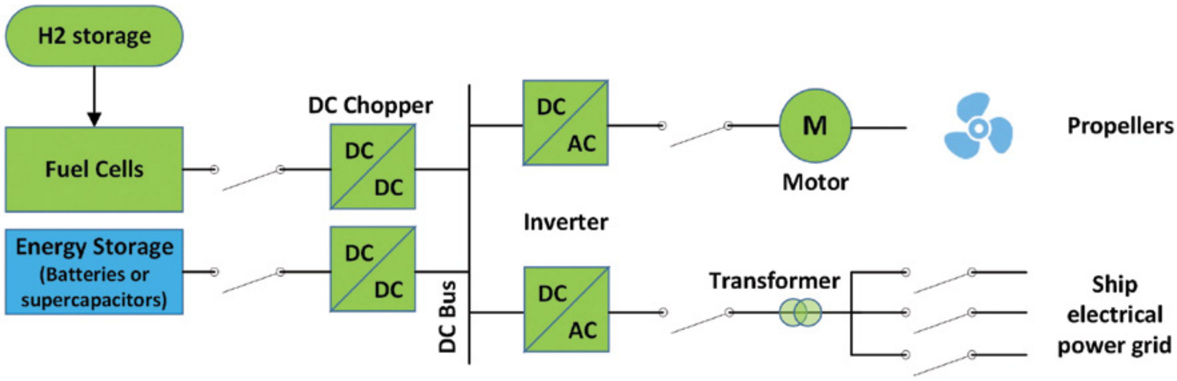


Figure 16. A simplified FC powertrain for a vessel.



Vessels experience frequent changes in load during navigation and operation. It is important for the hydrogen FC system to respond promptly to these variations.

However, FCs typically require several minutes to adjust to sudden changes in operating conditions, which may not meet the load demands of a vessel. Therefore, FC systems are often integrated with energy storage devices such as batteries and supercapacitors, to form hybrid propulsion systems, as depicted in Figure 16. Energy storage devices come into service in load variations.

When the ship requires low power and the FC system generates excess electricity, it can be used to charge the energy storage device via the DC bus. On the other hand, from the Safe Return to Port (SrtP) perspective, the energy storage device such as battery is necessary and its capacity should be sufficient, particularly for passenger ships. It is crucial to employ energy management coordination and control systems to regulate the flow of different energy sources for the hybrid propulsion systems. This ensures the stability, reliability, and safety of ship operations.

Currently, there are some commercialised maritime PEMFC systems in the market. Table 1 presents selected maritime PEMFC suppliers and their product parameters, where the maximum nominal rated output power is 600 kW. To achieve higher power output, individual FC modules can be connected in series and/or parallel to form a FC stack assembly to meet the power demands of vessels.

Nevertheless, the primary limitations of these maritime PEMFC products lie in their substantial weight and size. The most compact design currently available is 4.7 kg/kW and occupies 0.0072 m3/kW, making it considerably heavier and larger than traditional maritime ICEs.

Table 1. Selected market available maritime FC systems.

MAKER	COUNTRY	NOMINAL POWER OF SINGLE MODULE (KW)	REF.
Ballard	Canada	100-200	(Ballard, 2023)
Nedstack	The Netherlands	120-600	(Nedstack, 2023a, 2023b)
TECO 2030	Norway	325	(TECO 2030, 2023)
CSSC	China	70	(GGFC, 2021b)
Yanmar	Japan	300	(Yanmar, 2023)

3.1.2. Internal Combustion Engines

The predominant propulsion systems utilised on ships at present are centred around ICEs.

The adoption of hydrogen as a fuel provides the possibility to modify existing engine concepts to accommodate hydrogen, while also facilitating the development of dedicated engine designs for hydrogen fuel.

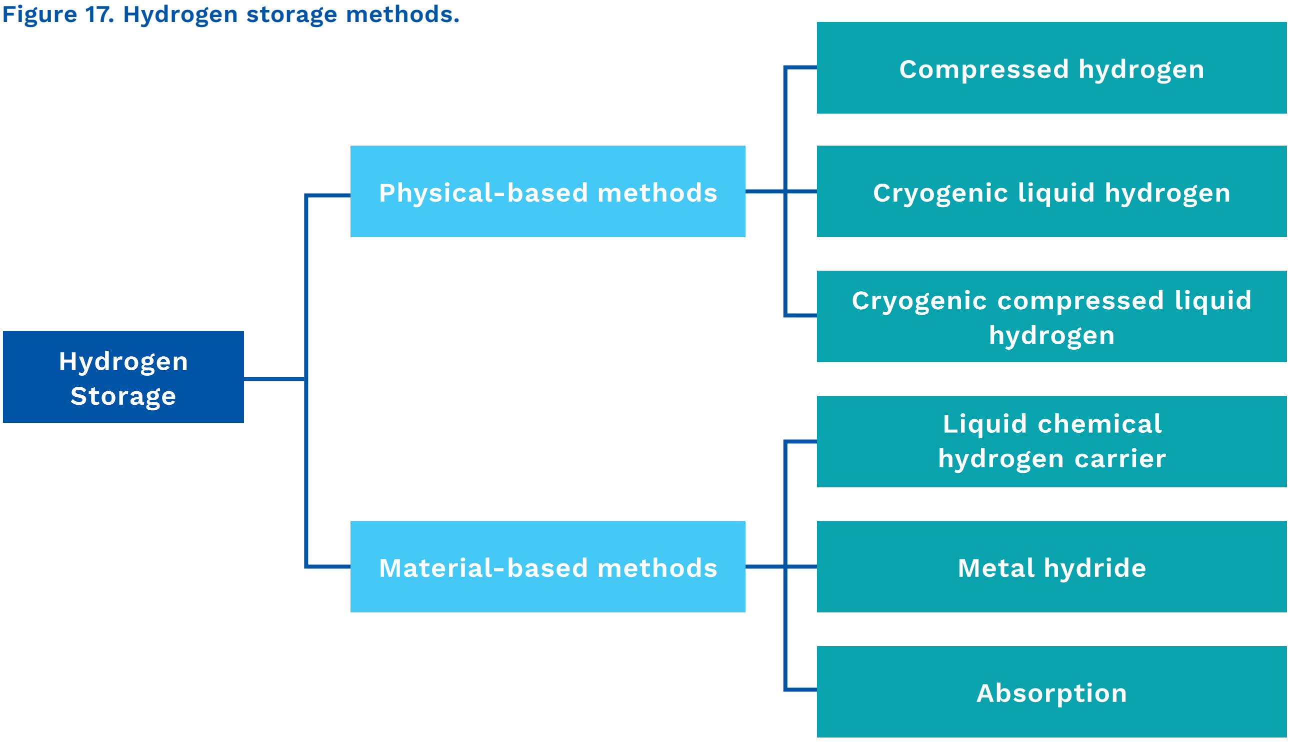
The structure and working principles of hydrogen ICEs are similar to conventional ones. It can operate with lower-grade hydrogen which is handy for specific use cases. Nevertheless, achieving optimal performance in a hydrogen ICE poses a significant challenge. Due to hydrogen's low ignition energy, hot gases and hot spots on the cylinder can act as potential ignition sources, leading to issues such as premature ignition and flashback. Additionally, the broad flammability range of hydrogen implies that a hot spot can ignite nearly any mixture it encounters.

Therefore, hydrogen ICE has not yet been used commercially on a large scale. Some engine manufacturers, for instance, Cummins, Toyota, and Yamaha, have been testing hydrogen engines to mitigate the risks associated with hydrogen (Cummins, 2022; Frangoul, 2022). To mitigate risks, hydrogen-diesel dual fuel engines are under development or tested (Ghazal, 2019; Schwartz, 2022). The world's first hydrogen-fuelled tugboat uses a hydrogen-diesel dual fuel ICE (MarineLink, 2022). However, utilising dual-fuel engines cannot achieve zero-emission target, and it is essential to ensure that NOx emissions comply with the international and flag regulations.

3.2. HYDROGEN STORAGE

The density of hydrogen gas at standard atmosphere is 0.084 kg/m3. Hydrogen's boiling point is -252.77 °C, its melting point is -259.1 °C, and its critical point is -240 °C at 1.32 MPa. Therefore, Hydrogen storage onboard is challenging. As shown in Figure 17, hydrogen can be stored using physical-based methods, such as compressed hydrogen, cryogenic liquid hydrogen, and cryogenic compressed liquid hydrogen, and material-based methods, including using liquid chemical hydrogen carriers, metal hydrides, and adsorbents.

Figure 17. Hydrogen storage methods.



3.2.1. Physical-based storage

(1) Compressed hydrogen

Compressed hydrogen storage refers to the storage of hydrogen gas under high pressure, and the required pressure level depends on specific applications.

For maritime applications, the volume of hydrogen is a critical factor for vessel designs, so higher pressures are necessary. Higher pressure means more hydrogen can be stored, allowing for longer distances to be travelled, but it also requires additional safety precautions.

As a result, two typical pressure levels, 350 and 700 bar, are currently used in the maritime sector. Some demonstration projects use lower pressure, for instances 200 and 300 bar, to reduce the risk of hydrogen release.

Compressed hydrogen gas storage tanks are categorised into Type I, II, III, IV, and V (Figure 18) based on their construction and operational characteristics (Langmi et al., 2022).

Type I tanks are made of metal and are heavy, suitable for low-pressure storage. Type II tanks are also made of metal but have an additional layer for increased pressure resistance. Type III tanks' liners are made of metal and their wrap layers are made of composite materials, such as carbon fibre reinforced polymer, offering higher strength and reduced weight. Type IV tanks are entirely composite, utilising composite materials and a plastic liner, providing excellent strength-to-weight ratios and high-pressure capabilities. Type V tanks do not have an internal liner so the composite acts as both the gas barrier and load bearing structure for further weight reduction and increased capacity (Air et al., 2023).

The choice of tank type depends on the specific application's requirements regarding pressure, weight, storage capacity, and cost. Type III and IV tanks have been used on the existing hydrogen-powered vessels (Figure 10).

(2) Cryogenic liquid hydrogen

The storage of hydrogen in a liquefied state offers the highest storage density, making it a preferred option for minimising storage size. Liquid hydrogen storage has the added benefit of being able to be stored at a low pressure of approximately 4 bar. However, the major disadvantage is that hydrogen becomes liquid at an extreme low temperature of -253°C (at atmospheric pressure), requiring specialised cryogenic tanks with reliable thermal insulation to reduce vapourisation caused by heating. Additionally, the current industrial capacity to produce liquid hydrogen is relatively low, which poses a challenge for the widespread adoption of this storage method.

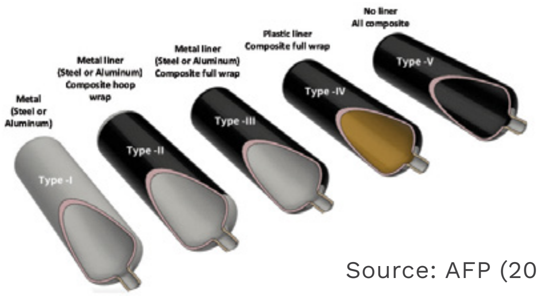
While cryogenic liquid hydrogen technologies have been utilised in the aerospace industry for several decades in the US and China (Ustolin et al., 2022), they are prohibitively expensive for civilian applications. Currently, there is only one known hydrogen-powered vessel named "MF Hydra" in Norway that utilises cryogenic liquid hydrogen for storing hydrogen (Ivan Østvik, 2021).

(3) Cryogenic compressed hydrogen

Cryogenic compressed hydrogen storage involves storing hydrogen at cryogenic temperatures in a pressurised vessel (for example, at 300 bar). This method differs from conventional cryogenic storage, which stores liquid hydrogen at near-ambient pressures. Cryogenic compressed hydrogen storage can encompass liquid hydrogen, cold compressed hydrogen, or hydrogen in a two-phase region (saturated liquid and vapour) (Langmi et al., 2022). It offers the potential for even higher densities compared to cryogenic liquid hydrogen. However, achieving these densities requires specific design considerations, including effective thermal insulation and the incorporation of a high-pressure accumulator. Consequently, cryogenic compressed hydrogen storage systems often have thicker walls and increased weight.

While this storage method shows promise in meeting volumetric capacity requirements in the maritime industry, it suffers from high manufacturing, operating, and maintenance costs.

Figure 18. Type I-V compressed hydrogen tanks.



Source: AFP (2022)

3.2.2. Material-based Storage

(1) Liquid chemical hydrogen carrier

Numerous chemical compounds can react with hydrogen and act as chemical storage. The promising chemical compounding forms are liquid ammonia, methanol, or liquid organic hydrogen carriers (LOHCs) such as methylcyclohexane (MCH) and dibenzyl toluene (DBT) (Hydrogen Council, 2021; Meca et al., 2022).

Ammonia is a compound of hydrogen and nitrogen in the form of NH3 synthesised via the Haber-Bosch process (MacFarlane et al., 2020). Methanol is a hydrogen carrier in the form of CH3OH. The reaction of H2 with CO2 to form methanol and water (IRENA, 2021). LOHCs are emerging hydrogen carriers, where hydrogen is stored inside a LOHC molecule (exothermic hydrogenation) and released (endothermic dehydrogenation) at the point of consumption. Then, the dehydrogenated LOHC returns to the hydrogenation point to start a new cycle (Niermann et al., 2021).

These chemical compounding forms can be stored under relatively easy conditions compared to compressed hydrogen and liquid hydrogen. Liquid ammonia can be stored at minus 33 °C under atmospheric pressure or at 0.8–1.0 MPa under atmospheric temperature (Al-Aboosi et al., 2021; Fan et al., 2022; Valera-Medina et al., 2021). Methanol and LOHCs can be stored in liquid forms at normal temperature and pressure (McKinlay et al., 2021; Raab et al., 2021). However, the use of liquid chemical hydrogen carriers can be constrained by reversibility issues, as not all compounds can efficiently regenerate pure hydrogen during the release process. Additionally, the onboard dehydrogenation processes consume a significant amount of energy, rendering them uncompetitive for maritime applications.

(2) Metal hydride

Hydrogen interacts with various metals and alloys at various temperatures and pressures to form metal hydrides. One of the significant advantages of metal hydrides for hydrogen storage is their high volumetric storage capacities. This characteristic enables a safer and more compact storage solution compared to conventional methods such as compressed and cryogenic storage (Gray, 2007; Hirscher et al., 2020). Metal hydrides can be classified into three groups: intermetallic hydrides, binary hydrides, and complex metal hydrides (Langmi et al., 2022).

More than 50 metallic elements of the periodic table can absorb hydrogen in good quantities; hence, the possible choices of hydride materials are enormous. But only some of them are suitable for hydrogen storage at moderate temperatures and pressures. For example, LaNi5, FeTi, and Mg2Ni. In practical applications, containers for hydrogen storage are filled with metal powders that can absorb and release hydrogen as required. When hydrogen is absorbed by a metal hydride, heat is released. To release the stored hydrogen, the hydride needs to be heated. However, the utilisation of metal hydrides for maritime applications is limited due to the complexity of hydrogenation and dehydrogenation processes onboard.

(3) Adsorption storage

In the adsorption storage of hydrogen, hydrogen molecules are bound to the surface of the pores of the materials through physical interaction (physisorption), which involves weak van der Waals forces. Numerous materials have been extensively studied for their potential in hydrogen storage via adsorption. These materials range from traditional options like zeolites and activated carbon to advanced ones such as carbon nanotubes, fullerenes, zeolite-templated carbons, as well as more recent categories like metal-organic frameworks (MOFs), covalent organic frameworks (COFs), and polymers of intrinsic microporosity (PIMs) (Langmi et al., 2022). However, the practical implementation of hydrogen storage management using adsorption is complex and not yet fully developed for maritime applications.

3.2.3. Suitable Hydrogen Storage Methods on Ships

Table 4 provides an overview of various storage technologies (Andersson & Grönkvist, 2019; Andersson et al., 2020; B.Gupta, 2009; Langmi et al., 2022; Niermann et al., 2019; Sekine & Higo, 2021; Toyota, 2023; Züttel, 2003).

Notably, the list is not exhaustive, as new methods are continuously being developed, and extensive research is underway to improve the technologies (Hirscher et al., 2020).

Table 2. Comparison of hydrogen storage types.

Storage type	State	H2 density (kg/m3) [1]	Volumetric energy density (MJ/m3) [2]	Relative density	Storage density (wt%) [3]
Standard hydrogen	Gas	0.084	10.08	1	/
Compressed hydrogen	Gas	23 (350bar); 42 (700 bar)	2760 (350bar); 5040 (700 bar)	274 (350bar); 500 (700 bar)	5.5;7.7 (Type IV tank)
Cryogenic Liquid hydrogen	Liquid	65 (-237 °C, 4bar); 71 (-253 °C)	7800 (-237 °C, 4bar); 8520 (-253 °C)	774 (-237 °C, 4bar); 845 (-253 °C)	10
Cryogenic compressed hydrogen	Liquid	88 (-253 °C, 300bar)	10,560 (-253 °C, 300bar)	1048 (-253 °C, 300bar)	9
Liquid ammonia (Chemical carrier)	Liquid	121 (-33 °C)	14,520 (-33 °C)	1440 (-33 °C)	17.8
Methanol (Chemical carrier)	Liquid	99	11,880	1179	12.1
MCH (Chemical carrier)	Liquid	47.3	5676	563	6.16
DBT (Chemical carrier)	Liquid	56.4	6768	671	6.21
Mg2FeH6 (Metal hydride)	Solid	150	18,000	1786	5.6
LaNi5H6 (Metal hydride)	Solid	117	14,040	1393	1.3
FeTiH1.7 (Metal hydride)	Solid	113	13,560	1345	1.7
MgH2 (Metal hydride)	Solid	109	13,080	1298	7.7
LiBH4 (Metal hydride)	Solid	121	14,520	1440	18
Carbon (Adsorbent)	Solid	18 (>100 °C)	2160 (>100 °C)	214 (>100 °C)	1-2
MOFs (Adsorbent)	Solid	5-45 (>100 °C)	600-5400 (>100 °C)	60-536 (>100 °C)	1-5
Zeolite (Adsorbent)	Solid	11-122 (>100 °C)	1320-14,640 (>100 °C)	131-1452 (>100 °C)	1-2

Note: 1 If not specified, the data is based on Normal Temperature and Pressure; 2 The lower heating value (LHV) is 120 MJ/kg; 3 Weight percentage (wt%) defines the net usable specific energy from the standpoint of the total onboard storage system, not just the storage medium.

Compressed hydrogen storage technology has attained a mature stage and has been employed in the maritime industry. Similarly, the practical use of cryogenic liquid hydrogen has made advancements.

Both compressed hydrogen and liquid hydrogen tanks have lifespans that align with the operational lifespan of vessels. As a result, in the short term, these two methods of hydrogen storage are poised to become the mainstream approaches in the maritime industry.

Looking towards the future, material-based storage methods hold potential for maritime use. Specifically, metal hydrides are well-suited for maritime applications due to their safety advantages and high hydrogen storage efficiency. However, technological advancements are necessary to ensure that fuel supply matches the real-time fluctuating characteristics of FCs or engine fuel demands.

On the other hand, the potential of liquid chemical hydrogen carriers is limited due to the complexity and high energy consumption involved in the dehydrogenation process. It is important to note that this conclusion is specific to hydrogen-powered vessels. Ammonia and methanol can be directly used as fuels for ship ICEs, although the advantages in this aspect are beyond the scope of this research.

It is worth noting that compared to traditional marine fossil fuels such as diesel and LNG, hydrogen has a relatively high lower heating value (LHV), 120 MJ/kg, which is 2.8 times that of diesel (42.7 MJ/kg) and 2.2 times that of LNG (53.6 MJ/kg). However, due to hydrogen's low density, its volumetric energy density is much lower than that of fossil fuels. For example, the volumetric energy density of hydrogen at 350 bar pressure (2760 MJ/m3) and cryogenic liquid hydrogen (8520 MJ/m3) is only 0.07 times and 0.23 times that of diesel (37,363 MJ/m3), respectively, and 0.11 times and 0.35 times that of LNG (24,120 MJ/m3), respectively. Even with high-efficiency solid-state hydrogen storage, its volumetric energy density still lags significantly behind fossil fuels. This presents challenges for vessel designs.

3.3. HYDROGEN BUNKERING

As compressed hydrogen and cryogenic liquid hydrogen are the viable storage options for vessels in the short term, the focus of fuel bunkering is primarily on these two forms of hydrogen. In the case of compressed hydrogen, land-based refuelling technologies for vehicles can be utilised for ship bunkering. For example, a compressed hydrogen bunkering station has been built in China (IN-EN.com, 2023), as depicted in Figure 19.

Additionally, the mobile compressed hydrogen bunkering method has been employed by the "Hydrocat 48" (CMB.TECH, 2022), as shown in Figure 20. As for cryogenic liquid hydrogen, similar to LNG, bunkering can take place through shore-based station-to-ship, truck-to-ship, or ship-to-ship modes (Fan et al., 2021). The world's first liquid hydrogen fuelled vessel, "MF Hydra", employs the truck-to-ship bunkering mode, as illustrated in Figure 21 (Ivan Østvik, 2021). For small-sized vessels, the portable tank swap mode can be a convenient option for both compressed and cryogenic liquid hydrogen. For example, the passenger vessel, "Hydro Bingo", is equipped with a mobile hydrogen trailer at the stern (Figure 22). Via a ramp, the trailer can be unloaded easily and can be brought to a refuelling station (CMB.TECH, 2021).

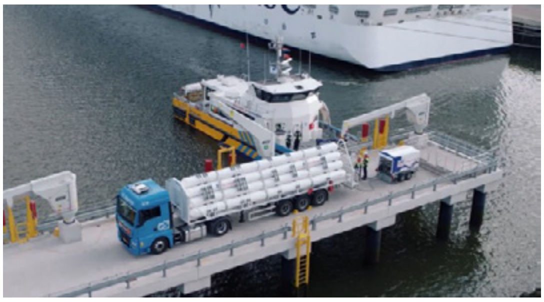
Figure 19. Compressed hydrogen bunkering station

(a) Layout of the station

(b) Hydrogen tanks

(c) Bunkering arm

Figure 20. Mobile compressed hydrogen bunkering truck.



Source: CMB.TECH (2022)

Figure 21. Cryogenic liquid hydrogen bunkering truck.

Source: Ivan Østvik (2021)

Figure 22. Hydrogen tank trailer onboard “Hydro Bingo”.

Source: CMB.TECH (2021)

4. TOTAL COST OF OWNERSHIP

The total cost of ownership (TCO) is the key factor in determining the feasibility of a hydrogen-powered vessel.

The TCO of a hydrogen-powered vessel can be evaluated from three aspects: capital expenditure (CAPEX), operational expenditure (OPEX), and carbon benefits. CAPEX primarily includes the initial investment in the hydrogen fuel system, while OPEX mainly consists of fuel costs, ship maintenance costs, parts replacement costs (FC system and battery replacement), and carbon taxes. This section introduces the fundamental data pertaining to CAPEX and OPEX. In terms of energy conversion, this section only considers commercially available hydrogen FC systems due to ICE technologies being in the research and development stage.

4.1. CAPITAL EXPENDITURE

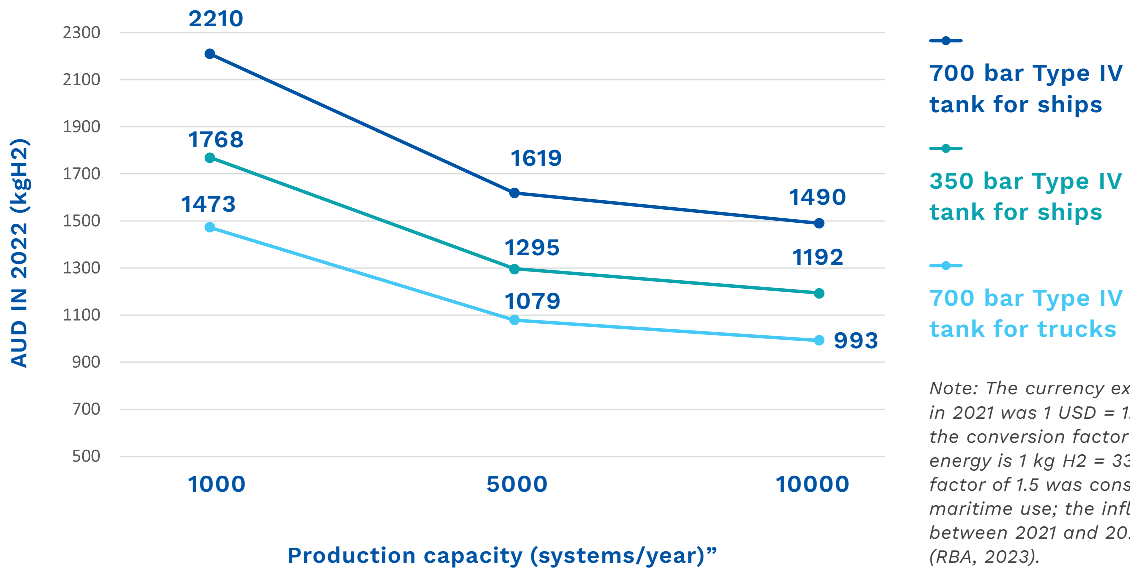
The primary initial investment for hydrogen FC-powered ships comprises hydrogen storage equipment, FC systems (including FC stacks and associated BoP systems), and batteries. The cost estimation is based on land-based equipment or systems. However, it is important to note that the investment cost of marine equipment and systems is considerably higher than similar products used on land. This is primarily due to the necessity of meeting stringent maritime environmental standards (such as vibration resistance and withstanding high-salinity environments) and obtaining certification from classification societies.

4.1.1. Hydrogen Storage Equipment

Among the feasible maritime hydrogen fuel storage methods, only compressed high-pressure gaseous hydrogen storage that have reached the commercial application stage. Therefore, this report only provides the estimated investment costs for high-pressure hydrogen tanks. Currently, hydrogen tanks for land-based vehicles have reached a certain market size. This report considers the cost of marine hydrogen tanks by multiplying the cost of automotive hydrogen tanks by 1.5 as the investment cost for marine hydrogen tanks.

In 2021, the US Department of Energy (DOE) evaluated the cost of 700 bar Type IV hydrogen tanks for long haul trucks, which included integrated valves and regulators. Based on higher end of the cost range in DOE's report (Houchins et al., 2021), this study estimated the 2022 constant cost of Type IV tank system for maritime use, as shown in Figure 23. The estimated cost range for 700 bar Type IV tanks for maritime use is AUD1490-2210 per kg of hydrogen; the estimated cost range for 350 bar Type IV tanks for maritime use is AUD1192-1768 per kg of hydrogen.

Figure 23. Estimated cost of Type IV tank system for maritime use.



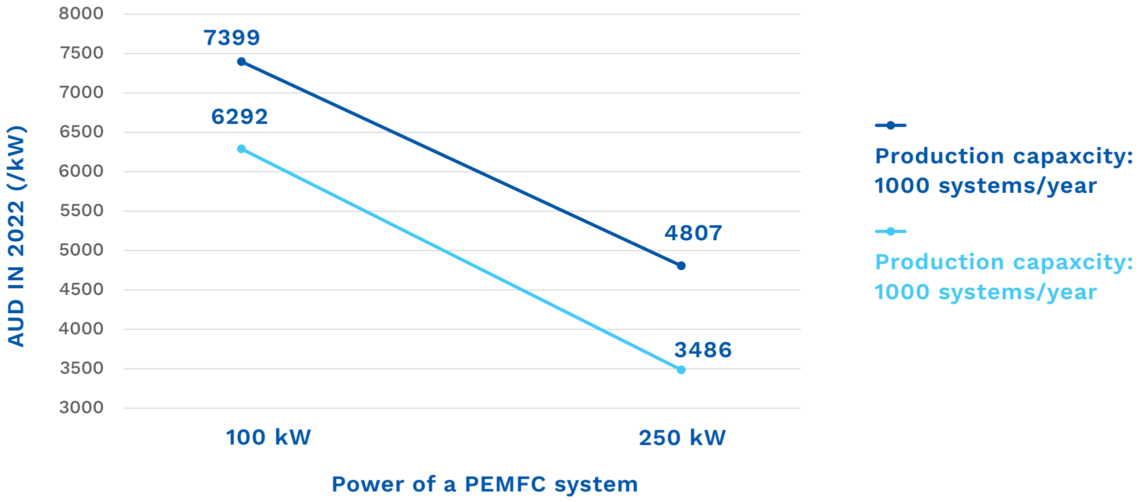
Note: The currency exchange rate in 2021 was 1 USD = 1.3323 AUD; the conversion factor for hydrogen energy is 1 kg H2 = 33.33 kWh; a factor of 1.5 was considered for maritime use; the inflation rate between 2021 and 2022 was 6.6% (RBA, 2023).

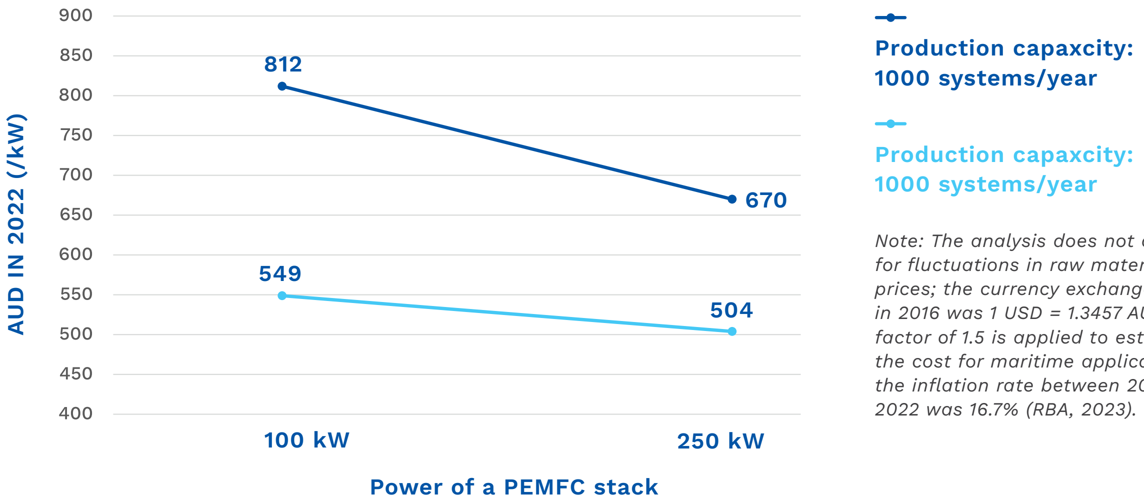
4.1.2. Hydrogen Fuel Cell System

PEM FC systems for automotive applications have reached commercial scale in the market. However, the power range of FC systems used in vehicles is smaller compared to those used in marine applications. Therefore, evaluating the cost of marine PEMFC systems based on automotive FC system costs would be inaccurate.

The US DOE evaluated the costs of 100 kW and 250 kW PEMFCs for land-based applications (Battelle Memorial Institute, 2016). This power range is close to the power range of small-scale vessels. Hence, this report relies on the conclusions drawn by the US DOE to assess the cost of marine PEMFC systems. Figure 24 provide the estimated 2022 constant costs of PEMFC systems and FC stacks. For PEMFC systems with a power output of 100-250 kW, the cost range is projected to be between AUD3486 and 7499 per kW, depending on the scale of production. As for PEMFC stacks, the cost range is estimated to be between AUD504 and 812 per kW, depending on the production scale.

Figure 24. Estimated costs of PEMFC systems and PEMFC stacks for maritime use.





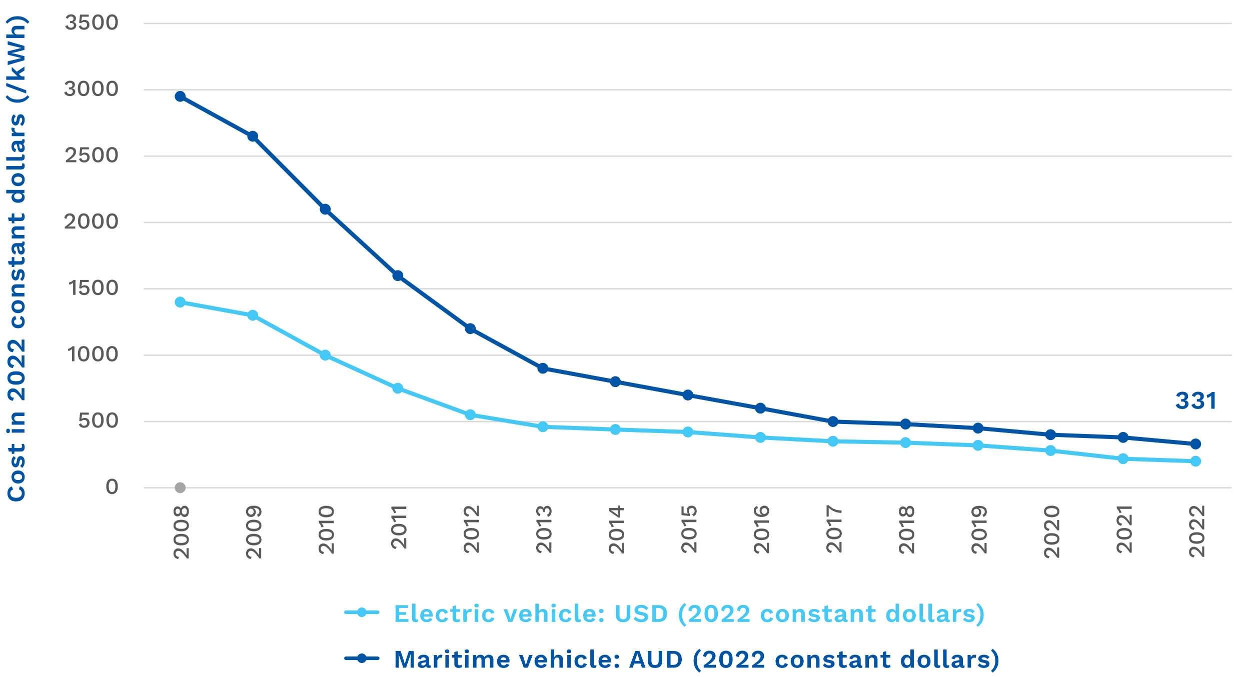
Note: The analysis does not account for fluctuations in raw material prices; the currency exchange rate in 2016 was 1 USD = 1.3457 AUD; a factor of 1.5 is applied to estimate the cost for maritime applications; the inflation rate between 2016 and 2022 was 16.7% (RBA, 2023).

4.1.3. Battery Pack

Lithium-ion batteries have reached a mature and well-commercialized state in the vehicle industry, and this study considers them as the energy storage device. According to the US DOE, the cost of an electric vehicle lithium-ion battery pack has seen a significant decline of 89% between 2008 and 2022 (using 2022 constant dollars) (DOE, 2023).

In 2022, the estimated cost was USD 153/kWh on a usable-energy basis for production at a scale of at least 100,000 units per year. This represents a considerable reduction compared to the cost of USD1355/kWh in 2008. The decline in cost can be attributed to advancements in battery technologies and chemistries, as well as increased manufacturing volume. Consequently, the estimated 2022 constant cost of a lithium-ion battery for maritime use 2022 is 331 AUD/kWh, as illustrated in Figure 25.

Figure 25. Estimated cost of Lithium-ion batteries for maritime use.



Note: The currency exchange rate in 2022 was 1 USD = 1.4421 AUD; a factor of 1.5 is applied to estimate the cost for maritime applications; a factor of 1.5 is applied to estimate the cost for maritime applications.

4.2. OPERATIONAL EXPENDITURE

The OPEX primarily come from fuel prices and the costs of system replacement and maintenance.

4.2.1. Hydrogen Fuel Cost

When determining the price of hydrogen fuel for ships, it is essential to consider various cost factors such as production, storage, transport, and bunkering operations.

Projections indicate that the costs of hydrogen production from renewable sources are expected to decrease, primarily driven by the declining costs of wind and solar power, as well as advancements in water electrolysers.

According to estimates by BloombergNEF, by 2050, the production costs of green hydrogen could potentially range from USD0.7 to 1.6 per kg in most countries, signifying a significant reduction in costs (BloombergNEF, 2020). Australia has set a target to reduce the production cost of green hydrogen to AUD2 per kg, while currently, the cost ranges from AUD4 to 6 per kg (Chang, 2022).

Furthermore, it is important to consider that the construction and operation of a hydrogen bunkering station generally entail an additional cost of approximately AUD9 (USD6) per kg of hydrogen (BIS Research, 2023).

According to the Hydrogen Vehicle Refuelling Infrastructure Report published by Australian government scientific research agency CSIRO (CSIRO, 2023a), the levelised cost of hydrogen dispensed by refuelling stations in Australia could range from AUD6.78-15.60/kg. In terms of energy value, this translates to approximately AUD0.057-0.13 per megajoule (MJ) of energy.

4.2.2. System Replacement and Maintenance Cost

The Balance-of-Plant (BOP) of the FC system has a projected lifetime of 20 years, while the FC stack is expected to run for approximately 24,000-30,000 hours. Typically, a vessel's lifespan ranges from 25 to 30 years.

Based on these figures, it can be concluded that the BOP does not require replacement during the operational life of the ship with proper maintenance.

However, the FC stack is anticipated to be replaced several times depending on different ship types throughout the ship's lifespan.

The cycle life of batteries refers to the number of charge and discharge cycles that a battery can undergo before experiencing a decline in performance. In the case of Lithium-ion batteries, the cycle life is significantly influenced by the depth of discharge, which indicates the extent to which the battery's storage capacity is utilised.

For example, a battery that is discharged only by 20% of its full energy capacity has a much greater cycle life than a battery that is discharged more deeply by 80% of its capacity. If a depth of discharge of 50% is considered, the cycle life of a Lithium-ion battery is estimated to be around 8,000 cycles (Qadrdan et al., 2018). Based on this estimation, it is anticipated that a Lithium-ion battery pack would need to be replaced several times over the lifespan of the ship.

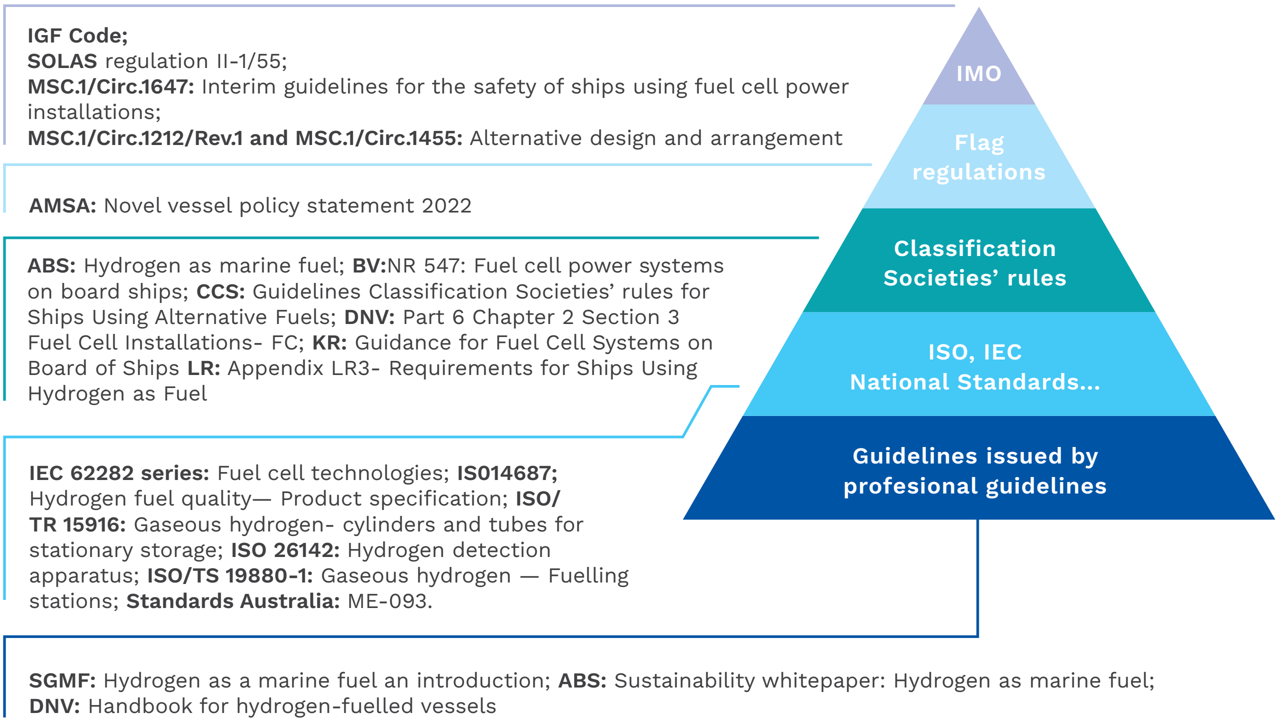
4.2.3. Carbon Taxes

To reduce the price gap between fossil fuels and zero-emission alternative fuels, many countries and shipping companies are considering implementing carbon taxes on fossil fuels. Although Australia has yet to implement a carbon tax on marine fossil fuels, the introduction of a carbon price is a possible trend. Green hydrogen-powered vessels do not need to pay carbon taxes, which is an advantageous factor.

5. REGULATORY FRAMEWORK

In the maritime industry, the regulatory framework resembles a pyramid structure. At the pinnacle are IMO regulations, followed by flag states' regulations, classification societies' rules, international and national standards, and guidelines from professional organisations. For hydrogen-powered vessels, Figure 29 shows the status and progress of the regulatory framework.

Figure 29. Status and progress of the regulatory framework for hydrogen-powered vessels.



5.1. IMO REGULATIONS

Using hydrogen on ships falls within the purview of the IMO International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code). Following the 5th session of the IMO Sub-Committee on Carriage of Cargoes and Containers in 2018, the correspondence group of the IGF Code initiated the drafting of the guidelines of utilising FC power installations on ships. In 2022, the IMO issued the Interim Guidelines for the Safety of Ships Using FC Power Installations (MSC.1/Circ.1647), which outlined safety design requirements for ships equipped with FC installations.

However, these guidelines did not address hydrogen storage and bunkering procedures on ships. Currently, the IGF Code correspondence group is drafting the full requirements for hydrogen FC powered vessels, which are expected to be finalised until 2025-26. Thus, at the moment, alternative design method should be used according to IGF Code Part A: 2.3, where state "The equivalence of the alternative design shall be demonstrated as specified in SOLAS (International Convention for the Safety of Life at Sea) regulation II-1/55 and approved by the Administration."

During implementing SOLAS regulation II-1/55, the documents, MSC.1/Circ.1212 Guidelines on alternative design and arrangements for SOLAS chapters II-1 and III and MSC.1/Circ.1455 Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments, shall be referred.

5.2. FLAG STATE'S REGULATIONS

The AMSA issued the Novel Vessel Policy Statement in June 2022 (AMSA, 2022). It clarified the novel vessel certification pathway, stating that "a novel vessel must be constructed and maintained in accordance with the class rules of a recognised organisation." Where a recognised organisation's rules do not extend to a novel vessel, then risk assessment-based method can be accepted.

5.3. CLASSIFICATION SOCIETIES' RULES

Classification societies have created their rules or guidelines for the use of hydrogen as a marine fuel, as listed in Table 3. In cases where a classification society has established a comprehensive set of rules for adopting hydrogen on vessels, which address specific requirements not covered by the IMO's regulations, the flag administration, AMSA, may accept the application of these rules to facilitate alternative design approaches. Furthermore, the rules developed by classification societies can serve as a foundation for the development of future IMO regulations.

Table 3. Classification societies' rules or guidelines.

Classification Society	Rules or guidelines	Ref.
ABS	Requirements for hydrogen fueled vessels	(ABS, 2023)
BV	NR 547: Fuel cell power systems on board ships	(BV, 2022)
CCS	Guidelines for Ships Using Alternative Fuels	(CCS, 2021)
DNV	Rules Part 6 Chapter 2 Section 3 Fuel Cell Installations	(DNV, 2022)
KR	Guidance for Fuel Cell Systems on Board of Ships	(KR, 2022)
LR	LR3 – Requirements for Ships Using Hydrogen as Fuel	(LR, 2023)

5.4. INTERNATIONAL AND NATIONAL STANDARDS

The International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO) have established hydrogen standards that primarily focus on safety and testing requirements for road vehicles. These standards, listed in Table 4, are widely adopted as regulatory components in several countries including Australia. However, there is currently an inadequate set of standards to comprehensively address hydrogen applications on ships.

In Australia, Standards Australia's Hydrogen Technologies committee, ME-093, was constituted to develop or adopt hydrogen standards to promote Australian decarbonisation transition (Standards Australia, 2019). The working scope of ME-93 spans the entire hydrogen value chain including the mobility use applications.

Table 4. Selected international hydrogen standards.

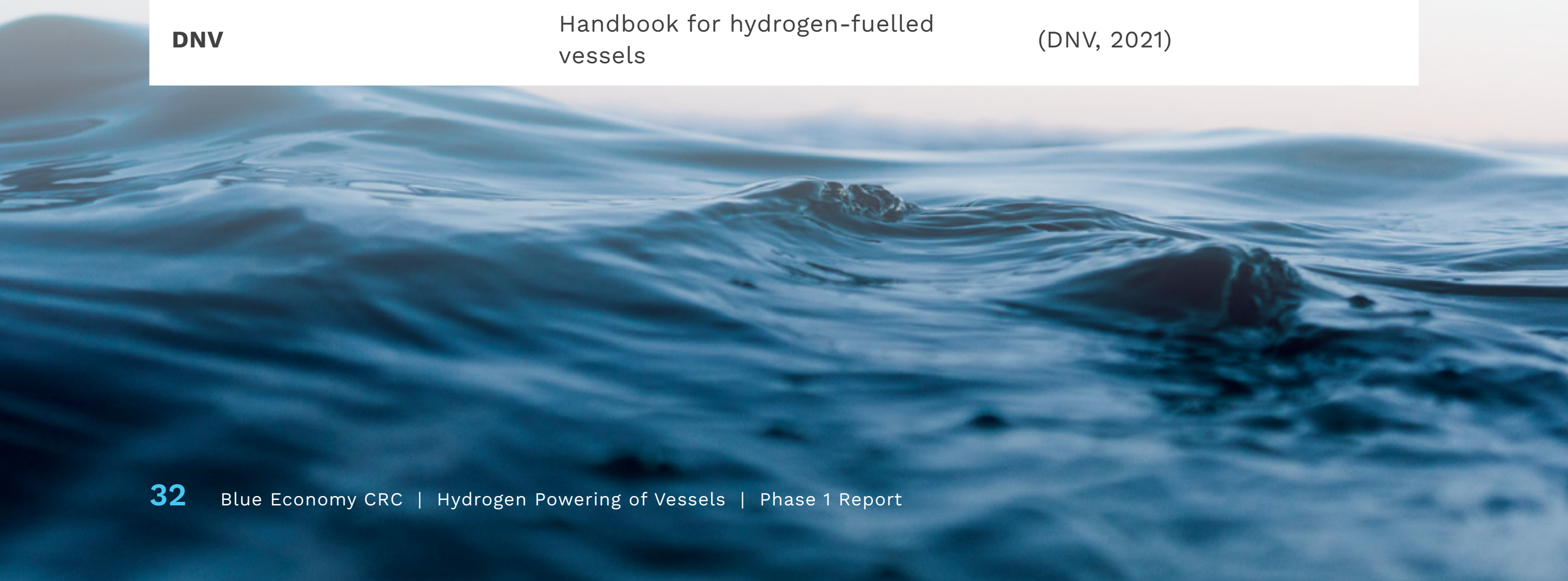
Category	Standard number	Title
Utilisation	IEC 62282 series	Fuel cell technologies
	ISO 14687	Hydrogen fuel quality — Product specification
	ISO 16110 series	Hydrogen generators using fuel processing technologies
Storage	ISO/TR 15916	Basic considerations for the safety of hydrogen systems
	ISO 15399	Gaseous hydrogen - cylinders and tubes for stationary storage
	ISO 26142	Hydrogen detection apparatus
Refuelling	ISO 17268	Gaseous hydrogen land vehicle refuelling connection devices
	ISO/TS 19880-1	Gaseous hydrogen — Fuelling stations

5.5. PROFESSIONAL ORGANISATIONS' GUIDELINES

Professional organisations are actively taking part in bridging the knowledge and expertise gaps related to hydrogen-powered vessels. The Society for Gas as a Marine Fuel (SGMF) has released an introductory book that focuses on the utilisation of hydrogen as a marine fuel. Classification societies like ABS and DNV have also published whitepapers and handbooks to provide guidance to the industry on the use of hydrogen. Table 5 summarises these publications.

Table 5. Professional organisations' guidelines.

Organisation	Publications	Ref.
SGMF	Hydrogen as a marine fuel: an introduction	(SGMF, 2023)
ABS	Sustainability whitepaper: Hydrogen as marine fuel	(ABS, 2021)
DNV	Handbook for hydrogen-fuelled vessels	(DNV, 2021)



6. TRAINING AND COMPETENCE

Hydrogen-powered ships require specialised systems and infrastructure that differ from conventional fuel-powered vessels. Proper training is essential to equip personnel with the necessary technical knowledge to understand and operate these specialised systems safely and efficiently.

The training should encompass ship crew members as well as bunkering workers. This section provides an overview of the essential steps and actions required for effective training.

6.1. SHIP CREW

The inclusion of crew training requirements for hydrogen-powered ships in the IMO International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW convention) is still pending. Additionally, AMSA has yet to establish crew training requirements specifically for hydrogen-powered vessels. Drawing from the crew training requirements for LNG-powered ships outlined in the STCW convention, it is advisable that crew training for hydrogen-powered ships incorporates both theoretical and practical components. The training concept can be divided into various methods as follows:

- **Courses:** These can be conducted in a classroom setting or through e-learning modules to provide theoretical knowledge on hydrogen systems.
- **Training with simulation programs:** Utilising simulation programs, crew members can gain practical knowledge and experience in the safe handling of hydrogen systems.
- **Trainings/Demonstrations:** This stage involves practical applications and can take place on an actual ship or within a real hydrogen facility. These sessions aim to deepen and consolidate the practical knowledge that has already been acquired.

By incorporating these training methods, crew members can acquire the necessary skills and expertise to operate hydrogen-powered ships safely and effectively.

6.2. BUNKERING WORKERS

The hydrogen fuel bunkering requires qualified personnel to perform the operation. Due to limited practical experience with hydrogen bunkering in the world, there are challenges in providing practical training for hydrogen bunkering. Some countries have set up hydrogen education systems (Beasy et al., 2023; Nowotny et al., 2014; Reijalt, 2010). In Australia, a National Hydrogen Skills and Training Analysis has been conducted in 2022 to identify and plan for the future skills and training needs of Australians working with hydrogen (PWC, 2021). However, these efforts did not specifically address the training needs for hydrogen bunkering operations.

To address the challenge of insufficient training preparation for hydrogen bunkering, this research provides the following solutions:

- Developing practical training programs specific to hydrogen bunkering operations, which cover handling procedures, emergency response protocols, and maintenance practices.
- Engaging professional hydrogen experts from the land transport and aerospace industries who can provide practical knowledge and hands-on training exercises to enhance the skill set of port professionals in the hydrogen bunkering sector.
- Establishing continuous professional development programs to keep personnel updated with the latest technologies and safety practices in hydrogen bunkering field.

Image courtesy of Huon Aquaculture

7. FEASIBLE SHIP TYPES FOR UTILISING HYDROGEN

The supply chain and bunkering infrastructure for hydrogen fuel have yet been established in Australia. Meanwhile, the commercialisation of maritime hydrogen FC is still limited, with feasible single-vessel total power remaining within 2 MW.

Taking these factors into consideration, in the initial stages, feasible hydrogen-powered ships should primarily target small vessels operating on fixed routes. This approach ensures both the practicality of fuel bunkering and the availability of hydrogen power system. It is crucial to prioritise the development of a robust supply chain and scalable FCs for large vessels before gradually expanding the application of hydrogen to larger ships.

Currently, ferries, port working vessels (dredger, floating crane, pilot boat, tugboat, etc), aquaculture support vessels, and offshore wind farm support vessels are considered suitable for using hydrogen for they often operate on fixed routes with predetermined schedules, making them well-suited for hydrogen bunkering infrastructure planning. With proper infrastructure in place, these vessels can be bunkered during scheduled stops or overnight, ensuring continuous operation without disruptions.

8. SAFETY

Safety is of paramount importance for adopting hydrogen on vessels. This section identifies hydrogen's safety hazards and preventions and proposes a safe design process for hydrogen powered vessels.

8.1. HAZARDS AND PREVENTION

Hydrogen bunkering, storage, and utilisation present potential safety hazards that can be categorised as physical hazards (related to phase changes, component failures, and embrittlement) and chemical hazards (such as ignition and burning). Many historical incidents and accidents involve a combination of both physical and chemical hazards.

The most significant hazard associated with hydrogen is the inadvertent creation of a flammable or detonable mixture, which can result in fires or explosions. Enhancing safety requires ship designers and crew to have a thorough understanding of the specific hazards associated with hydrogen handling. Table 6 lists the hydrogen safety hazards and preventions (NASA, 1997).

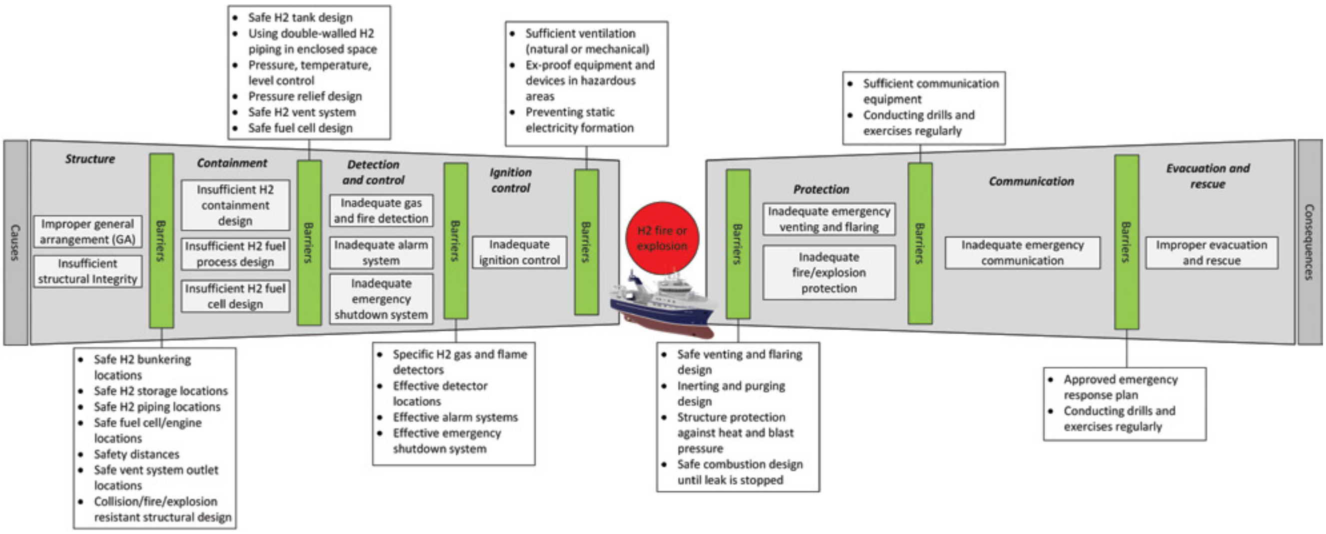
Table 6. Hydrogen safety hazards and preventions.

Hazards	Description	Prevention
Leak	Deformed seals or gaskets, valve misalignment, or failures of flanges or equipment usually cause leaks. A leak may cause further failures of construction materials.	The construction quality of piping and tanks and well-designed monitoring and detection systems are essential to mitigate hydrogen leaks.
Dispersion	Gaseous hydrogen is lighter than air, making the cloud positively buoyant. The dispersion of the cloud is affected by wind speed and direction and can be influenced by atmospheric turbulence and nearby structures.	Monitoring and detection systems should be in place to capture flammable hydrogen cloud.
Ignition	Fires and explosions could occur due to various ignition sources, including mechanical sparks from rapidly closing valves, electrostatic discharges in ungrounded particulate filters, sparks from electrical equipment, welding and cutting operations, catalyst particles, and lightning strikes near the vent stack.	There shall be no ignition sources, such as from open flames, electrical equipment, or heating equipment in rooms containing hydrogen systems.
Fire and explosion	A hydrogen-air-oxygen flame is colourless. Any visibility is caused by impurities. At reduced pressures, a pale blue or purple flame may be present. A deflagration could occur if a mixture within flammability limits is ignited at a single point. A detonation could occur if the hydrogen-air mixture is within detonability limits, and an appropriate energy source is available. A deflagration could transform into a detonation if there is confinement or a mechanism for flame acceleration.	Fire and explosion can be prevented if there is a missing part of the fire triangle, representing fuel, heat, and oxygen.
Vent and exhaust system accident	Vent and exhaust system accidents are attributed to inadequate ventilation and the inadvertent entry of air into the vent.	Backflow of air can be prevented with suitable vent stack designs, provision of makeup air (or adequate supply of inert gas as the situation demands), check valves, or molecular seals.
Hydrogen Embrittlement	There are three types of hydrogen embrittlement: hydrogen reaction embrittlement, internal hydrogen embrittlement, and environmental hydrogen embrittlement (Verfondern, 2022). When hydrogen embrittlement occurs, containment systems may fail, and the subsequent spills and leaks will create hazards when the mechanical properties of materials degrade from hydrogen embrittlement.	Hydrogen embrittlement is related to the carbon content in metal alloys. Generally, high-strength steels, titanium alloys, and aluminium alloys are prone to hydrogen embrittlement. Pure unalloyed aluminium has high resistance to hydrogen embrittlement, 316-grade stainless steel and copper-nickel alloy can be used in hydrogen tanks, and copper can be used in low-pressure equipment.

Based on the safety hazards and protective measures related to hydrogen, this study proposes the utilisation of the Bow-tie diagram model, as depicted in Figure 27, to address the safety design considerations for a hydrogen-powered ship. The top event in the Bow-tie diagram is defined as a hydrogen fire or explosion.

The causes represented on the left side of the diagram include ship structure, fuel containment, detection and control, and ignition source control. The consequences depicted on the right side of the diagram encompass fire and explosion protection, communication, evacuation, and rescue. Safety barriers are suggested based on the protective measures identified in Table 6.

Figure 27. Bow-tie diagram model for the safety design of a hydrogen-powered vessel.



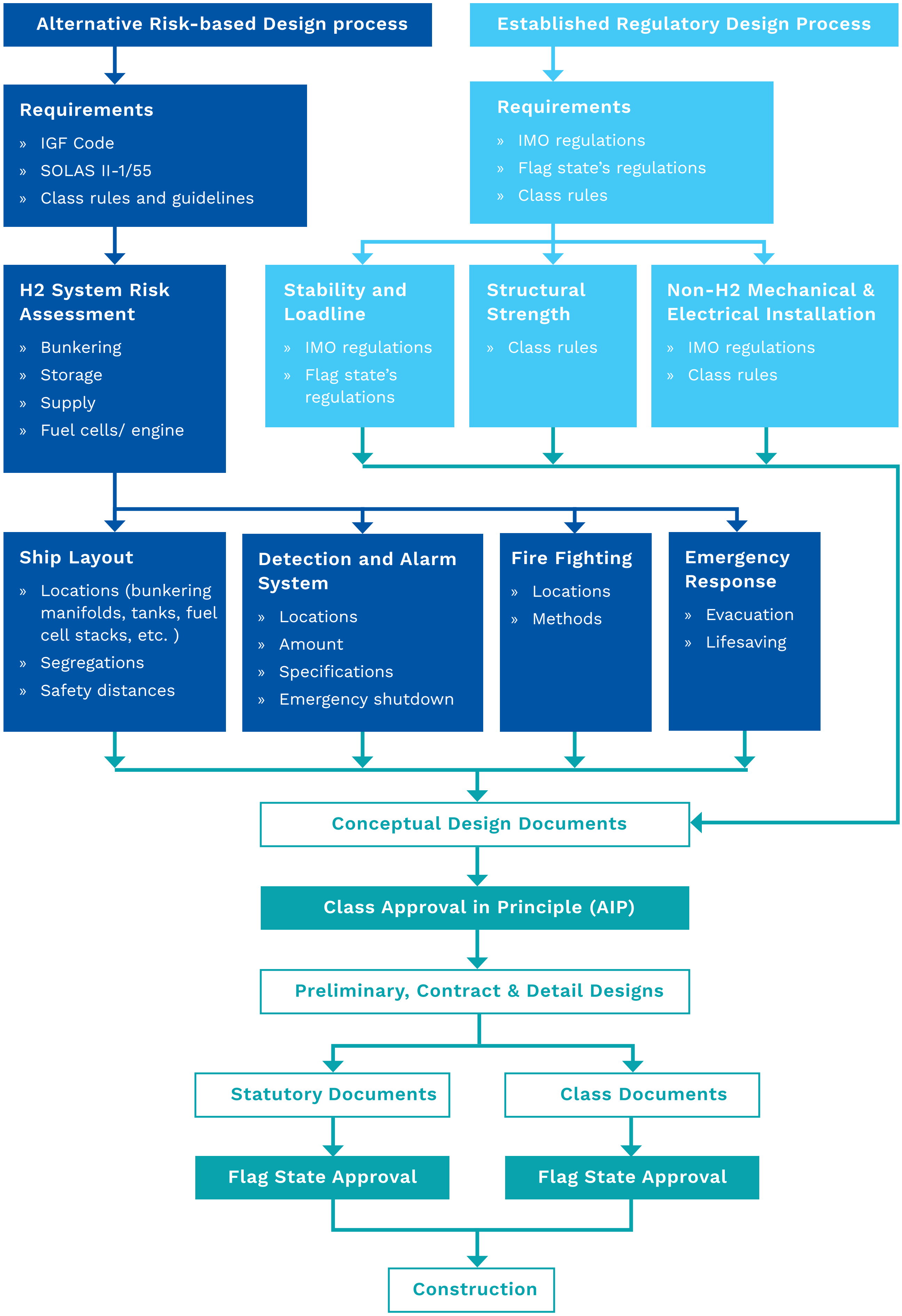
8.2. SAFE DESIGN PROCESS OF A HYDROGEN-POWERED VESSEL

Given the lack of specific IMO and flag state regulations for hydrogen-powered vessels, this study proposes a safe design process outlined in Figure 28. The design process incorporates both the regulatory established design method and an alternative risk-based design method. For ship stability and load line, ship structural strength, and non-hydrogen mechanical and electrical installations, the established regulations and rules can be followed. However, for hydrogen-related systems and safety measures, the alternative risk-based methods should be employed.

The safety goals for a hydrogen-powered vessel are defined in existing regulations and rules, but the specific means to achieve those goals should be determined through comprehensive risk assessments that cover ship layout, gas detection and alarm systems, firefighting systems, and emergency response plans.

It is recommended to seek an Approval in Principle (AIP) from classification societies before proceeding with preliminary, contract, and detailed designs. Statutory and class documents will be developed for approval, after which the construction phase can commence.

Figure 28. Safe design process of a hydrogen-powered vessel.



9. CONCLUSIONS & RECOMMENDATIONS

This study provides a review of the factors driving the adoption of hydrogen as a marine fuel, the current and future developments in hydrogen-powered vessels, the technological and economic aspects, the readiness of regulations and standards, and the demand for training.

Additionally, the study proposes potential ship types suitable for hydrogen use and outlines safe design processes. The key findings and recommendations of the study are summarised in this section.

9.1. FINDINGS

The key findings of this study are as follows:

- Australia's domestic maritime fleet is predominantly composed of small vessels, and at present, hydrogen energy solutions are better suited for these smaller vessels. This aligns well with the need for Australia's domestic maritime sector to achieve net zero emissions by 2050.
- Existing hydrogen-powered vessels worldwide, predominantly small-sized vessels, serve as valuable references for adopting hydrogen technology in Australian waters.
- Hydrogen FC systems, well-established in the automotive sector, can be utilised on ships considering the marine environment. However, hydrogen ICEs for ships are still in the research stage.
- Compressed hydrogen and cryogenic liquid hydrogen storage methods are feasible in the short term. Metal hydrides offer safety advantages and high storage efficiency, making them suitable for maritime applications in the future. The potential of liquid chemical hydrogen carriers is limited due to the complexity and high energy consumption associated with the dehydrogenation process.
- Hydrogen bunkering operations have been carried out around the world. The high-pressure refuelling technologies in the automotive industry provide valuable references for vessel bunkering. Similar to LNG, cryogenic liquid hydrogen bunkering can be conducted through shore-based station-to-ship, truck-to-ship, or ship-to-ship modes. For small-sized vessels, the portable tank swap mode using ISO tank containers can be a convenient option for both compressed and liquid hydrogen.
- The CAPEX and OPEX of a hydrogen FC-powered vessel can be evaluated using available data. The estimated 2022 constant cost range for 700 bar Type IV tanks for maritime use is AUD1490-2210 per kgH2, while for 350 bar Type IV tanks, the estimated 2022 constant cost range is AUD1192-1768 per kg of hydrogen. For PEMFC systems with a power output of 100-250 kW, the projected 2022 constant cost range is between AUD3486 and 7499 per kW, depending on the production scale. The estimated 2022 constant cost range for PEMFC stacks is between AUD504 and 812 per kW, depending on the production scale. The 2022 constant cost of a lithium-ion battery pack for maritime use is estimated to be AUD331/kWh. The estimated levelised cost of hydrogen dispensed by refuelling stations in Australia could range from AUD6.78-15.60/kg. The FC stack and battery are anticipated to be replaced several times throughout the ship's lifespan.
- The regulatory, normative, and standard framework for hydrogen-powered ships is steadily taking shape, with obstacles in this regard gradually being overcome.
- Training programmes related to hydrogen-powered vessels have not yet been built and conducted in Australia. It is imperative to promptly initiate training programs for the operation and bunkering of hydrogen-powered ships.
- In the initial stages, the implementation of feasible hydrogen-powered ships should primarily target small-sized vessels operating on fixed routes. This approach ensures the practicality of fuel bunkering and the availability of hydrogen power systems.
- The design process of a hydrogen-powered vessel incorporates both the regulatory established design method and the alternative risk-based design methods, considering the safety risks associated with hydrogen and the current insufficiency of regulations and standards.

9.2. RECOMMENDATIONS

To address the identified gaps in this study, the following actions are necessary:

- Development or adoption of regulations and standards for designing, building, and certifying hydrogen-powered vessels in Australia.
- Establishment of risk assessment methods recognised by the administration for designing and assessing hydrogen-powered vessels.
- Establishment and implementation of a comprehensive training program for ship crew and bunkering workers to facilitate the adoption of hydrogen on vessels.

To accelerate utilising hydrogen on vessels in Australian waters to meet with the country's net zero emission target, the study recommends the following:

- Conducting conceptual hydrogen powertrain design for selected target vessels in Australia.
- Evaluating and comparing the TCO of potential hydrogen-powered vessels with other zero-emission solutions.
- Assessing and comparing the lifecycle GHG emissions of potential hydrogen-powered vessels with other zero-emission solutions from a lifecycle perspective.
- Constructing or retrofitting hydrogen-powered ships, testing relevant data, lays the foundation for the widespread adoption of hydrogen-powered vessels on a large scale in Australia.

10. APPENDIX

Table A1. Existing or demonstration hydrogen-powered vessels.

NO.	YEAR	SHIP NAME	FLAG	SHIP TYPE	REF.
1	2000	Hydra	Germany	Passenger ship	(Butler, 2019)
2	2003	Duffy-Herreshoff DH30	The US	Passenger ship	(Hydrogen House, 2003)
3	2006	Frisian Hydrogen Xperiance	The Netherlands	Passenger ship	(Wikipedia, 2006)
4	2007	Ross Barlow	The UK	Test boat	(Bevan et al., 2011)
5	2008	Alsterwasser	Germany	Passenger ship	(Blue Growth, 2008)
6	2008	ELDING I	Iceland	Passenger ship	(Konrad, 2008)
7	2009	Nemo H2	The Netherlands	Passenger ship	(S Chakraborty, 2013)
8	2009	Frauscher 600 Riviera	Austria	Passenger ship (Yacht)	(Bednarova, 2012)
9	2010	MF Vågen	Norway	Passenger ship (Ferry)	(Stensvold, 2010)
10	2012	Marti	Turkey	Test boat	(IISD, 2012)
11	2012	Hornblower Hybrid	The US	Passenger ship	(RespectPlanet, 2012)
12	2012	Hydrogenesis	The UK	Passenger ship	(BBC, 2013)
13	2016	Gold Green HYGEN	South Korea	Passenger ship	(Choi et al., 2016)
14	2016	Cheetah	The UK	Passenger ship (Yacht)	(Cheetah Marine, 2016)
15	2016	Race For Water	Switzerland	Passenger ship (Sailing boat)	(Race For Water, 2016)
16	2017	Energy Observer	France	Passenger ship (Sailing boat)	(Energy Observer, 2017)
17	2017	Hydroville	Belgium	Passenger ship	(The Maritime Executive, 2017)
18	2018	Jules Verne II	France	Passenger ship	(AFBE, 2019)
19	2018	Shimpo	Japan	Test boat	(YANMAR, 2018)
20	2019	Raicho N	Japan	Test boat	(FuelcellsWorks, 2019)
21	2019	MV Emeli	The Netherlands	Bulk	(MARIKO GmbH, 2019)
22	2020	MV Shapinsay	The UK	Passenger ship (Ferry)	(Orkney Islands Council, 2022)
23	2021	Elektra	Germany	Push boat	(Maritime, 2022)
24	2021	Hydro BINGO	Japan	Passenger ship	(JPNH2YDRO, 2021)

NO.	YEAR	SHIP NAME	FLAG	SHIP TYPE	REF.
25	2021	Lihu	China	Passenger ship (Yacht)	(FuelCellsWorks, 2021a)
26	2021	Xianhu 1	China	Passenger ship	(GGFC, 2021a)
27	2021	Hydra	Norway	Passenger ship (Ferry)	(FuelCellsWorks, 2021b)
28	2021	Yanmar	Japan	Passenger ship (Fishing cruiser)	(Vella, 2021)
29	2021	Sea Change	The US	Passenger ship (Ferry)	(All American Marine, 2021)
30	2021	Hydro Motion	The Netherlands	Passenger ship (Race boat)	(Bedggood, 2021)
29	2021	Sea Change	The US	Passenger ship (Ferry)	(All American Marine, 2021)
30	2021	Hydro Motion	The Netherlands	Passenger ship (Race boat)	(Bedggood, 2021)
31	2021	The New Era (Hynova 40)	France	Passenger ship (Yacht)	(BarcheaMotore, 2021)
32	2022	Hydrocat 48	The UK	Passenger ship (Offshore crew transfer vessel)	(CMB.TECH, 2022)
33	2022	Viking Neptune	Norway	Passenger ship (Cruise)	(FincaNTIERI, 2022b)
34	2022	Chase Zero	New Zealand	Passenger ship (Race boat)	(Baird Maritime, 2022)
35	2022	Hydrogenia	South Korea	Passenger ship (Yacht)	(Danfoss, 2022)
36	2023	San Xia Qing Zhou 1	China	Passenger ship	(Guan et al., 2023)
37	2023	Hydrotug 1	Belgium	Tugboat	(ABC, 2022)
38	2023	Zulu 06	France	Inland multi cargo barge	(Buitendijk, 2022)
39	2023	Antonie	The Netherlands	Inland cargo barge	(NPRC, 2023)
40	2023	H2 Barge 1	The Netherlands	Inland container ship	(Currie, 2023b)
41	2023	FPS Waal	The Netherlands	Inland container ship	(BBN, 2022)

Table A2. Future hydrogen-powered vessels.

NO.	EXPECTED DELIVERY YEAR	COUNTRY	SHIP TYPE	AMOUNT	PROPONENTS	REF.
1	2024	Japan	Tug	1	Tsuneishi, CBM	(Argus, 2021)
2	2024	Japan	Passenger ship (100 passengers)	1	NYK Line, Toshiba Energy Systems & Solutions Corporation, Kawasaki Heavy Industries Ltd, ClassNK, and ENEOS	(Snyder, 2020)
3	2024	China	Passenger ship	1	Huxin Tech and Wuhan University of Technology	(China Chemical News, 2023)
4	2024	Norway	Bulk carrier	2	Egil Ulvan Rederi, Norwegian Ship Design, Heidelberg Cement and Felleskjøpet Agri	(Egil Ulvan Rederi AS, 2023)
5	2024	Norway	Ferry (Ro-Ro)	2	Topeka	(The Maritime Executive, 2021)
6	2024	France	Dredger	1	The ports of Occitania	(FuelcellsWorks, 2022)
7	2024	India	Passenger ship	1	Cochin Shipyard Limited (CSL), KPTI Technologies, and Indian Registry of Shipping (IRS)	(Bahtić, 2023b)
8	2024	The Netherlands	Passenger ship	1	H2Ships, Port of Amsterdam, TU Delft Fuel, MARIN, Wijk Yacht Vision, Lloyd's Register, and Baumuller	(Davemart, 2023)
9	2024	The UK	Test vessel	1	Hydrogen Innovation – Future Innovation & Vessel Evaluation and Demonstration (HI-FIVED) consortium	(h2-view, 2023)
10	2025	China	Passenger ship	1	FTXT, Dalian Maritime University	(FTXT 2023)
11	2025	Norway	Ferry (ROPAX, 599 passengers and 120 cars)	2	Torghatten Nord, PowerCell, SEAM	(Howard, 2023)
12	2025	Norway	Ferry (high-speed 35 knots, 300 passengers)	1	Teco, Umoe Mandal, Blom Maritime	(Hampel, 2022)
13	2025	The Netherlands	Containership (500TEU, Rotterdam-Oslo)	2+2	Samskip, Ocean Infinity	(Chambers, 2023; Zasiadko, 2022)
14	2025	The Netherlands	Offshore commissioning service operation vessels (CSOVs)	2	Windcat Offshore	(Durakovic, 2022)

NO.	EXPECTED DELIVERY YEAR	COUNTRY	SHIP TYPE	AMOUNT	PROPONENTS	REF.
15	2025	France	multi-purpose cargo ship	1	Energy Observer	(TransGlory, 2022)
16	2025	Germany	Superyacht	1	Lurssen	(Cormack, 2021)
17	2025	The US	Cargo ship (20TEU, high-speed 40 knots, hydrofoil)	1	Boundary Layer Technologies	(Chambers, 2022)
18	2025	Norway	Container ships (365 TEU)	2	Samskip Group, Cochin Shipyard Limited (CSL)	(Currie, 2023a)
19	2025	The UK	Research vessel (Prince Madog, retrofit)	1	Bangor University, OS Energy	(BBC, 2023)
20	2025/2026	Norway	Cruise	1	Northern Xplorer, AS Norwegian Hydrogen AS, HYON AS, Multi Maritime AS, Hexagon Purus Maritime AS.	(Hydrogen Central, 2023)
21	2026/2027/2028	Italy	Cruise	4	FINCANTIERI, Viking Line	(Prevljak, 2022)
22	2027	Denmark	Ferry (Copenhagen-Oslo)	1	DFDS, Ørsted, ABB, Ballard	(Kobie, 2021; Morgan, 2020)
23	2027/2028	Italy	Cruise	2	FINCANTIERI, MSC	(FINCANTIERI, 2022a)
24	2045	The US	/	(at least 25% of ships in California waters)	The California Air Resources Board	(Mandra, 2022)
25	Unknown	Australia	Ferry (200 passengers)	1	SeaLink Gladstone	(CSIRO, 2022)
26	Unknown	Australia	Ferry (high-speed, 130 m long)	1	Austal, Sweden's Gotlandsbolaget (Gotland Company)	(MarineLink, 2023)
27	Unknown	Norway	Cruise	1	Norwegian Electrical Systems (NES), Havyard Design, Havila	(Radowitz, 2020)
28	Unknown	The UK	Ferry	1	HySEA III	(HySea III, 2022)
29	Unknown	The US	Research ship	1	The University of California San Diego's Scripps Institution of Oceanography	(Bahtić, 2023a)
30	Unknown	South Korea	Passenger ship (16m long)	1	Vinssen	(Laity, 2023)

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