WHEN TRUST MATTERS

ALTERNATIVE FUELS FOR NAVAL VESSELS

WHITE PAPER

Rendering of the MEKO® 5.0 courtesy of thyssenkrupp Marine Systems GmbH

Contents

Introduction

As the world is increasingly turning its attention towards the impact of human activity on climate, the importance of using alternative fuel in the transportation sector is an omnipresent subject. Of course, requirements for operating naval vessels differ significantly from those for operating commercial vessels. These unique characteristics must be considered when making decisions about the use of alternative fuels.

The white paper 'Alternative fuels for naval vessels' was developed with the objective of presenting technical and operational information on a range of alternative fuels that can enable the naval sector's transition towards a less carbon-intensive future. In addition to the basic requirement that such fuels need to deliver sufficient energy for propulsion, storage on board and supply chain resilience are matters of particular importance to ensure that changes to the status quo do under no circumstances jeopardize the operational tasks the naval vessel is intended for.

The DNV team responsible for this report was able to draw on extensive in-house knowledge and experience in both the alternative fuel and naval sector as well as on published research from around the globe. The result is an excellent starting point for any navy looking for facts on the possible options for introducing alternative fuels into their respective fleets.

This white paper also provides an excellent starting point for us to work together to protect our environment and at the same time ensure the operational readiness of our navies.

Vice Admiral Jan Christian Kaack
Chief German Navy, Commander Fleet and
Supporting Forces

Preface

Following on from the global climate change summit in Glasgow in November 2021, there is not only a greater sense of urgency on leaving no stone unturned in reducing emissions to air from human activity, but simultaneously, there has been an increased focus on the transportation sector to decarbonize radically and quickly. This attention includes the outcomes from the IMO's MEPC 76 meeting in June 2021 and the omnipresent public pressure placed on both government and commercial enterprises to adopt aggressive GHG-related targets. As we know, the naval sector is not subject to the same regulatory constraints as the commercial world; however, there is an accepted acknowledgment that governments should apply similarly high ambitions to their activities as those imposed on the general public.

On the back of this and at the direction of the DNV Naval Committee, the development of this white paper on alternative fuels for naval vessels, which you are now reading, was initiated.

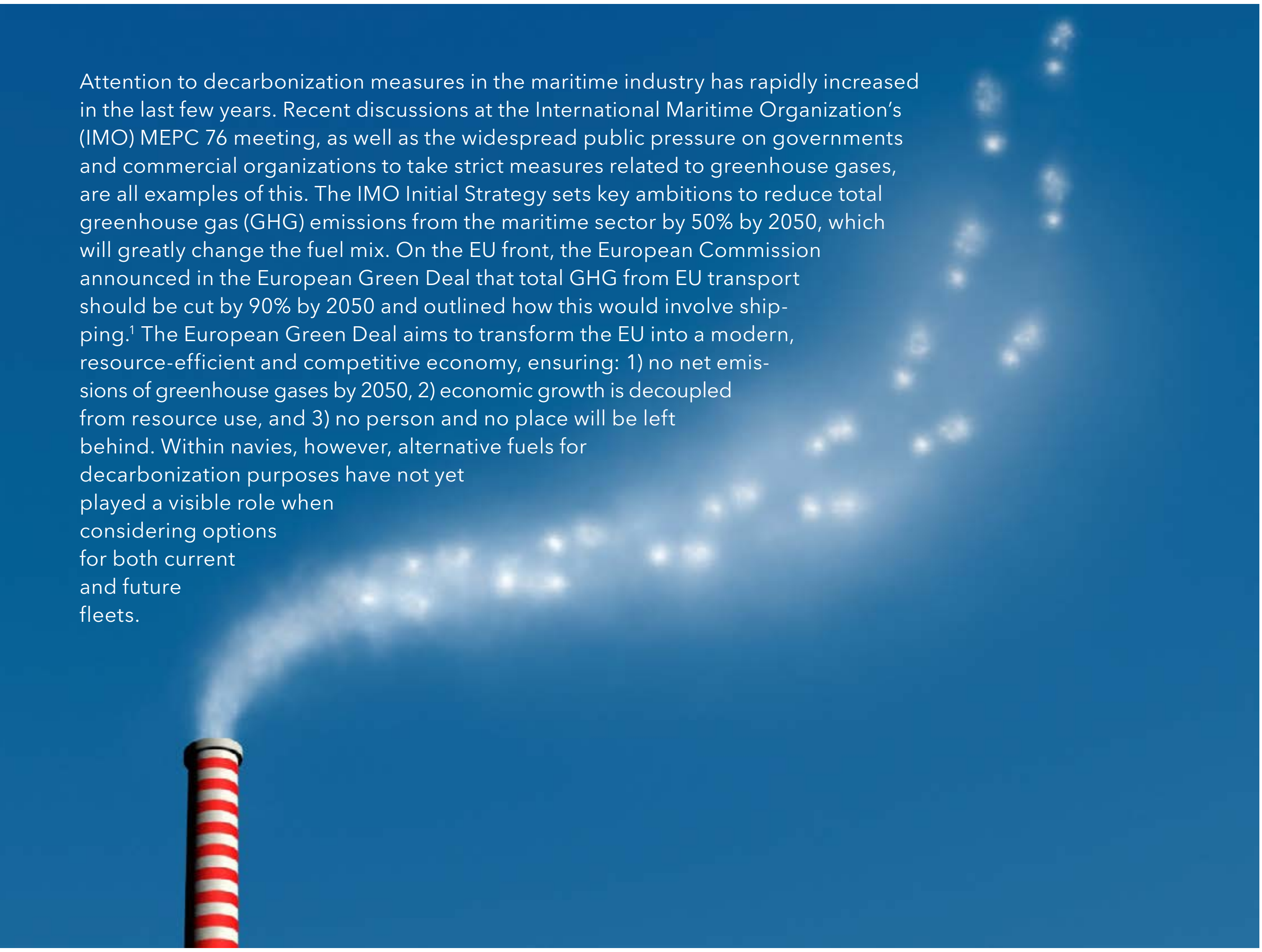
It is not intended to draw any particular conclusion or promote one type of fuel over another; instead, it aims to provide a robust, fact-based summary of the pros and cons of each type which can then be used to support naval decision-making for both newbuild and retrofit activities. The objective of this white paper is to describe the technical merits of alternative fuels in terms of the balance between capability, acquisition cost, technology maturity (current and future), use/access globally and operational costs for both combatant and non-combatant (auxiliary) ship types, including an examination of supply chain features, characteristics or constraints.

This white paper presents a broad overview of the considerations combining studies conducted on alternative fuels used for naval vessels with a survey of DNV Naval Committee members on this topic. A range of alternative fuels – from biofuels to hydrogen fuel cells – is studied and considered for both non-combatant and combatant naval vessels. Operational characteristics of the vessels are also discussed within this white paper.

As you can appreciate, the topic is rapidly evolving with new developments in alternative fuels being launched continuously. In this sense, the journey is only just beginning, but as the foundation of successful naval operations is the ability to be flexible, agile and resilient in the face of adverse conditions, I recommend this report and encourage everyone to consider not 'if' alternative fuels can support naval vessels, but 'when' they will become simply a business-as-usual scenario.

Rear Admiral (rtd) Karl-Wilhelm Ohlms
Chair, DNV Naval Committee

1 Executive summary



Attention to decarbonization measures in the maritime industry has rapidly increased in the last few years. Recent discussions at the International Maritime Organization's (IMO) MEPC 76 meeting, as well as the widespread public pressure on governments and commercial organizations to take strict measures related to greenhouse gases, are all examples of this. The IMO Initial Strategy sets key ambitions to reduce total greenhouse gas (GHG) emissions from the maritime sector by 50% by 2050, which will greatly change the fuel mix. On the EU front, the European Commission announced in the European Green Deal that total GHG from EU transport should be cut by 90% by 2050 and outlined how this would involve shipping.[1] The European Green Deal aims to transform the EU into a modern, resource-efficient and competitive economy, ensuring: 1) no net emissions of greenhouse gases by 2050, 2) economic growth is decoupled from resource use, and 3) no person and no place will be left behind. Within navies, however, alternative fuels for decarbonization purposes have not yet played a visible role when considering options for both current and future fleets.

The purpose of this white paper is to provide an overview of the current use and a comprehensive factual summary of the advantages and disadvantages of various alternative fuels. A review of existing naval assets that are currently utilizing alternative fuels is documented. However, this does not draw specific conclusions or a preference for one fuel over another. Based on research from case studies and survey results, there are several considerations for the use of alternative fuels for naval vessels (combatants and auxiliary) in the near future. This white paper aims to enable informed decision-making within the context of both newbuild and upgrade (improvement) projects.

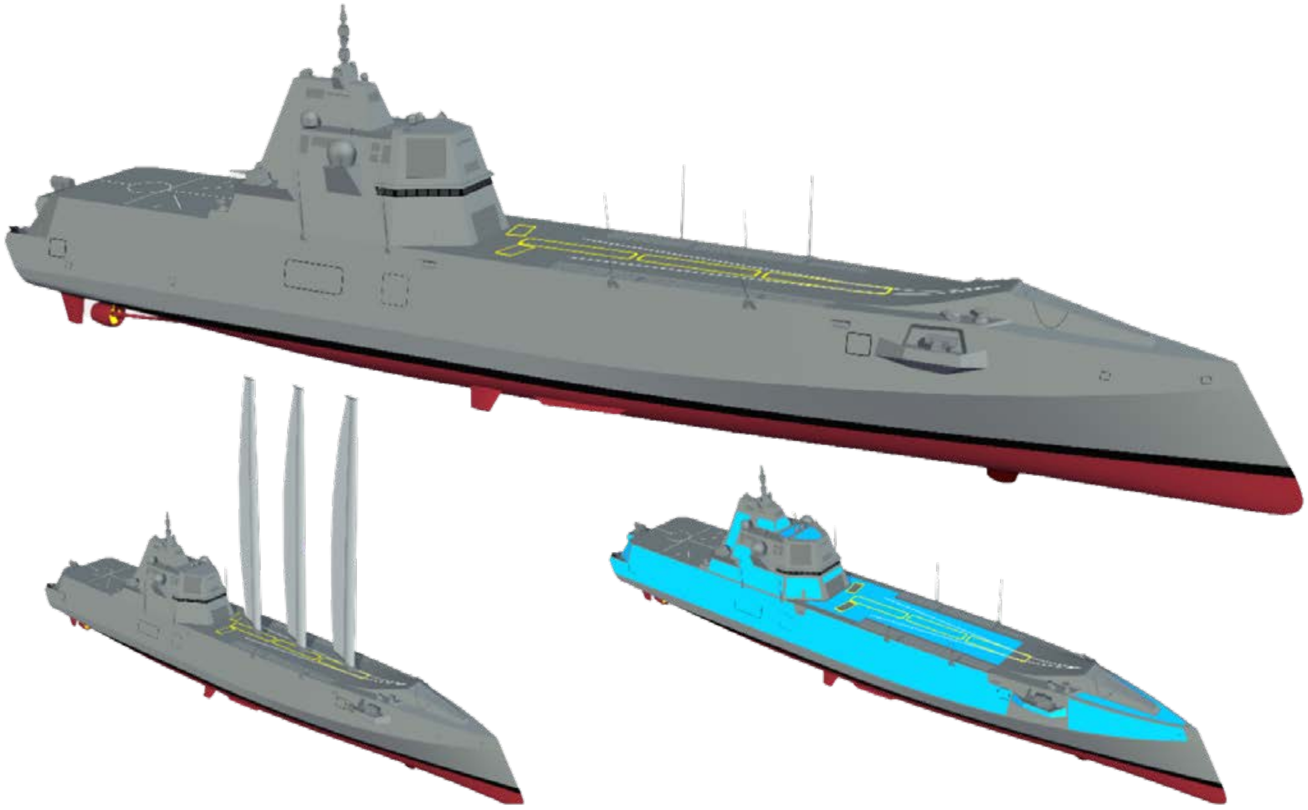
In recent years, the shipping industry has faced increasing pressure to minimize its greenhouse gas (GHG) footprint. Several public and commercial projects and programs have been launched that acted as catalysts for this shift to decarbonize shipping. Based on DNV's Maritime Forecast to 2050, decarbonization is driven by three reasons: regulations and policies, access to investors and capital, as well as expectations of cargo owners and consumers. This white paper attempts to draw parallels to these reasons from the perspective of navies.

Alternative fuels, in this paper, are defined as anything beyond traditional fossil-based fuels such as marine gas oil. These include biofuel (i.e. biodiesel), ethanol, methanol, hydrogen, electrical power, natural gas, propane gas, or a synthetic transportation fuel. Nuclear has been prevalent within the U.S. Navy since the 1960s and is also included in the discussion. Implementation of nuclear within the merchant segment has thus far been limited, although there have been preliminary discussions in exploring its viability within the commercial world. In recent years, methanol, hydrogen and ammonia have led as the most feasible options for the maritime sector.

In 2018, the U.S. Department of Defense announced formally that alternative fuels were allowed for operational use. Alternative fuels such as biofuels, nuclear fuels, and fuel cells (hydrogen and bioethanol) are being considered for naval vessels. Taking into account the types of naval vessels (such as submarines and surface combatants) is also an important factor. Specifying concepts of operations would provide a better understanding of the basic principles behind the construction of these warships, which may benefit future naval applications using alternative fuels.

A survey of some 130 stakeholders[2] from 12 countries was conducted to identify trends in thinking and opinion. Based on the responses from 12 different countries, Fuel Availability / Fuel Change Flexibility was ranked as one of the top four concerns by 79.2% of respondents for alternative fuels, with Noise and Detectability being the least of their concerns. However, according to the survey, Logistics will have to be addressed before it can be successfully utilized in the navy, with the concepts of Standardization and Safety coming into play subsequently. Furthermore, more than 83.3% of respondents chose biofuels over other options such as ammonia, methanol and hydrocarbons. The ideal final goal to decarbonize is to develop a fuel that has a net-zero carbon footprint, but also one that is relatively cheap to produce. With the IMO guideline of cutting total greenhouse gases (GHG) down by 30% by 2030 and by 50% by 2050, research and development into alternative fuels is expected to be sped up by increased government support. As to the application of new fuels, the majority of respondents believe that non-combat vessels will be the first to adopt alternative fuels, rather than fighting vessels such as frigates and destroyers. The choices given by respondents are primarily categorized as support vessels.

Please note that aspects pertaining to replenishment at sea (RAS) and survivability require further technological and safety analyses and are not covered in the current version of this white paper.



The MEKO® 5.0 in a combat state (top), with extended wing sails (bottom left) with areas covered by solar cells highlighted in light blue (bottom right)

2 Introduction

Over the last 12 months in particular, the focus on actions to decarbonize shipping has increased exponentially. This has included the outcomes from the recent IMO's MEPC 76 meeting and pervasive public pressure placed on both government and commercial enterprises to adopt aggressive GHG-related targets. Even though the naval sector is not subject to the same regulatory constraints as the business world, there is a general acknowledgement that governments should apply similarly high ambitions to their activities as those imposed on the public.

Shipping is experiencing increased pressure to decarbonize its operations and to reduce greenhouse gas (GHG) emissions. In April 2018, the IMO initiated an ambitious GHG emissions reduction strategy for international shipping, shifting focus to decarbonize among key stakeholders, including banks and cargo owners. This will consequently reshape the future fleet in several aspects, including the choice of fuels and technologies together with the impacts on costs, asset values and earning capacity.

The IMO Initial Strategy on the reduction of GHG emissions from shipping sets key ambitions.[3] As a policy framework, the main goals are: 1) cut annual GHG emissions from international shipping by at least half by 2050, compared with their level in 2008, and work towards phasing out GHG emissions from shipping entirely as soon as possible in this century; 2) reduce carbon intensity of international shipping (to reduce CO_2 emissions per transport work), as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008. The Initial Strategy will be revised by 2023.

The European Green Deal aims to make Europe climate-neutral by 2050.[4] To make this objective legally binding, the Commission proposed the European Climate Law, which also sets a new, more ambitious net GHG emissions reduction target of at least 55% by 2030, compared to 1990 levels. Encompassing aggressive targets in vehicles, aviation and aviation fuels, to ensure a fair contribution from the maritime sector to the effort to decarbonize the economy, the Commission proposes to extend carbon pricing to this sector.[5] The Commission will also set targets for major ports to serve vessels with onshore power, reducing the use of polluting fuels that also harm local air quality.

Decarbonization in shipping is part of the global transition across all industries towards lesser use of fossil fuels and greater use of renewable energy. Future policies and regulations play essential roles in driving the transitional change and thus achieving the IMO's ambitions.

An increasing number of studies have been performed on the topic of decarbonization in shipping, developing scenarios for the transition from conventional to zero-carbon or carbon-neutral fuels, along with technical and operational energy optimization. Carbon-neutral fuel refers to fuel that produces no net greenhouse gas emissions within its carbon footprint. Amongst the studies is DNV's Maritime Forecast to 2050, which aims to enhance a shipowner's ability to navigate technological, regulatory and market uncertainty due to decarbonization – thus maintaining competitiveness, profitability and value over time.[6]

Alternative fuels, in this paper, are defined as anything beyond traditional fossil-based fuels such as marine gas or diesel. These include biofuel (often referred to as biodiesel), ethanol, methanol, hydrogen, coal-derived liquid fuels, electricity, natural gas, propane gas, or a synthetic transportation fuel. Nuclear, although generally absent within commercial shipping, has been prevalent within the U.S. Navy since the 1960s and has been included in the discussion.

Even though the naval sector is typically not subject to GHG-related regulatory restrictions, some countries have started looking into the possibility of working towards having a zero-carbon navy by considering the use of alternative fuels.[7] In that regard, the main aim of this white paper is to provide a robust factual summary of the pros and cons of each type which can then be used to support naval decision-making for both newbuild and retrofit activities. In drafting this white paper, considerations have been placed on the technical facts of alternative fuels from a supply-chain perspective, enabling their implementation in the navy. This will be in a form that describes the merits of alternative fuels in terms of the balance between capability, technology maturity (current and future), use/access globally, and operational costs for both combatant and non-combatant (auxiliary) ship types, including an examination of supply chain features, characteristics or constraints.

This white paper has been developed based on reports published internally within DNV, as well as external open-source information. Surveys to both naval stakeholders as well as fuel suppliers were also performed. All information is correct to the best of our knowledge. Contributions by external authors do not necessarily reflect the views of the editors and DNV.

We first present an executive summary and introduction in Chapters 1 and 2, respectively. In Chapter 3, we discuss the alternative fuels in commercial shipping with a focus on fuel uptake and implementation timelines. For illustrative purposes, case studies with regards to alternative fuel types currently implemented in the navy and predominant use of alternative fuels in the navy are presented in Chapter 4. In Chapter 5, the state of technological implementations in commercial shipping as well as in the navy are presented. Based on case studies and survey results, several considerations for the use of alternative fuels for naval vessels (combatants and auxiliary) in the near future are highlighted in Chapter 6. Finally, results of the survey conducted as a part of this white paper's development are summarized – with commentary – in Chapter 7.

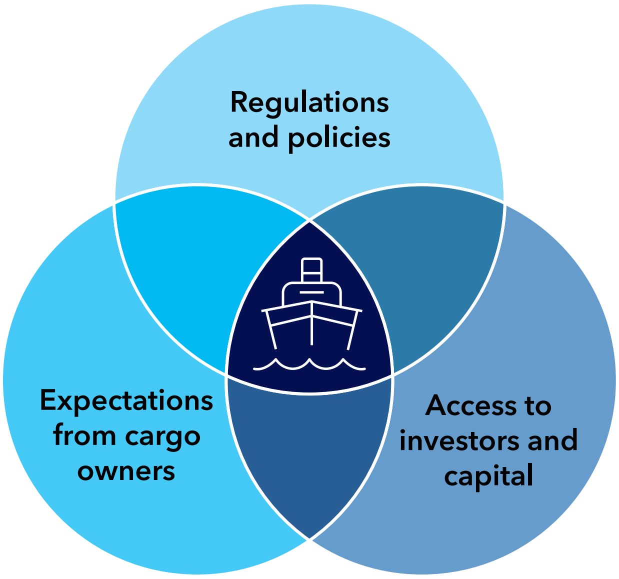
3 Adoption of alternative fuels in commericial vessels

The pressure on shipping to reduce its greenhouse gas (GHG) footprint has been intensifying over the past few years. Public and private initiatives and plans, which act as the drivers for this development, have been put in motion heading towards the decarbonization of shipping. According to the Maritime Forecast to 2050, there are three fundamental key drivers that will push decarbonization in merchant shipping in the coming decade: 1) regulations and policies, 2) access to investors and capital, and 3) cargo owner and consumer expectations. In this chapter, the key drivers, as well as the current uptake of fuel types and implementation timelines, are discussed.

Regulations and policies will set direct requirements for ships and shipping companies. There is an expectation of an increasing market pull from stakeholders which will require more transparency on GHG emissions and subsequently promote decarbonization in the supply chain. Part of this market pull is due to reporting requirements and regulations put on stakeholders, in particular cargo owners and the finance sector. Many cargo owners and shipping companies are seen to have decarbonization as part of their business strategy and publicly announcing decarbonization targets. Behind all three drivers shown in Figure 3.1 is the growing awareness of climate change in the general public, and how this increasingly translates into more climate-conscious behaviour affecting the way we act as consumers, voters or investors.

FIGURE 3.1

Key drivers influencing ship decarbonization[6]



These requirements and expectations will require a large degree of control of one's own emissions to ensure compliance, an exchange of information so that other companies may complete their reporting, and the meeting of expectations towards financial institutions and cargo owners. With increased transparency on emissions and the establishment of a carbon intensity rating by the IMO, we can expect that poor-performing ships and shipping companies will be less attractive in the charter market, and they may also struggle to gain access to investors and capital. This, in turn, will drive companies to ensure that they achieve acceptable carbon intensity ratings and deliver according to other performance frameworks such as the Poseidon Principles and the Sea Cargo Charter climate alignment.[8] Older ships that are not easily upgraded to meet carbon intensity targets may become stranded assets. This can have a significant impact on the equity and balance sheet of shipping companies and may result in the early scrapping of the same assets.

All shipping companies need to fulfil the minimum compliance requirements from the IMO, but depending on the strategy, environmental ambitions, and market situation, they may also aim for a leading position in decarbonization.

Within the commercial setting, the available GHG mitigation measures range from easily achievable operational measures to capital-intensive technical solutions. Newbuilds will have more available options than ships in operation. Abatement measures such as wind power, air lubrication systems, and various hull and machinery measures are now emerging. Equally, there is also a focus on the category with the highest reduction potential, but also with significant uncertainty: Fuels and Energy (Figure 3.2).[9] All alternative fuels for shipping face challenges and barriers to their uptake – although the severity of each barrier will vary between fuel types. Typical barriers include the cost of required machinery and fuel storage on board vessels, additional storage space demand, low technical maturity, high fuel price, limited availability of fuel, and a lack of global bunkering infrastructure. Safety will also be a primary concern, with a lack of prescriptive rules and regulations complicating the use of such machinery and storage systems.

FIGURE 3.2

One of the available technologies to decarbonize shipping and its GHG emission reduction potential[6]

LOGISTICS AND DIGITALIZATION	HYDRODYNAMICS	MACHINERY	FUELS AND ENERGY	AFTER TREATMENT MEASURE
Speed reduction Vessel utilization Vessel size Alternative routes	Hull coating Hull-form optimization Air lubrication Cleaning	Machinery improvements Waste-heat recovery Engine de-rating Battery hybridization	**LNG, LPG** **Biofuels** **Electrification** **Methanol** **Ammonia** **Hydrogen** **Harvesting from the surroundings**	Carbon capture and storage
>20%	5%-15%	5%-20%	0%-100%	>30%

3.1 Current alternative fuel uptake

All alternative fuels for shipping face challenges. The technical applicability and commercial viability of alternative fuels will vary greatly for different ship types and trades. Short-sea shipping plays an important role in the maturing of some of the fuels and technologies for later use in deep-sea shipping.

> The recent uptake of batteries by ferries / passenger ships and service vessels has been more rapid. Some of the ships can operate fully electric, but nearly all are still hybrid solutions where diesel (or biofuels) is used to extend the operating range or redundancy against power loss.

Data from DNV's Alternative Fuel Insight shows that currently, less than 1% of the ships in operation are running on alternative fuels, with the current uptake of low- and zero-emission fuels and technologies being dominated by the short-sea segment and non-cargo ships.

However, when we look at the order book in 2021, around 10% of current newbuilds are ordered with alternative fuel systems. Looking ahead over the next few years, we find that there is likely to be an increase in LNG ships globally, and in batteries for full- or part-electric operations in the short-sea segment. Except for the electrification underway in the short-sea segment, the alternative fuels currently adopted are still based mainly on fossil fuels such as fossil-based LNG and LPG.

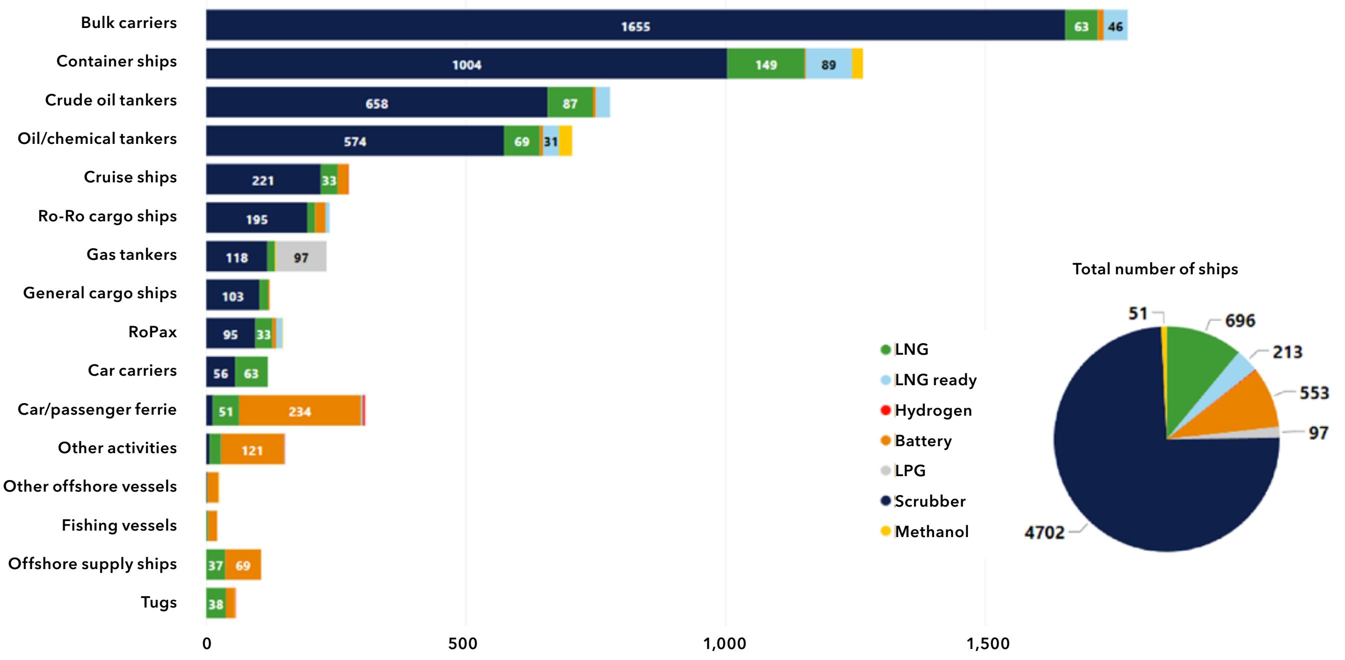
For deep-sea applications, fuel storage capacity is a key barrier to many alternative fuels, and the current options for the deep-sea trade are limited to LNG, which is not carbon neutral, or to biofuels, which are far more expensive and not yet widely available. As of September 2021, there are also currently in operation and on order 68 ships using LPG and 25 ships using methanol. These ships are LPG carriers and chemical tankers, utilizing their cargo as fuel, which effectively counters the fact that fuel infrastructure for these types is not yet developed. Among the methanol-fuelled ships in operation is the passenger ferry Stena Germanica. It is thus important now to find technically feasible and cost-effective solutions for large-scale uptake in the deep-sea segment, which accounts for more than 80% of CO_2 of world-fleet emissions. In summary, LNG is currently the only alternative fuel that is scalable commercially and globally for long-distance transport at sea.

The total number of vessels using some form of alternative fuel (and scrubbers) both in operation and on order is shown in Figure 3.3. A total of 14 vessel types are categorized, as well as the alternative fuel that was used. With reference to the data, there is a push toward LNG-fuelled ships, with 300 ships in operation and on order that can use LNG as bunkering fuel.

Figure 3.4 depicts the LNG-fuelled fleet up until 2028. As of September 2021, the global order book surpassed 300,

FIGURE 3.3

Number of vessels with implemented alternative fuels and scrubber installations that are under operation[10]



bringing the total number of LNG-fuelled ships confirmed to more than 500. LNG-powered car and passenger ferries are the most common, with 43 in service, followed by offshore supply ships (26) and oil/chemical tankers (21). With 57 units apiece, LNG-powered container ships and crude oil tankers make for most of the orders.

The projected number of ships with battery installations is depicted in Figure 3.5. As of September 2021, there are 160 ships that will be powered by batteries and under development, and 330 in operation.

FIGURE 3.4

Projected number of LNG-fuelled ships up to 2028[10]

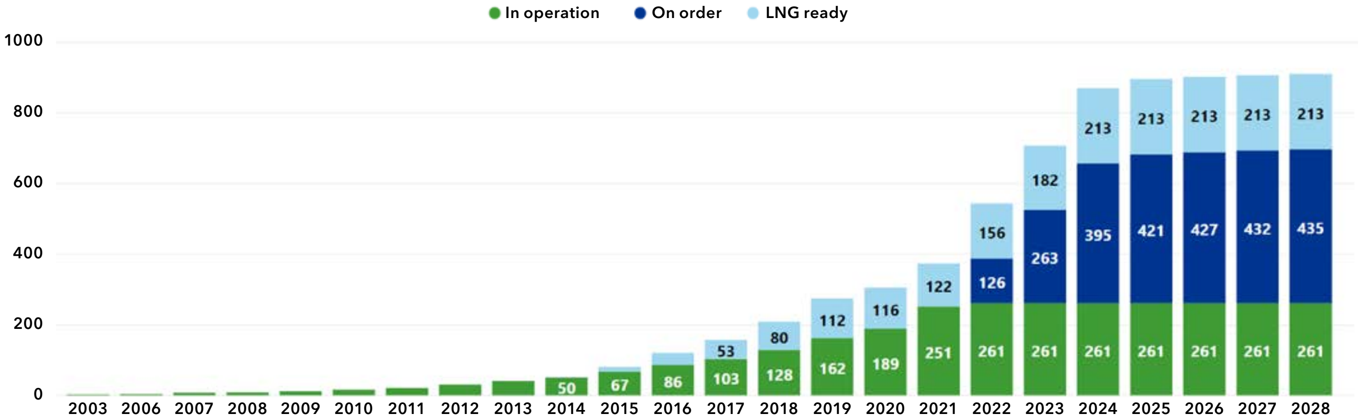


FIGURE 3.5

Projected number of ships with battery installations[10]

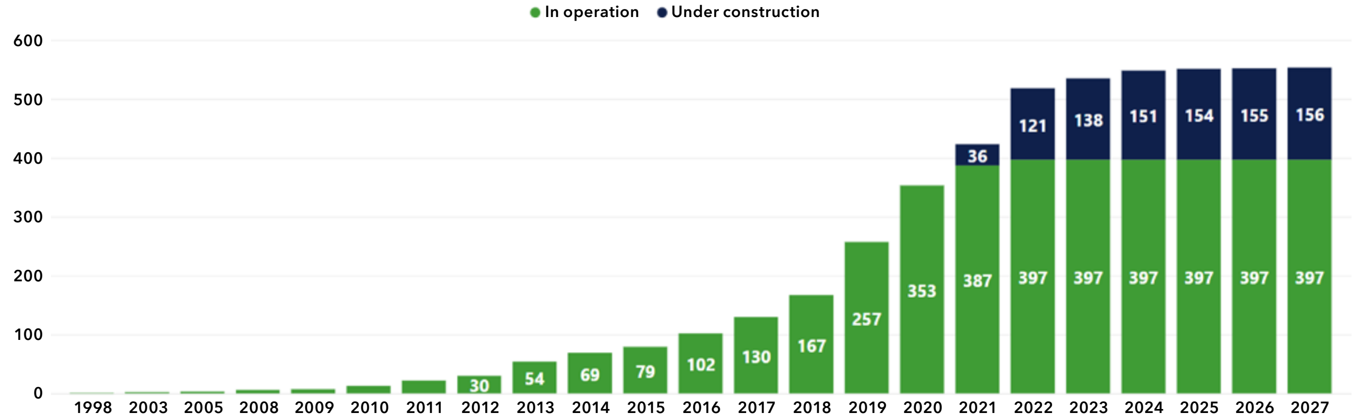
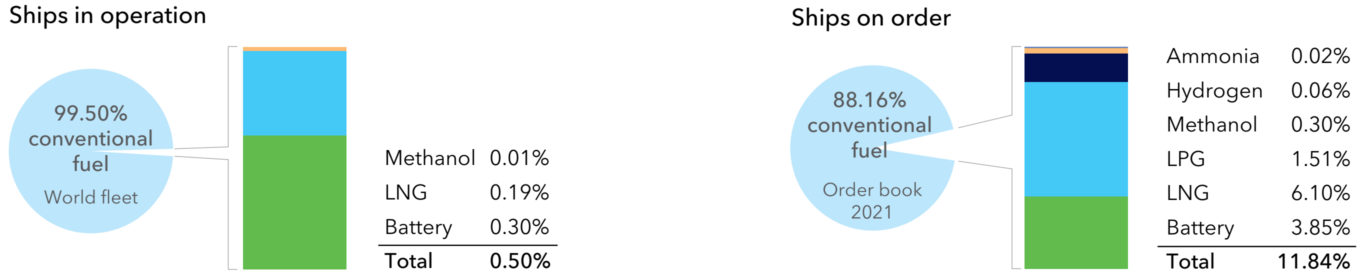


FIGURE 3.5

Projected number of ships with battery installations[10]



3.2 Alternative fuel types

As mentioned, alternative fuels in the context of this white paper are defined as anything beyond traditional fossil-based fuels such as marine gas or diesel. In this section, the current usage, availability, and global production capacity and logistics of LPG, LNG, batteries, hydrogen, ammonia and methanol are summarized in Table 3.1. The use of LPG, LNG and batteries has been prevalent due to the maturing of both technologies and supply chains. Fossil-based LNG has gained a substantial share following the IMO ambitions. However, as regulations tighten in the period 2030 to 2040, depending on the decarbonization pathway, we see bio-LNG[11], e-LNG[12], bio-MGO and e-MGO used as drop-in fuel for existing ships, while bio-methanol, blue ammonia or e-ammonia is used for newbuilds and some retrofits[13]. In addition, the key aspects in relation to challenges, current status, and rules and regulations on the potential future alternative fuels, comprising hydrogen, ammonia and methanol, which are in their infancy, are summarized in Table 3.2.

Hydrogen is the most well-known non-fossil fuel, whilst another is ammonia, which can be produced either as green or blue ammonia[14]. This fuel is classified as synthetic fuel, similar to methanol. DNV predicts ammonia as a fuel for carbon-free sailing in the 'best estimate future' of 2035. MAN Energy Solutions is looking into the possibility of an ammonia-fuel engine and has indicated that it will take roughly 200 million tonnes of ammonia per year to use ammonia as a carbon-free fuel for shipping, which is more than that which is now generated globally[15]. Another viable fuel – methanol – has already been used in piloted trials. The *Stena Germanica*, which runs between Gothenburg and Kiel, uses a methanol-based fuel mix[16]. Two Methanex Corporation seagoing vessels have been using dual-fuel methanol engines since 2016. In the Netherlands, a sector-wide Green Maritime Methanol initiative will look into the potential of this fuel for newbuild boats and conversions.

The statistics indicate an increasing uptake of alternative fuel in the world fleet, with LNG, battery, LPG, methanol, hydrogen and ammonia emerging as the most viable potential options for vessels, as illustrated in Figure 3.6. The timeline for the expected availability of ammonia, hydrogen and methanol for on-board use is depicted in Figure 3.7.

TABLE 3.1

Alternative fuels in commercial shipping[17]

Main current usage	Availability	Global production capacity and logistics
LNG		
• LNG is usually re-gasified and distributed through gas networks when it reaches its destination (import terminal) – just like gas from pipelines. • Currently, the largest uses of natural gas are for power generation (35%), followed by residential (22%) and manufacturing (17%) usage. • LNG is also increasingly used as fuel in transportation, and the People's Republic of China (China) already has over 300,000 LNG-fuelled trucks and buses on the road. • There are 251 LNG-powered ships in operation (excluding LNG carriers and inland waterways vessels) as of January 2022, and 403 confirmed orders for vessels that will be built in the next five years. In addition, there are approx. 500 LNG carriers in operation using LNG as fuel. • Approximately 6.5 million tonnes of LNG are consumed by ships (around 2% of the total marine consumption), of which around three-fourths are consumed by LNG carriers, presumably in the form of boil-off gas. After more than 18 years of phasing-in LNG (for non-LNG carriers), it still represents less than 1% of the global ship fuel consumption derived from LNG. However, the LNG consumption is projected to increase significantly over the next years due to the phasing in of new LNG-fuelled ships, including the introduction of larger ships such as container and cruise ships.	• In principle, LNG is available worldwide (large-scale import and export terminals), and investments are underway in many of these places to make LNG available to ships. • Dedicated LNG bunkering infrastructure for ships is currently limited but improving rapidly. Continuously updated information is available at afi.dnvgl.com. • A large share of LNG bunkering as well as LNG distribution to bunkering locations is still taking place by road. • In 2017 and 2018, several LNG bunker vessels were delivered for operation in key locations such as the Amsterdam, Rotterdam, Antwerp (ARA) region, the North Sea, the Baltic Sea and at the coast of Florida. • Bunker vessels for other key locations such as the Western Mediterranean, the Gulf of Mexico, the Middle East, Singapore, China, South Korea and Japan have recently been ordered or are under development and will likely materialize in parallel with significant orders for LNG-fuelled deep-sea ships within the next few years. • We expect to see a focus on developing LNG bunker vessels for refuelling seagoing ships in the near future. Bunkering by truck and permanent local depots will also continue to grow for certain trades and segments. Dual-fuel engine technology may also offer some flexibility and redundancy as the LNG bunkering network for the deep-sea fleet evolves.	• LNG has a share of approximately 10% in the overall natural gas market. • As of March 2018, global nominal liquefaction capacity totalled 369 million tonnes. Asia Pacific accounts for 38% of the production, followed by the Middle East with 28% and Africa with 19% (in 2017). • Capacity under construction amounted to 92 million tonnes as of March 2018. Most of the current liquefaction build-out, led by Australia and the USA, is expected to be completed by 2020. • Large volumes of natural gas are available today and will be available in the coming decades. There are no principal limitations to production capacities that could limit the availability of LNG as ship fuel.
Hydrogen		
• Currently, 65% of the hydrogen demand globally is from the chemicals sector, and 25% by the refining sector for hydrocracking and the desulphurization of fuels. • About 55% of the hydrogen is used for ammonia synthesis (chemicals sector), and 10% for methanol production (refining sector). • Hydrogen is also used by other industry sectors, such as producers of iron and steel, glass, electronics, specialty chemicals and bulk chemicals, but their combined share of total global demand is small. • The use of hydrogen in shipping is currently negligible, totalling 4 vessels, but several projects are under development for use of both liquified hydrogen and compressed hydrogen. The planned applications are in the short-sea segment.	• Currently, infrastructure and bunkering facilities are not developed. • Hydrogen production from electrolysis is a well-known and commercially available technology suitable for local production of hydrogen, e.g. in ports, as long as an adequate supply of electricity is available. This would eliminate the need for a long-distance distribution infrastructure. • In future, liquid hydrogen might be transported to ports from storage sites where hydrogen is produced from surplus renewable energy, such as wind power, whenever energy production exceeds grid demand. • Hydrogen can also be produced from natural gas, which is available globally.	• About 55 million tonnes of H_2 is produced per year globally. This is equal to the energy content of 165 million tonnes of fuel oil. • Hydrogen can be produced from various energy sources, such as by electrolysis powered by renewables, or by reforming natural gas, oil or coal. • Today, 95% of the hydrogen is produced from fossil fuels. The dominating production path is from natural gas (48% of the total), but there is also significant production from oil (30%) and coal (18%). The last 4% is produced from electrolysis. • As hydrogen can be produced from a range of different energy sources, including electricity, and is suitable both for distributed small-scale and centralized large-scale production, there are no principal limitations to production capacity that could restrict the amount of available H_2 to the shipping industry.

Main current usage	Availability	Global production capacity and logistics
Ammonia		
• Currently, 80% or more of the ammonia produced is used within agriculture (as fertilizer). • Ammonia is also used to produce plastics, fibres, explosives, nitric acid and intermediates for dyes and pharmaceuticals. It is also used in selective catalytic reduction (SCR) systems to reduce nitrogen oxide (NOx) emissions from industrial plants and ships. • Use of ammonia as fuel in shipping is currently non-existent, but the shipping industry is beginning to evaluate the use of fuel in combustion engines and fuel cells. • Ammonia is being used as cooling liquid on most fishing vessel applications requiring a large capacity for refrigeration. It has been used for a long time now, and current usage has increased.	• Ammonia has existing infrastructure for transport and handling, since it is used in large quantities as fertilizer. However, the development of a bunkering infrastructure remains a barrier for use as ship fuel. • Ammonia production from hydrogen and nitrogen is a well-known and commercially available technology suitable for local production of ammonia, e.g. in port, if an adequate supply of electricity is available. This would eliminate the need for a long-distance distribution infrastructure. • In future, liquid ammonia might be transported to ports from storage sites where ammonia is produced from surplus renewable energy, such as wind power, whenever energy production exceeds grid demand. • Ammonia can also be produced from natural gas, which is available globally. Other feedstocks include naphtha, heavy fuel oil and coal.	• There are numerous large-scale ammonia production plants worldwide, producing more than 170 million tonnes per year of NH_3 globally, most of it from natural gas. This is equal to the energy content of 76 million tonnes of fuel oil. • China produces 32% of the worldwide production, followed by Russia with 9%, India with 8%, and the USA with 8%. • Ammonia can be produced from renewable sources, utilizing electrolysis. Production via electrolysis is reported to have been made previously by 10 plants where the electricity was obtained from hydropower. The ageing plants have suffered from the price of electricity consumed and the cost for the process equipment, and only three plants may still be in operation. • An alternative promising path in early development stages is ammonia produced from wind energy or solar power.
Methanol		
• Methanol is a basic building block for hundreds of essential chemical commodities and is also used as fuel in the transportation sector. • In 2018, 25% of methanol was consumed in the production of formaldehyde, followed by 19% for production of alternative fuels and 12% for production of methyl tert-butyl ether (MTBE). • There are currently 47 methanol-fuelled ships in operation or on order.	• Methanol is one of the top five chemical commodities shipped around the world each year. It is readily available through existing global terminal infrastructure and well positioned to reliably supply the global marine industry. However, dedicated bunkering infrastructure for ships is currently limited. • Distribution to ships can be accomplished either by truck or by bunker vessel. In the Port of Gothenburg, Stena Lines has created a dedicated area for bunkering the vessel *Stena Germanica*. • In Germany, the first methanol infrastructure chain, from production using renewable energy to transport and ship bunkering to consumption in a fuel cell system on board the inland passenger vessel *MS Innogy*, was launched in August 2017.	• Methanol can be produced from several different feedstock resources, like natural gas or coal, or from renewable resources, such as biomass, CO_2 and hydrogen. • The methanol industry spans the entire globe, with production in Asia, North and South America, Europe, Africa and the Middle East. • Worldwide, over 90 methanol plants have a combined production capacity of about 110 million tonnes. The energy content is equal to approximately 55 million tonnes of oil. The global methanol demand was approximately 80 million tonnes in 2016, twice the 2006 amount. • More than 60% of methanol is currently consumed in Asia, where demand has been increasing for the last few years. Approximately 30% is used in North America, Western Europe and the Middle East, and this figure has been largely stable over the past decade. • It is expected that the current production can safely cover the demand for shipping until 2030, if the demand for methanol as ship fuel grows slowly initially and remains at a moderate level.

Main current usage	Availability	Global production capacity and logistics
LPG		
• In 2015, domestic (residential) use of LPG was 44%, followed by chemical industries at 26%, industry at 12%, transport at 9%, refineries at 8% and agriculture at 1%. • Of the fuel used for transportation, half is consumed in South Korea, Turkey, Russia, Thailand and Poland. Use as fuel for transportation has increased by 24% from 2009 to 2014. • The uptake of LPG fuel for ships is in its infancy, numbering 97 vessels all in the gas tanker segment.	• A large network of LPG import and export terminals is available around the world, but the development of a bunkering infrastructure for ships remains a barrier for the use of the fuel. • The established infrastructure already in place could be used as the basis for expanding the distribution and bunkering of LPG as a fuel for the marine market. Bunkering can be made available by truck or bunker vessels, from LPG terminals. • It is reported that there are more than 1,000 import and secondary terminals for pressurized LPG. Recently, more LPG export terminals have been developed in the USA to cover the increased demand for competitively priced LPG products.	• Global LPG production in 2017 was 309 million tonnes. This is equal to the energy content of 354 million tonnes of fuel oil. • LPG has two origins: approximately 60% is recovered during the extraction of natural gas and oil, and the remaining 40% is produced during the refining of crude oil. LPG is thus a naturally occurring by-product. • As part of the first process – known as flaring – an additional 265 million tonnes approximately of potential LPG are burnt annually. • The production increase has been most profound in North America and the Middle East. The production increase in North America in the last few years can be attributed to the substantial increase in shale gas production, which has turned the USA into a net exporter of LPG since 2012. • The USA is the world's largest producer of LPG. In 2017, over half of all US LPG production (67 million tonnes) was exported.
Electricity		
• The first fully electric car ferry, *MF Ampère*, has been in service between Lavik and Oppedal on the west coast of Norway since 2015. The next fully electric car ferry started operating between Pargas and Nagu in Finland in 2017. About 70 plug-in hybrid car ferries with a high degree of electrification (90%–100% of the energy output) are currently contracted for future ferry operation in Norway, and several more are anticipated. • Today, around 559 ships with batteries are in operation or on order, and approximately one-third of these operate close to fully electric (mostly car/passenger ferries). A total of 410 ships with batteries are in operation, of which 135 are fully electric. Limited shore-based infrastructure for charging is available today, but progress is being made in certain regions.	• In general, onshore power supply infrastructure is well developed, also for covering potential needs for shipping. However, limited shore-based infrastructure is available today for charging, but progress is being made in certain regions.	• The global electricity production is currently reported to be 27,382 TWh (about 2,300 million tonnes oil equivalents, when not adjusting for differences in energy converter efficiency) and is expected to increase by almost 40% by 2030. In 2016, approximately 33% of electricity was generated from other sources than combustible fuels. The renewables share of electricity production is expected to accelerate especially due to onshore wind and solar energy. • About 15% of the global population still lives without access to electricity. The electricity access deficit is concentrated in Sub-Saharan Africa and South Asia, followed by East Asia and the Pacific, Latin America, the Middle East and North Africa. At the country level, India alone has a little less than one-third of the global deficit. This will hamper the possibility for global uptake.

Main current usage	Availability	Global production capacity and logistics
Biofuel		
- *Stena Bulk* has completed a successful sea trial voyage using sustainable marine biofuel oil (BFO) derived from forest residues and waste oil products. The fuel proved to be a technically compliant alternative to the fossil fuel typically used for ocean-going tankers. During a 10-day trial voyage, the 50,000 dwt MR tanker *Stena Immortal* ran on 100% biofuel during typical commercial operations. The BFO, created by GoodFuels Marine, was loaded at the Port of Rotterdam and tested in tanks and storage, and was burned in the engines. - Announcing the completion of the trials, *Stena Bulk* and GoodFuels said it demonstrated sustainable marine biofuel's position within the marine fuel mix and provides owners and operators a new option to address current and impending environmental regulations. - The fuel, which GoodFuels launched in 2018, is reported to reduce greenhouse gas emissions by 83%. Because it substantially reduces CO_2 and SOx emissions, GoodFuels' biofuel oil complies with the International Maritime Organization's (IMO) 2020 sulphur cap, greenhouse gas reduction requirements, and upcoming regulations to reduce carbon intensity from shipping.[19]	- Only biodiesel made from plant oil or pulping leftovers and bioethanol are now commercially available and can supply considerable amounts of gasoline. The current renewable diesel fuels are primarily made from plant-based oils or by-products, such as used cooking oil (UCO), and the current technology estimates a 10- to 20-million-tonne supply of sustainable renewable diesel. Another concern is that plant oil-based fuels are currently the most widely used fuel type for bio jet fuels, resulting in feedstock competition between the shipping and aviation industries. Bioethanol can be produced sustainably from waste and lignocellulosic feedstocks, with far greater supply potential and the ability to replace all fossil fuels in the shipping sector, but it is incompatible with present marine diesels and cannot be utilized as a drop-in fuel. Multifuel engines, however, are a result of advancements in engine technology. In a diesel cycle, these engines can run on oil, gas or alcohols (such as methanol or ethanol). As a result, as ships with new engines are introduced, the consumption of ethanol may increase dramatically in the medium to long term. Biofuels are more expensive than fossil fuels, and this is projected to continue in the short to medium term. Biofuels will become more economically competitive as a result of specific biofuel mandates or carbon prices. Low-carbon transportation, however, might be introduced as a business model, with a value placed on decreased CO_2 emissions.	- The shipping sector consumes more than 330 million tonnes of fuel per year. Marine fuels are primarily produced from crude oil, with heavy fuel oil (HFO) and marine diesel oil (MDO) being the main fuels used. Higher quality distillate fuels are primarily used in Emission Control Areas (ECAs) and are known as ULSD (ultra-low-sulphur diesel). ECAs have been created in coastal areas in North America and Europe, and enforce strict limits on SOx, NOx and particulate matter emissions. To fulfil these, ULSD or other low-polluting fuel alternatives or exhaust gas cleaning systems must be used within ECAs.[18]

Main current usage	Availability	Global production capacity and logistics
Nuclear		
• The first nuclear power plant was built for the U.S. Navy in 1955, more than half a century ago. Since then, around 700 reactors have been operating at sea, with around 100 currently in operation. • Ships that use nuclear power may be assured that they are employing a zero-emission solution, as it produces no SOx, NOx, CO_2 or particulates. Nuclear power, according to Lloyd's Register, is millions of times more powerful than fossil fuels and alternative fuels like methanol, ammonia and hydrogen. In practice, this means that shipping may meet the IMO's 2050 greenhouse gas (GHG) reduction goal by utilizing such technology, as it will replace fossil fuels. • Keep in mind that the energy source is currently not included in the Energy Efficiency Design Index (EEDI). This means that vessels equipped with this technology face no obstacles. • Nuclear power can be extremely beneficial to ferries. This is due to two key reasons: to begin with, ferries will be zero-emission ships because they will not be required to bunker when boarding or disembarking people. Second, they will not need to utilize shoreside electricity to reduce emissions, and it may even be able to supply power from the vessel to shoreside, resulting in an additional revenue stream. Furthermore, nuclear-powered ships require far less refuelling. This allows them to travel large distances with a single energy production, speeding up the journey. This is particularly evident in nuclear military ships, such as submarines, which may stay below for months at a time without needing to resurface for refuelling. Furthermore, nuclear energy has a higher power-to-weight ratio. This means that ships equipped with the technology will be able to carry greater weight and travel longer distances faster, even if they are carrying more cargo.[21]	• Reasons why nuclear power for commercial ships has made almost no material grounds:[20] • The nuclear industry up until now has built itself into a small corner of the market by only building gigantic utility plants. Ships have power requirements many times smaller than this, so there have been no available reactors to purchase, let alone to do the full design and safety analyses needed for ships. While some marine nuclear reactors have been proposed in a multitude of studies, with at least one being fully designed in the 1960s as a standardized marine nuclear propulsion plant, building a specifically sized reactor with a small production volume is economically prohibitive. • The cost of fuel is nuclear power's key advantage, but only relatively recently has the cost of oil become significantly higher than nuclear fuel. This widens the number of ship types that nuclear power can be economical for compared to in the past. For example, this lack of fuel price differential, and the corresponding lack of availability of nuclear reactors, likely discouraged the use of nuclear propulsion for the SL-7 class of high-speed fuel-oil-burning container ships that were built in the early 1970s, whose economic employment were destroyed by the OPEC oil embargo in 1973. • Lack of confidence in investors that any nuclear-related project will be protected from political opposition or clever public delays, such as was the case for the Shoreham nuclear power plant debacle (Cohen, 2004). • Most studies have focused on high-speed applications in which the transit times are well above industry standard. Such low transit times may not have customer bases that are strong enough to pay the higher premiums, even if a nuclear-powered service is significantly cheaper than a fossil-fuelled equivalent. Such high-speed services are able to absorb the costs of purpose-built maritime nuclear reactors, but only if there is demand for such services, which remains to be determined.	• There are opportunities for the USA in nuclear-powered commercial shipping. The technical and regulatory familiarity with nuclear power puts the USA in a position to lead the world in the development of modern nuclear ships, but only if there is a national interest to do so. Building the reactors, training the crews, or performing maintenance and repair on nuclear-powered ships are ways to grow the US maritime industry, as well to increase the USA's influence on global maritime matters. The USA will likely still have to reduce the costs from shipyards if it wants to build nuclear-powered ships for foreign trade, but nuclear power is a way to overcome the price differential.

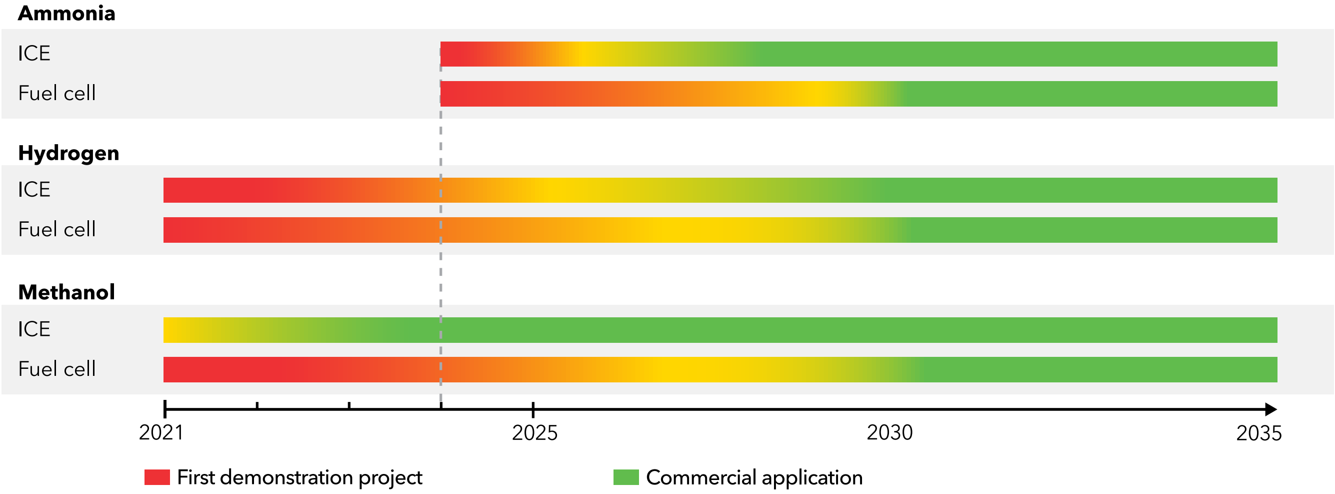
TABLE 3.2

Assessment summary of potential alternative fuels in commercial shipping[6]

Key challenges	Status	Rules and regulations
Hydrogen		
• High investment cost • Low maturity of technology • Availability and price of H_2 • On-board storage requirement • Lack of safety and approval requirements	• Demonstration prototypes have been initiated for both ICE and FC installations. • Since 2017, smaller vessels have used internal combustion engines running on H_2 (*Hydroville*). • Using compressed or liquefied H_2 in fuel cells is a realistic option for the short-sea shipping segment in the medium term. • Plans exist to introduce hydrogen as fuel for large ships (e.g. Japan's roadmap for shipping by 2030). • A Norwegian fuel cell / battery-powered vessel using liquid hydrogen as fuel is planned to be introduced next year. • The first limited commercial applications are expected by 2025. • Scaled commercialization is not expected before 2030 at the earliest.	• Lack of rules for use of H_2 on board; ongoing efforts on developing input for rules and standards. • Based on the alternative design approach in the IGF Code, which is a risk-based approach intended to demonstrate equivalent safety.
Ammonia		
• Very high auto-ignition temperature • Low flame speed • High heat of vaporization • Narrow flammability limits • Toxicity	• Prototyping of technology and demonstration projects are in progress. • The demonstration of an ammonia-powered fuel cell of 2 MW is planned during 2024 for retrofitting an existing supply vessel, *Viking Energy*. • Some commercial applications are also expected as several players such as *Grieg Star* (tanker, 2024) and *DFDS* (RoPax ship, 2026) have announced plans for use. • Development work on engines that can burn NH_3 is underway as indicated in the timeline, expected to be ready within the next few years.	• Class rules have recently been released, based on the alternative design approach in the IGF Code, which is a risk-based approach intended to demonstrate equivalent safety. • Class rules may be used to ease this approach if accepted by the flag administration.
Methanol		
• Low flashpoint properties	• Fuel cell technology utilizing methanol has been demonstrated in test installations (Viking Line Ferry *MS Mariella*). • Methanol engines are commercially available and already have more than 100,000 hours of operation. • It has attracted interest as an alternative, low-carbon fuel as it is also possible to produce with renewable feedstocks such as municipal and industrial waste and biomass, together with CO_2 and hydrogen.	• Regulations for fuel cell installations are currently under discussion in the IMO but have not been completed. • Methanol will have to resort to the alternative design approach laid out in the IGF Code for approval of fuel cell installations. • Class rules are in place, and the IMO has approved interim guidelines, providing an international standard for the use of methanol as fuel. • Class rules for fuel cells may be used to ease this approach if accepted by the flag administration.

FIGURE 3.7

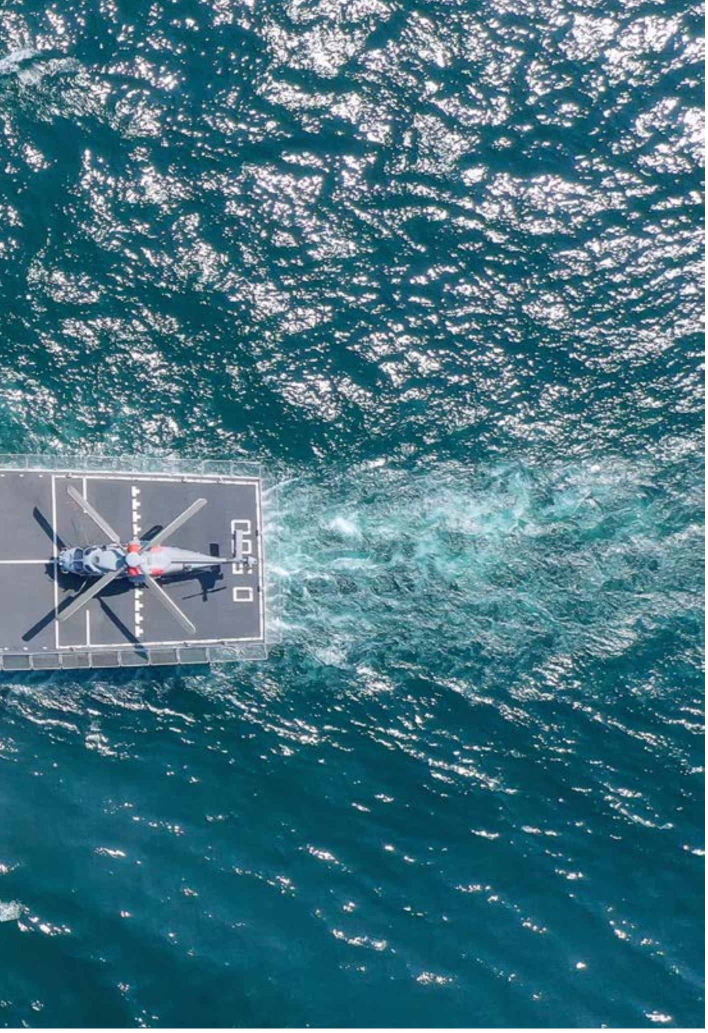
Timeline for expected availability of ammonia, hydrogen and methanol for on-board use



Key: Internal combustion engine (ICE)

4. Adoption of alternative fuels in naval vessels

For more than 100 years, the world's militaries, including its navies, have taken a leadership role in the research and development (R&D) of specific technologies – especially where they are applicable in combat theatres. Over many decades, that leadership has involved issues relating to energy supply and use. Recently, this interest has not diminished but rather expanded to bring in stronger consideration of resource efficiency and environmental impacts. This chapter presents the drivers for adopting alternative fuels in naval vessels as well as reviews the currently implemented alternative fuel types and predominant use to date of these alternative fuels in the navy sector. The findings have also been substantiated with insights from a survey of a wide range of respondents (navy, shipyards, OEMs and fuel suppliers) originating from 12 different countries.



In recent years, there has been increased emphasis on the efficiency of home-country installations, and the development of unconventional energy projects, including renewables, for areas as diverse as microgrids for installations to alternative fuels for major weapons systems such as aircraft and ships. A driver for utilizing an alternative fuel within the navy stems from the need to diversify its energy source, thereby enhancing its operational flexibility. An omnipresent and effective combat capability option requires energy sources that are equally ever-present. For example, secure energy sources combined with a strong logistics train have allowed the U.S. Navy to maintain a global presence.[22] Within that domain, the goal has been to find the most cost-effective solutions to improve energy security, or energy availability and accessibility. To achieve this, the developed policies and strategies must be robust and competent. This includes managing the strategic tension between investing in fuel-saving modernization and funding survivability and combat capability improvements.

Fuel efficiency is vital for closing the logistics gap, boosting combat capability and extending operational range, giving commanders greater options when engaging enemies. One strategy to enhance energy efficiency is to better plan operations, reduce greenhouse gas (GHG) emissions in a cost-effective manner and cut operating expenses, and hence maximize the total global competitive advantage. Operational flexibility also covers an efficient use of the vessel's installed machinery and propulsion systems, ensuring optimum manoeuvrability, while built-in system redundancies (for example through dual-fuel or hybrid propulsion systems) offer inherent system robustness when dealing with unexpected events.

The survey, conducted as a part of the development of this white paper, suggests good agreement with the findings from the review above. Of the responses received, results indicated that practical considerations such as logistics, fuel availability and fuel change flexibility proved to be critical factors in determining the feasibility of utilizing alternative fuels.

Logistics (fuel availability / fuel change flexibility), Fire Safety (survivability/safety), and Compatibility (combatant/non-combatant) were the top three priorities for many industry stakeholders surveyed when considering the future of alternative fuels in the navy, with 79.2%, 70.8% and 58.3% prioritizing these three options respectively.

Respondents also ranked the overall operational aspect of a naval asset as key to determining the viability of implementing alternative fuel. Naval vessels can be conveniently divided into two categories: combatant and non-combatant. Non-combatant vessels include vessels such as auxiliary, service support, or merchant/recreational vessel types, which tend to be role-specific. Combatant vessels, however, are categorized as naval, coast guard, and government-owned vessels/craft that possess an inherent armed or combat capability primarily intended for offensive use. A 'support' or 'coastal defence' vessel has been suggested by survey respondents most likely to implement alternative fuels, suggesting greater viability within the non-combatant vessel type.

4.1 Current implementations of alternative fuel types

Alternative fuels have been in use by navies around the world for many years and across many platforms. This section serves as a reference to what has happened in the past. Close examination of the successful projects may offer insights into the future of alternative fuel development for the navy, in terms of the most promising fuel types to deploy and their applications on specific naval vessel types.

Respondents to a recent survey of members of the DNV Naval Committee were asked 'When the topic of alternative fuels for navy vessels is raised, which types spring to mind?', and 83.3% of them chose biofuels as the top option. A large majority also picked the 'Others' option and brought up many other alternative fuels such as ammonia, methanol and hydrocarbons. These are fuels that are also being looked at in the maritime industry in general and which show great potential in being the future of decarbonization in shipping. The same survey response also indicated that 'synthetic diesel manufactured using renewable energy and net-zero carbon cycle is ideal but likely to be expensive'.

In addition to the survey, a review was performed based on a comprehensive search and analysis of available sources and case studies with regards to currently implemented alternative fuel types and the predominant use of alternative fuels in naval vessels. The sources are wide-ranging, including, but not limited to, online portals, news articles, research articles, technical reports and naval blogs. The collated results are listed in the Appendix (Table 7.2).

This chapter represents a substantiation of alternative fuel types that are currently being implemented within navies: nuclear, fuel cell, biofuel and battery.

Nuclear

The USA started alternative fuel research and nuclear propulsion applications for naval vessels in the 1960s.[23] A 2005 'quick look' analysis by the Naval Nuclear Propulsion Program concluded that total life-cycle costs for nuclear-powered versions of these ships would equal those of oil-fuelled versions when oil reaches about $70 and $178 per barrel, respectively. The study did not attempt to quantify the mobility-related operational advantages of nuclear propulsion. These include the ability to transit long distances at high speeds (so as to respond quickly to distant contingencies) without having to slow down for refuelling, the ability to commence combat operations immediately upon arrival in the theatre of operations without having to first refuel, and the ability to manoeuvre at high speeds within the theatre of operations without having to refuel. Nuclear-powered ships also have the advantage that they do not emit the hot exhaust gases which contribute to the infrared detectability of fossil-fuelled ships. Furthermore, nuclear power produces fewer or no emissions during operation. The avoidance of emissions prevents detection, as nothing is discharged when underwater, thereby making detection more difficult due to the absence of rising bubbles.

Nuclear application in the commercial sector:

General arrangement of fusion-powered container vessel. The fusion engine is located amidships in a sealed engine room below and forward from the deckhouse.

The general layout of an FPVC is similar to that of a standard 20,000 TEU vessel. The principal changes include the placement of the fusion engine in a sealed chamber amidships, below and forward from the deckhouse. Next to the fusion engine room is a steam plant with heat exchangers, steam turbines, and generators. Due to a larger engine room beneath the deckhouse, the nominal capacity is reduced to 19,338 TEU when compared to the reference ship. Twin propellers are driven by six electric motors in the aft engine room. The auxiliary power plant is located below the deckhouse and is designed to allow for a cold start-up of the fusion system. After five years, FPCVs have lower cumulative expenses than traditional cases, saving nearly $1 billion after 15 years.

A nuclear surface ship brings an optimum capability to bear. A study by the U.S. Navy found the nuclear option to be superior to conventional fuels in terms of surge ability, moving from one theatre to another and staying on station. An admiral once said, 'Without the encumbrances of fuel supply logistics, our nuclear-powered warships can get to areas of interest quicker, ready to enter the fight, and stay on station longer than their fossil-fuelled counterparts.'[24]

On the flip side, the radioactive waste coming from nuclear power is a great caution and peril to the environment. In terms of operating cost, challenging market conditions have left the nuclear industry struggling to compete. Strict regulations on maintenance, staffing levels, operator training and plant inspections have become a burden for sustenance. Apart from the USA, nuclear-powered naval vessels have also been constructed and operated by Russia, the UK, France and China, as depicted in Figure 4.1.

Fuel cell (hydrogen and bioethanol)

In addition to the USA, there is strong interest in other countries (e.g. Germany and South Korea) in developing and adopting shipboard hydrogen fuel cell technology for powering both shipboard equipment and ship propulsion. Fuel cell technology has been incorporated into non-nuclear-powered submarines, such as the German Type 212 or Type 214, and is starting to be applied to civilian surface ships. The USA's ONR (Office of Naval Research) and the Naval Sea Systems Command (NAVSEA)[25] have a shipboard hydrogen fuel cell programme for developing fuel cell power systems for naval ships, with an acquisition cost, weight and volume comparable to other market options. Instead of the hydrogen-fuelled system, a bioethanol processor system that transforms the bioethanol into high-purity hydrogen has been adopted by the Spanish Navy (S-80 Plus-class submarines). Briefings suggest that fuel cell technology has been available for use on naval ships and could be widely adopted within the next few to several years.[23] Fuel cells have the best efficiency at low power, but as power increases, the efficiency decreases. With an engine, it is the opposite; a low efficiency is yielded at low load and higher efficiency at high load. So, whatever technology delivers the most benefits depends entirely on the application. As a result, this might greatly increase combat capability as well as decarbonization.

Hydrogen application in the commercial sector:

The world's first hydrogen-powered car ferry, Norled's *MF Nesvik*, undergoing sea trials in March 2021. (Image courtesy of Westcon / Økland foto.)

Vessels in the short-sea segment are typically smaller, with more varied operational profiles, and a greater share of their time and energy is spent on purposes other than steady propulsion. For these ships, the shorter distances and highly variable power demands often make electric and direct use of H_2 highly relevant. This is reflected by the world's first hydrogen-powered car ferries, planned to be put into operation this year in Norway.

DNV Technology Progress Report:
https://bit.ly/3uliDCx

Biofuel

Alternative hydrocarbon fuels are currently being studied as well for naval ships and these include biodiesel and liquid hydrocarbon fuels using the Fischer-Tropsch (FT) process. A 2005 Naval Advisory Research (NRAC) study from the USA and a 2006 Air Force Scientific Advisory Board both discussed FT fuels. A January 2006 'quick look' study by the U.S. Air Force Scientific Advisory Board examined several potential alternative fuels for air force use.[26] The study noted that FT fuels offered certain 'significant benefits' in terms of their technical properties and stated that the 'air force has the ability to catalyze large-scale transition to alternative fuels'. As one of its recommendations for the near term, the study said the air force should 'ramp up development and utilization of FT fuels' and 'take the lead in the Department of Defense transition to new fuels via blends'. One of its recommendations for the mid and far term was 'alternative fuels, for example biofuels and alternative hydrocarbon fuel blends'.[23]

Nevertheless, biofuels for current civilian uses (so-called FAME biofuels) present compatibility issues in the marine sector owing to their physical and chemical properties that make them hard to mix with fossil fuel, and difficult for long-term on-board storage. Biofuels include fatty acid methyl esters (FAME) compositions that are made up of different ratios of saturated and unsaturated fatty acids which influence combustion. The influences on oxidation stability and compatibility of biofuel blends are some of the effects that can arise from the differences in the characteristic of the biofuel. Many of these have been well researched over the last few years, but a lot more research is required to determine the compatibility between the different bio blends with fossil fuels, in other words VLSFOs.[27]

In December 2012, the Italian Navy signed a cooperation agreement with the ENI for the development and testing of an alternative fuel produced from renewable sources, in accordance with NATO naval fuel standards. This resulted in the production of GreenDiesel™ fuel which can be blended up to 50% with conventional fossil fuel, in accordance with NATO specifications, with no need for engine or equipment modifications. GreenDiesel is currently produced from certified sustainable palm oil, not competing with food production, and the Italian Navy successfully tested biofuel on the offshore patrol vessel, *Foscari*, the first European military vessel to sail using GreenDiesel. Testing activities and trials were conducted throughout 2015 on other naval units, and in particular the use of the Green F-76 on board the *ITS Cavour* allowed a 6% reduction in NOx emissions; on the destroyer *ITS Caio Duilio*, GreenDiesel was tested in the gas turbine-based propulsion systems, reaching top speed. GreenDiesel was also tested on the submarine Gazzana (June 2015) and on the *ITS Maestrale* (November 2015).[28]

The research interests in alternative fuels for the U.S. Navy have been focused on drop-in fuels only, which are biofuels that can directly replace petroleum-based gasoline and distillate fuels, as these fuels would not require modifications to the ship infrastructure and regular operation procedures.[29] This can, in turn, improve its operational flexibility and combat capability. The U.S. Navy's Self Defense Test Ship successfully completed trials involving two alternative fuels in 2016, demonstrating that the alternative fuels could function as a drop-in replacement, requiring no changes to equipment or operating procedures. Two fuels were developed using different methods: synthetic iso-paraffin (SIP) and catalytic hydrothermolysis conversion diesel (CHCD). SIP is a fuel derived from alternative feedstock and blended with military-grade petroleum-based fuel, known as F-76, with 20% non-petroleum-sourced. CHCD is a military-grade drop-in replacement for the traditional F-76 that is 100% non-petroleum-sourced. The objective of this particular test was twofold: first, to demonstrate that these alternative fuels are drop-in replacements for petroleum-sourced F-76, meaning they require no equipment modifications or operational modifications by the crew; and second, to ensure that approved alternatively sourced fuels perform equal to, or better than, existing petroleum-sourced fuels.[30] ReadiDiesel, termed catalytic hydrothermolysis conversion diesel (CHCD-76) by the navy, is a military-grade drop-in replacement for traditional F-76 that is produced from fats, oils and greases by the biofuel isoconversion process. ReadiDiesel has the same molecular composition, boiling range distribution, and physical and energy density as petroleum fuels, but reduces greenhouse gas emissions by 80% compared to petroleum.[31]

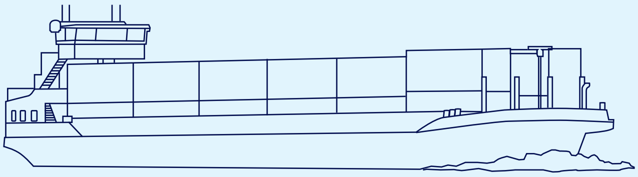
In contrast to first-generation biofuels, second-generation biofuels are often made from lignocellulosic biomass, which consists of non-edible feedstocks.[32] Lignocellulosic biomass is a non-edible, high-aromatic, complex three-dimensional polymer biomass with the potential to be turned into biofuels for use in diesel engines.[33] The chemical pulping business produces up to 70 million tonnes of lignin biowaste per year, and the growing cellulosic ethanol industry may produce a similar quantity in future. Researchers studied the engine performance of different biofuels, including three types of low-toxicity, lignin-derived aromatic oxygenates. Biofuels use about the same amount of fuel as diesel, however 2-phenyl ethanol produces the most smoke.[34] It was claimed that the biofuel's thermal efficiency and fuel consumption were lower than those of diesel fuel.

Battery

Battery solutions for naval vessels are currently not yet available, with the exception of already well-documented and proven battery technology on submarines. Thus, its application for surface ships in commercial shipping is elaborated.

The *Alphenaar* is the first ship to be propelled with interchangeable energy containers. This ZES project will sail for Heineken. Two ZESpacks are on board the *Alphenaar*. These appear to be ordinary containers, but they are actually batteries that are later charged with green electricity. Wärtsilä supplied the containers, which contain 45 battery modules with a total capacity of 2 MWh, equivalent to 36 electric automobiles. One battery is needed on the voyage to Moerdijk, which takes around six hours. On the way back, the second container is used. The batteries can be charged at CCT's Alphen aan den Rijn container terminal. ENGIE created this charging station. The containers may be swapped out, allowing the ship to continue sailing. Inland navigation contributes significantly to the reduction of greenhouse gas emissions. Within the transportation sector, inland shipping accounts for 5% of CO_2 emissions in the Netherlands. In addition, inland shipping is responsible for 11% of total NOx emissions in the Netherlands. Engie, ING, Wärtsilä and the Port of Rotterdam Authority formed Zero Emission Services (ZES) last year. In the near future, ZES plans to expand to eight ships, eight charging stations and 14 ZESpacks.[35]

Battery application in the commercial sector:

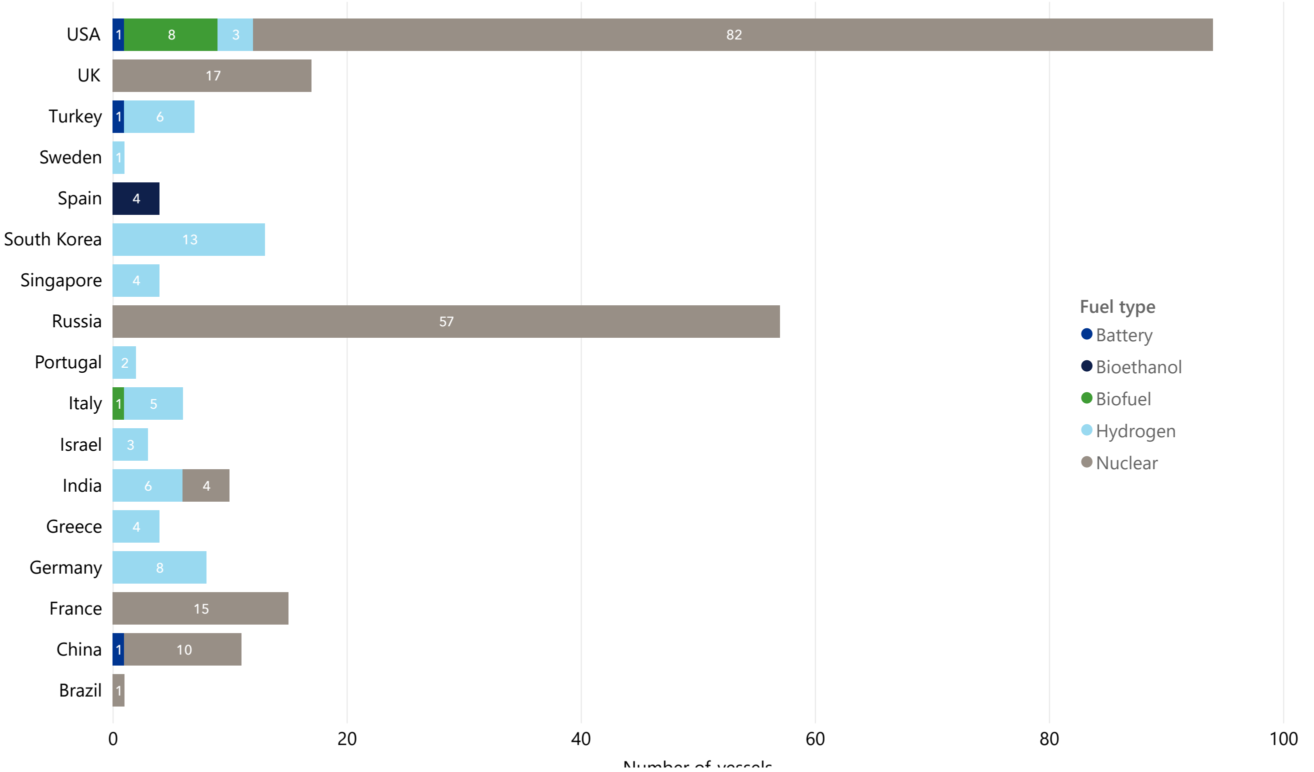


The Dutch inland vessel began a scheduled run on electric power in September 2021. It gets its power from batteries kept in containers that can be swapped out when leaving or arriving at port. The *Alphenaar* can sail 50 to 100 kilometres with two power containers. The group that allows the *Alphenaar* to sail on batteries is preparing new places and ships to expand battery-powered inland waterway sailing.

The *Alphenaar* sails: First electric ship with interchangeable batteries: https://bit.ly/3ufksAI

FIGURE 4.1

Number of naval vessels that currently utilize alternative fuels in the navy across different countries based on information attained from open-sourced data (see Table 7.2 in the Appendix for the full list). Decommissioned vessels are excluded from the figure.



4.2 Predominant use of alternative fuels in naval vessels

This section details the three types of naval vessels that have been utilizing alternative fuels: submarines, support (i.e. auxiliary) ships, and surface combatants.

Submarines

Submarines have taken the lead in terms of the adoption rate of alternative fuels, thanks to the emergence of the air-independent propulsion (AIP) system. AIP is any marine propulsion technology that allows a non-nuclear submarine to operate without access to atmospheric oxygen (by surfacing or using a snorkel). AIP can augment or replace the diesel-electric propulsion system of non-nuclear vessels. AIP, while not granting a diesel-electric submarine the same underwater staying power as a nuclear-powered submarine, is still a radical improvement. This system increases the vessel's combat capability and can contribute to decarbonization. First fielded in the 1990s, the development of AIP changed the way non-nuclear submarines operated, allowing them to fight – and hide – underwater for longer. Combined with the system's extreme quietness, the use of AIP has made modern diesel-electric submarines highly efficient, capable of combat even in a challenging anti-submarine warfare environment.[36]

Although nuclear submarines offer far better endurance and speeds, they are unsuitable for shallow littoral waters and most navies cannot afford to build and maintain them, as they are very expensive. Diesel submarines possess the advantage of being able to switch off their engines completely and lie in wait, unlike nuclear submarines whose reactors cannot be switched off at will. This, combined with the ultra-quiet nature of modern diesel submarines, has made AIP-equipped diesel submarines a very attractive alternative for many countries. Many countries (seven in total)[37] are operating both nuclear and diesel-powered submarines for their respective advantages. Navies who wish to operate non-nuclear submarines with long-range and large weapon payloads are now opting for large diesel submarines equipped with AIP, which provide the closest alternative to nuclear-powered submarines. Figures 4.2 to 4.4 show the number of submarines that utilize alternative fuels in the navy across different countries based on information attained from open-sourced data. In general, there are four types of AIP systems: closed-cycle diesel engines, closed-cycle steam turbines, Sterling cycle engines, and fuel cells.[38] The commonly used AIP systems are the Sterling cycle engines and fuel cells. A typical fuel cell converts hydrogen (fuel) and oxygen (oxidizer) into electricity, with water and heat released as by-products. Apart from hydrogen being used as the fuel, an AIP system which is built on a bioethanol processor that transforms the bioethanol into high-purity hydrogen has been adopted by the Spanish Navy (S-80 Plus-class submarine, namely *Issac Peral*, *Narciso Monturio*l, *Cosme Garcias* and *Mateo Garcia de los Reyes*).

The turn of the 20th century marked a change in the development of submarines. Diesel electric propulsion would become the dominant power system. Batteries were used for running submerged, and gasoline or diesel engines were used on the surface and during snorting to recharge the batteries. Early boats used gasoline, but quickly gave way to diesel due to its reduced flammability. Yet, over the years, other power sources have been investigated and successfully applied.

Alternative Power Sources for Submarines: https://bit.ly/3kHNAxi

Submarine application in the commercial sector:

As a research vessel, U-Boat Worx' submersibles can be applied in various fields of marine and related sciences. They are powered by a lithium-ion battery system, which provides a 350% increase in battery capacity when compared to traditional submersibles that use lead-acid battery power. The technology has been tested down to 4,000 metres under water and stores a total of 62 kWh.

FIGURE 4.2

Number of submarines that utilize alternative fuels in the navy across different countries based on information attained from open-sourced data (based on case studies obtained, see Table 7.2 in the Appendix). Decommissioned vessels are excluded from the figure.

Number of vessels by country and vessel type

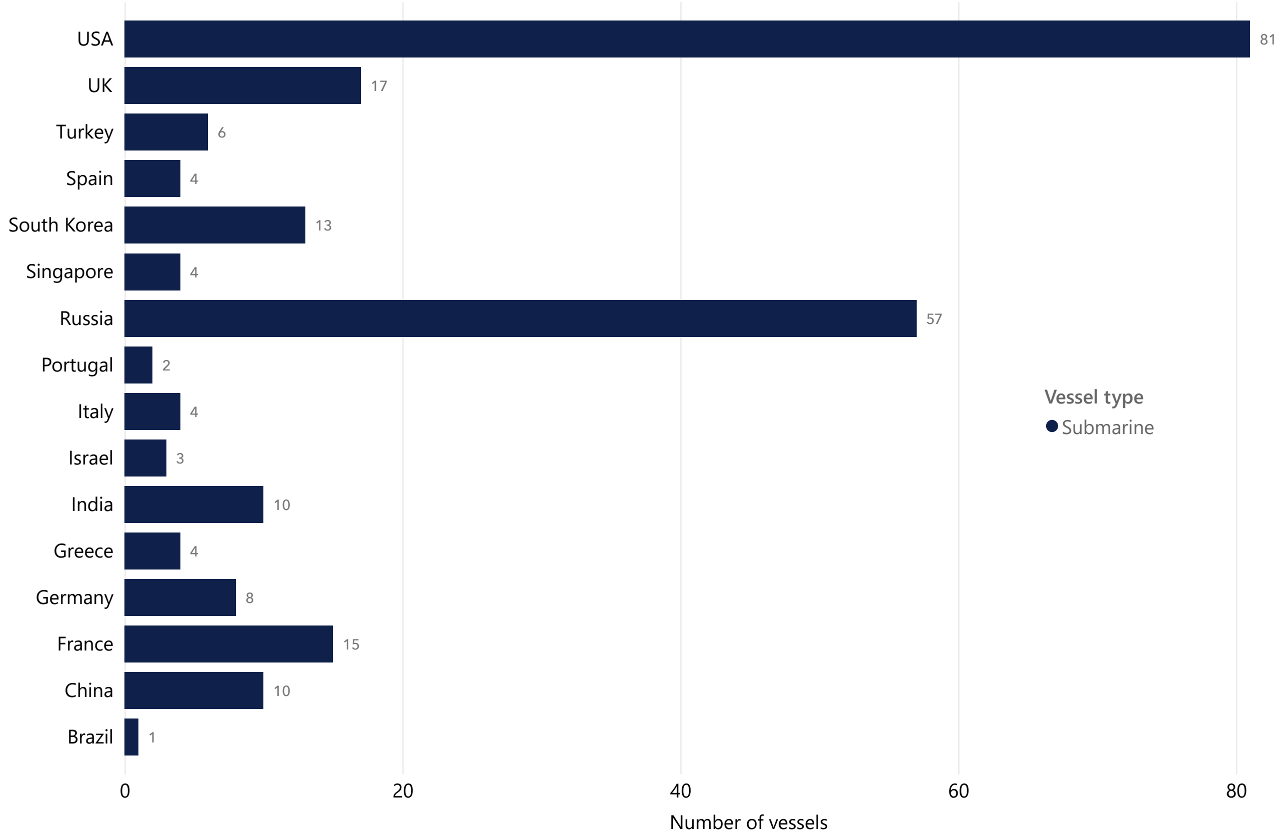
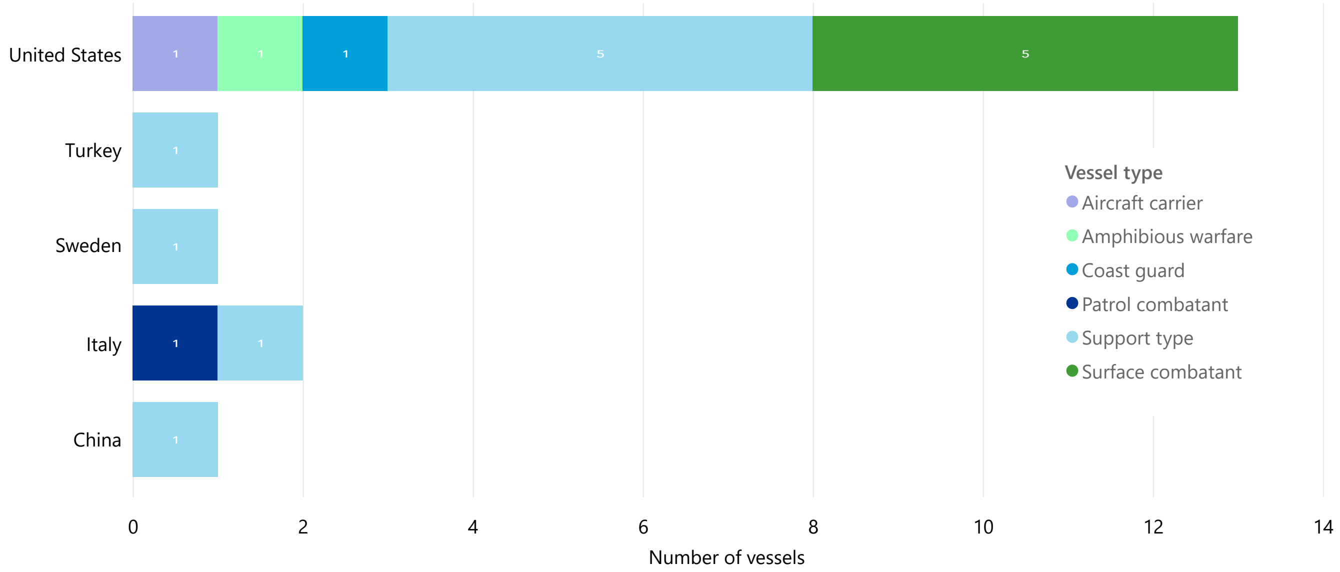
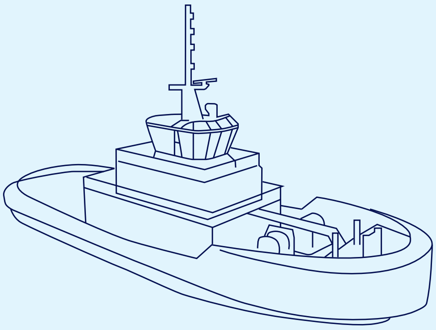


FIGURE 4.3

Number of naval vessels (except submarines) that utilize alternative fuels in the navy across different countries based on information attained from open-sourced data (see Table 7.2 in the Appendix for a full list). Decommissioned vessels are excluded from the figure.

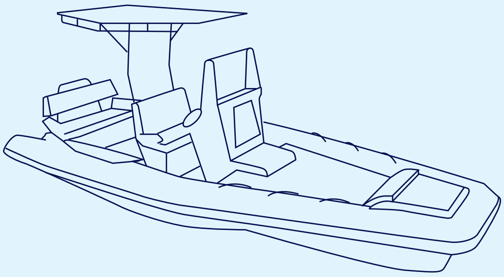


Support ships application in the commercial sector:



Tokyo Kisen Co., Ltd. and e5 Lab Inc. (a shipping systems provider) reported that they had jointly developed a new design concept, the e5 Tug. Tokyo Kisen has been consistently engaged in the operation of assisting the navigational safety of ships throughout Tokyo Bay, the centre of Japanese marine transport and one of the busiest sea traffic areas in the world. This electric propulsion harbour tug is powered by a large-capacity battery and a hydrogen fuel cell.

Electric tug e5 Tug powered by battery and hydrogen fuel cell: https://bit.ly/39FvnKl



The RS electric boat can be used for either work or leisure. The characteristics of the battery monitoring system are to monitor performance, system health, battery capacity and remaining range in real-time via the on-board touch-screen display. The Pulse 63 electric RIB can run at speeds of up to 23 knots with a range of up to 100 nautical miles, depending on the average speed.

RS Electric Boats:

Support ships

Support ships are not designed to participate in combat and are generally not armed. They include ocean tugs, research vessels, sealift vessels, etc. Figures 4.3 and 4.5 show that a number of naval vessels have been adopting alternative fuels. In 2016, biofuel was first tested and proven to be an ideal renewable fuel source for an academic research vessel, the *Robert Gordon Sproul*, but there is one slight hitch: it (currently) costs about 10% more than fossil fuel. Apart from these, the U.S. Navy's Self Defense Test Ship has also successfully completed trials involving two different types of biofuels, namely synthetic iso-paraffin (SIP) and catalytic hydrothermolysis conversion diesel (CHCD). The trials demonstrated that the biofuels tested could function as drop-in replacements for petroleum-sourced fuel, requiring no equipment modifications or operational modifications.[30]

Apart from biofuel, electric tugs powered by batteries have been a topic of interest, as these can result in decarbonization particularly in and around port precincts typically accommodating large populations that are susceptible to the impacts of harmful emissions to air associated with fossil fuels. China recently reported that it has put into service its first fully electric tugboat, one of a small number of electric tugs in the world. According to estimates, the electric tugboat can save about 300 tonnes of fuel consumption each year and will reduce carbon emissions of about 900 tonnes each year, which is equivalent to the emission reduction of more than 400 cars.[39] Due to the advent of LNG technologies as well as the maturing LNG supply chain, the recent uptake of LNG fuels by service vessels and tugs has been more rapid. Nearly all the ships are still hybrid solutions in which diesel (or biofuel) is used to extend the operating range or provide power redundancy. Singaporean owners are leading the world in adopting LNG and hybrid propulsion to power their tugs, in which they have seen a 22% reduction in CO_2 and 15% lower noise levels for better crew comfort, compared with conventional diesel-fuelled tugs.[40] The increasing number of LNG-powered vessels in commercial shipping indirectly signifies the possible implementation of LNG fuels on naval support ships in the near future.

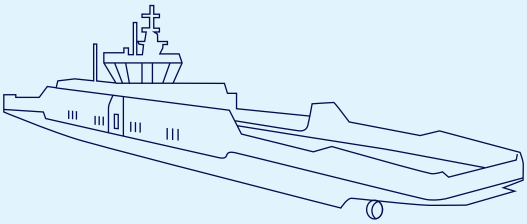
The European innovation project FLAGSHIPS will be an inland waterway vessel set to ply the Seine River in Paris and is scheduled for delivery in September 2021. It will be fitted with a hydrogen power generation system, i.e. hydrogen fuel cells.

Clean waterborne transport in Europe. FLAGSHIPS: https://bit.ly/39FvBRH

FIGURE 4.4

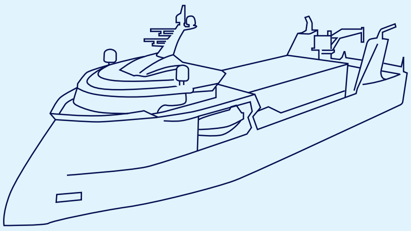
Number of submarines that utilize alternative fuels in the navy across different countries based on information attained from open-sourced data (based on case studies obtained, see Table 7.2 in the Appendix). Decommissioned vessels are excluded from the figure.

Surface vessel application in the commercial sector:



Wärtsilä has launched a complete concept for a series of innovative and cost-effective shuttle ferries, featuring zero or very low levels of emissions. The design characteristic focuses on high energy efficiency with low resistance, both above and below the waterline.

Wärtsilä – zero-emission ferries: https://bit.ly/3kDvsEO



Norway's maritime start-up EDGE Navigation and shipbuilder Ulstein are evaluating the use of a hydrogen fuel cell solution to achieve non-fossil propulsion for a container vessel concept.

Ulstein and edge looking into hydrogen fuel cells for X-bow. Offshore Energy: https://bit.ly/3o7hY6m

Surface combatants

One of the reasons surface combatants are looking to adopt alternative fuels is to improve combat capability and operational flexibility. Alternative fuels have also been widely used by surface combatants, as shown in Figures 4.3 and 4.5. The primary surface combatants are battleships, cruisers, destroyers and frigates. Several nuclear-powered cruisers (CGNs) were previously built by the U.S. Navy in the 1960s and were then decommissioned in the 1990s when nuclear power was deemed too expensive to use on surface combatant ships smaller than an aircraft carrier.[23]

The October 2009 energy vision from the U.S. Secretary of the Navy, Ray Mabus, addresses the navy's mission areas at sea, ashore and in the air. In the transformative spirit of the Great White Fleet, it envisions a 'Great Green Fleet' made up of nuclear carriers, hybrid electric biofuelled surface ships and biofuelled aircraft, supported by shore-based installations that run largely on renewable electricity.[41] On 20 January 2016, the U.S. Navy commenced the use of biofuel as part of its regular operations when the Secretary of the Navy, Ray Mabus, and the Secretary of Agriculture, Tom Vilsack, witnessed the deployment of the *USS John C. Stennis* carrier strike group. The Great Green Fleet is an initiative of the Department of the Navy highlighting how the U.S. Navy and the U.S. Marine Corps are using energy efficiency and alternative energy to increase combat capability and operational flexibility.[42]

FIGURE 4.5

Number of non-submarines that utilize alternative fuels in the navy across different countries based on information attained from open-sourced data (based on case studies obtained, see Table 7.2 in the Appendix). Decommissioned vessels are excluded from the figure.

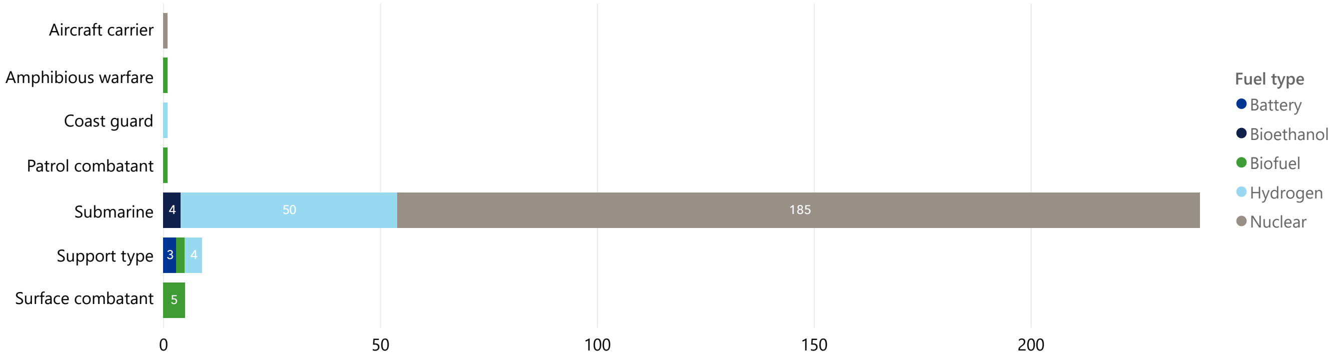
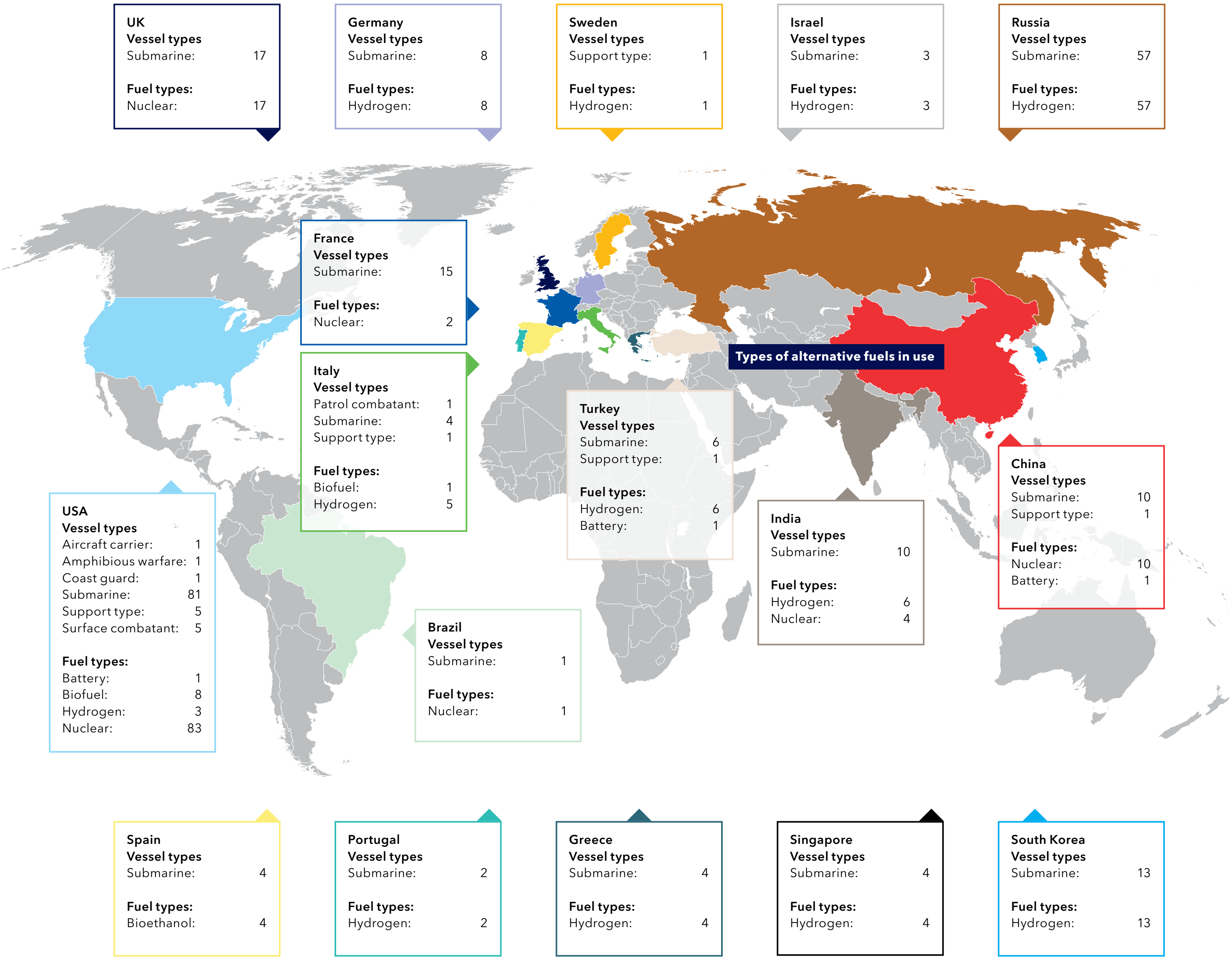


FIGURE 4.6

Map depicting the case studies obtained (see Table 7.2 for the full list)



Types of alternative fuels in use

UK

Vessel types	
Submarine:	17
Fuel types:	
Nuclear:	17

Germany

Vessel types	
Submarine:	8
Fuel types:	
Hydrogen:	8

Sweden

Vessel types	
Support type:	1
Fuel types:	
Hydrogen:	1

Israel

Vessel types	
Submarine:	3
Fuel types:	
Hydrogen:	3

Russia

Vessel types	
Submarine:	57
Fuel types:	
Hydrogen:	57

France

Vessel types	
Submarine:	15
Fuel types:	
Nuclear:	2

Italy

Vessel types	
Patrol combatant:	1
Submarine:	4
Support type:	1
Fuel types:	
Biofuel:	1
Hydrogen:	5

Turkey

Vessel types	
Submarine:	6
Support type:	1
Fuel types:	
Hydrogen:	6
Battery:	1

USA

Vessel types	
Aircraft carrier:	1
Amphibious warfare:	1
Coast guard:	1
Submarine:	81
Support type:	5
Surface combatant:	5
Fuel types:	
Battery:	1
Biofuel:	8
Hydrogen:	3
Nuclear:	83

India

Vessel types	
Submarine:	10
Fuel types:	
Hydrogen:	6
Nuclear:	4

China

Vessel types	
Submarine:	10
Support type:	1
Fuel types:	
Nuclear:	10
Battery:	1

Brazil

Vessel types	
Submarine:	1
Fuel types:	
Nuclear:	1

Spain

Vessel types	
Submarine:	4
Fuel types:	
Bioethanol:	4

Portugal

Vessel types	
Submarine:	2
Fuel types:	
Hydrogen:	2

Greece

Vessel types	
Submarine:	4
Fuel types:	
Hydrogen:	4

Singapore

Vessel types	
Submarine:	4
Fuel types:	
Hydrogen:	4

South Korea

Vessel types	
Submarine:	13
Fuel types:	
Hydrogen:	13

5. State of the technological implementations

In this chapter, we shift focus to present an outlook on the state of technological implementations in commercial shipping and in the navy. We shed light on the advancement of propulsion technologies with respect to different alternative fuels as well as the key parameters, including the advantages and disadvantages. Technology maturity is also highlighted.

On-board solutions that reduce emissions by increasing a vessel's energy efficiency or reducing bunker fuel consumption in other ways, new propulsion systems that reduce drag, and technologies that improve existing power and propulsion systems are all available now for adoption. This section elaborates on the maturity of engine technology and systems for different fuels.

LNG

Gas engines are now available in a wide range of power levels as proven and readily available alternatives. Gas-only engines, dual fuel 4-stroke engines, and 2-stroke engines are among the engineering concepts already commercially available. Modern 2-stroke engines virtually eliminate methane slip (which contributes to greenhouse gas emissions) during combustion, and 4-stroke engines should lead to even further reductions. On the production side, the recent surge of non-traditional gas (shale) has had a significant impact on the gas market, especially in North America. Shale gas exploration in other parts of the world could also be crucial for LNG uptake. The extraction process (hydraulic fracturing, or fracking), however, remains a contentious technology due to growing public worries about its influence on public health and the environment, particularly in terms of air and water quality. In the next 5 to 10 years, LNG use is likely to increase rapidly, beginning with relatively small ships operating in places with a developed gas bunkering infrastructure, where LNG prices are competitive with HFO pricing. When bunkering infrastructure becomes available around the world, larger ocean-going vessels will follow.

Hydrogen

Fuel cells are the most prevalent systems for converting hydrogen's chemical energy into electricity. Other fuels, such as natural gas or methanol, can be used to power a fuel cell if a fuel reformer is available. Although operational experience has demonstrated that fuel cell technology can operate effectively in a maritime setting, more research and development is required before fuel cells may be employed to supplement existing ship powering systems. High investment prices, the dimensions and weight of fuel cell installations, and their estimated lifetime are all challenges. To ensure safe operations, special consideration must be paid to hydrogen storage on board ships. If fuel cells are to become cost-competitive for ships, significant technological advancements and cost reductions are required. There is reason to expect that costs will decline as a result of the recent commercialization of certain land-based fuel cell applications. Reductions in size and weight are also critical for ship applications, but transient load response remains a major concern. Fuel cells have the potential to become a part of future ship power generation, and in the near future, effective niche applications for some specialized ships, particularly in combination with hybrid battery systems, may be viable. Several technical features of engine design derived from non-gas (NG) engines are listed as follows:[35]

- Spark ignited (with cold-rated plugs)
- Port injected
- Lean burn
- Capable of low NOx without after-treatment
- Requires high dilution ($\lambda > 2.5$)
- Compression ratio lower than natural gas engines
- Crankcase monitoring and ventilation
- Material premium over NG engine
- Fuel storage as cryogenic liquid: 20K at ambient pressure

Ammonia

Ammonia as fuel has more obstacles before it can be used commercially by NG carrier fleets. Although ammonia has been used as fuel in IC engines in the past, it is still in the early phases of development for marine propulsion. Ammonia-fuelled engines are being developed, and the use of ammonia in fuel cells is being investigated. Ammonia has the potential to be a zero-carbon fuel and give some hope for worldwide fleet decarbonization. Ammonia combustion produces water and nitrogen primarily when utilized as fuel in IC engines. The IMO NOx limitations would also apply to ammonia combustion. Existing technologies and prescriptive criteria can be used to create fuel containment, distribution, and supply systems. If ammonia is stored in a cold environment, tanks must be constructed for temperature and/or pressure control, as ammonia continuously evaporates and generates boil-off gas due to heat gain, which increases pressure in tanks if not handled. Type C tanks can also be used to store ammonia. When employed as a maritime fuel, ammonia has the same hurdles as other novel fuels. Crew training,

bunkering availability, compliance with port discharge restrictions, tank venting, and preparing for human exposure beyond acceptable limits are all part of the challenges.

New engine technology for ammonia includes the following features:[43]

- The most promising design uses spark-ignited, carbureted with heated fuel, and >5% vol hydrogen (reformed fuel)
- The high ignition energy required and slow burn rate necessitate a second fuel
- Inexpensive catalyst to reform fuel using heat from the exhaust
- SCR and AMOX required, leading to high NOx
- >10,000 ppm NH_3 in the exhaust
- Material premium over NG engine

Methanol

Methanol can be used as fuel in 2-stroke diesel-cycle engines or 4-stroke lean-burn Otto-cycle engines in conventional ship engines. Only one commercially accessible 2-stroke diesel engine, the MAN ME-LGI series, is currently in use on methanol tanks, as is the case with LPG. On board the passenger ferry *Stena Germanica*, Wärtsilä 4-stroke engines are in use. The use of methanol in fuel cells is another alternative (see section 5.10 on fuel cells). Since 2017, the Viking Line ferry *MS Mariella* has been home to a test installation. Methanol is a liquid fuel that may be stored in ordinary liquid fuel tanks with some changes to account for its low-flashpoint features and the IGF Code requirements that are currently being developed at the IMO. Safe, inert gas purging and gas freeing should be included in the design of fuel tanks.

The following is a list of new engine technology for methanol:[43]

- Direct injection
- Spark-ignited
- Stoichiometric, plus EGR and catalyst
- Efficiency close to diesel
- Material premium over NG engine

LPG

LPG can be utilized in a 2-stroke diesel engine, a 4-stroke lean-burn Otto-cycle engine or a gas turbine as ship fuel in three different methods. Only the MAN ME-LGI family of 2-stroke diesel engines is currently commercially available. In 2017, a stationary power generation system with a Wärtsilä 4-stroke engine was installed (34SG series). This engine has to be de-rated in order to maintain a safe knock margin. Installing a gas reformer to convert LPG and steam into methane by mixing them with CO_2 and hydrogen is an alternative technology offered by Wärtsilä. This mixture can then be used in a conventional gas or dual-fuel engine without de-rating. LPG can be stored under pressure or chilled. It will not always be available at the temperatures and pressures that a ship can handle. As a result, both the bunkering vessel and the ship being bunkered must have the necessary equipment and infrastructure. Because the vessel can bunker using either pressurized or semi-refrigerated tanks without making significant alterations, a pressurized LPG fuel tank is the preferred option.

Fuel cell and battery-electric

Over the previous five years, the development of batteries has been driven by advances in production procedures and quality control, as well as incremental improvements in the current (cathode) chemistries and combinations. Iron phosphate (LFP) and nickel cobalt manganese (NCM) are the market leaders. These gains have been matched by an increasing understanding of the complex electrochemical processes that occur in batteries, leading to better battery design and usage. Furthermore, new anode developments – the use of silicon or titanium – have just hit the market, representing the competing goals of more affordable energy density and superior performance, respectively. The strict rules of the maritime industry have significantly increased the level of safety that lithium-ion battery systems can provide, particularly in terms of propagation and off-gas handling. One of the most anticipated pending advances is solid electrolyte technology, which could give significant safety benefits. Although this enhancement must demonstrate that it can meet demanding marine performance criteria, the additional level of safety it could provide to the maritime industry would surely be advantageous. The performance of lithium-ion batteries in maritime applications is frequently higher than in other industries, such as consumer electronics or stationery/grid support. Depending on the application, these requirements vary; nonetheless, many maritime systems require much more power and longer life cycles than conventional lithium-ion battery systems. These requirements differ from the urge to improve cost and energy density, which drives much of today's technological growth. It could be 10 years before new technology has a big or disruptive impact on the market. The most noticeable technology advancements are expected to come from incremental cost and performance improvements in current battery types. Moreover, many of the technologies on the horizon are expected to struggle with the maritime environment and application requirements, delaying market adoption.

According to the ranking system in Table 4.1, the three most promising fuel cell technologies are proton exchange membrane fuel cell (PEMFC), high-temperature PEMFC, and solid oxide fuel cell (SOFC).[44] The ranking and scores given throughout the nomination and selection process are qualitative in nature and used to compare the technologies. This illustrates the challenge of putting numbers on new technology that is still in development. The table below shows the results of the rating process. The PEMFC and high-temperature PEMFC received the highest scores in the rating. While there are many similarities between these two technologies, they also differ in key areas such as installation difficulty, fuel availability, fuel impurity tolerance, and total efficiency, which includes waste heat recovery. As a result, it was decided to use both methods in the risk assessment that followed. The third and last technology chosen for the risk evaluations was the SOFC, which is a high-temperature fuel cell. To continue the risk evaluation, the project has designated one low-temperature fuel cell, one medium-temperature fuel cell and one high-temperature fuel cell.

Table 5.1 shows types of fuel cells and their technological properties. The majority of active research, as indicated by the summary of battery technologies in development, is focused on discovering cheaper materials, which compromises the specific energy and the energy density in general.[45] Improvements in specific energy, energy density, and specific power frequently result in structural changes in the electrodes, reducing their lifetime and compromising their safety. Finding appropriate trade-offs between these effects while keeping production costs low are significant issues in the development of battery technology. This tendency can be seen in the current battery technologies on the market. Higher energy alternatives often have a lower cost, lower lifetime capability, lower power capability and lower thermal stability; higher power options, however, typically have a longer lifetime and better safety, but at the sacrifice of cost and energy density. The details of battery technologies are summarized and can be found in Tables 5.2 and 5.3. When these technologies evolve, warships will be able to sail longer distances entirely on electricity, reducing the risk of thermal runaway. Before this technology can be used, however, conductivity and longevity difficulties must be resolved.

TABLE 5.1

Types of fuel cells and their technological properties[44]

Types of fuel cells	Relative cost	Module power levels (kW)	Lifetime	Tolerance for cycling	Fuel	Maturity	Size	Sensitivity to fuel impurities	Emission	Safety aspect	Efficiency
Alkaline fuel cell (AFC)	Low	Up to 500	Moderate	Good	High-purity hydrogen	High, experience from several applications including one ship	Small	High	No	Hydrogen	50–60% (electrical)
Phosphoric acid fuel cell (PAFC)	Moderate	100–400	Excellent	Moderate	• LNG • Methanol • Diesel • Hydrogen	High, extensive experience from several applications	Large	Medium	• CO_2 • Low levels of NOx if carbon fuel is used	• High temperature (up to 200°C) • Hydrogen and CO in a reforming unit	• 40% (electrical) • 80% (with heat recovery)
Molten carbonate fuel cell (MCFC)	High	Up to 500	Good	Low	• LNG • Methanol • Diesel • Hydrogen	High, extensive experience from several applications including ships	Large	Low	• CO_2 • Low levels of NOx if carbon fuel is used	• High temperature (up to 600–700°C) • Hydrogen and CO in cell from internal reforming	• 50% (electrical) • 85% (with heat recovery)
Solid oxide fuel cell (SOFC)	High	20–60	Moderate	Low	• LNG • Methanol • Diesel • Hydrogen	High, experience from several applications including ships	Medium	Low	• CO_2 • Low levels of NOx if carbon fuel is used	• High temperature (up to 600–700°C) • Hydrogen and CO in cell from internal reforming	• 60% (electrical) • 85% (with heat recovery)
Proton exchange membrane fuel cell (PEMFC)	Low	Up to 120	Moderate	Moderate	• Hydrogen	High, extensive experience from several applications including ships	Small	High	No	• Hydrogen	• 50–60% (electrical)
High-temperature PEM fuel cell (HT-PEMFC)	Moderate	Up to 30	Unknown	Good	• LNG • Methanol • Diesel • Hydrogen	Low, experience from some applications including ships	Small	Medium	• CO_2 • Low levels of NOx if carbon fuel is used	• High temperature (up to 200°C) • Hydrogen and CO in a reforming unit	50–60% (electrical)
Direct methanol fuel cell (DMFC)	Moderate	Up to 5	Moderate	Good	• Methanol	Under development	Small	Low	No	Methanol	20% (electrical)

TABLE 5.2[45]

The benefits, drawbacks and assessment of whether present battery technologies are suitable for maritime application.
Green: Can be used in maritime applications **Yellow:** Appropriate for some marine applications **Red:** Not suited for marine use

Types of batteries	Specific energy (Wh/kg)	Advantages	Disadvantages	Applicable for maritime
Nickel manganese cobalt oxide (NMC)	150–220	• Combination for high specific energy • Adjustable power density, energy density cost and safety	• Key properties equilibrium may be difficult to ensure for a stable lifespan	• Flexible design with respect to energy and power capabilities • The most used chemistry in marine applications at present
Lithium iron phosphate (LFP)	90–120	• Higher safety considerations • Resilient to temperature fluctuations • Cathode doping possible for higher power applications	• Relatively low specific energy • Lower voltage • Lower power capabilities	• Used in marine applications because of its good safety features
Nickel cobalt aluminium (NCA)	200–260	• High specific energy and energy density • Good calendar life	• Lower safety • Higher cost	• Suitable because of its high energy density
Lithium cobalt oxide (LCO)	150–240	• High specific energy and energy density	• Lower power (rate) • Shorter cycle life • Impedance increase over time • Safety concerns (thermal stability)	• Suitable because of its high energy density • Drawbacks such as shorter cycle life and safety concerns makes it less attractive compared to other lithium-ion chemistries
Lithium manganese oxide spinel (LMO)	100–150	• Higher thermal stability • Current material modifications possible to improve cycle life	• Lower energy capacity • Shorter cycle life at higher temperatures	• Shorter cycle life makes it less attractive compared to the other lithium-ion chemistries
Lithium titanate oxide (LTO)	50–80	• Higher safety characteristics • Very high cycle life • High power capability	• Relatively low specific energy • Initial cost is high, but total lifetime cost might be cheaper	• Suitable for applications that require fast charging, high power or very large amounts of cycling
Lead-acid	33–42	• Very low-cost • Electrodes and electrolyte not flammable • Commercially available worldwide • High specific power	• Low specific energy and energy density • Low cycle life	• Too low specific energy and energy density
Nickel cadmium	40–60	• Very low cost • Electrodes and electrolyte not flammable • Commercially available worldwide	• Low specific energy and energy density • Explosive hydrogen gas during charge • Memory effect	• Too low specific energy and energy density
Nickel metal hydrid	60–120	• Low cost • Electrodes and electrolyte not flammable	• Relatively low specific energy and energy density • Release of hydrogen gas during charge, with potential for creation of an explosive atmosphere • High self-discharge rate	• High self-discharge rate

Types of batteries	Specific energy (Wh/kg)	Advantages	Disadvantages	Applicable for maritime
Nickel iron	50	• Long lifetime • Resilient to vibrations and high temperature	• Low specific energy and energy density • High cost • High self-discharge rate • Poor low-temperature performance	• Too low specific energy and energy density • High self-discharge rate • High cost
Nickel zinc	100	• No toxic materials • Low cost • High power output • Good temperature operating range	• Low specific energy and energy density compared to lithium-ion • Dendrite growth • High self-discharge rate	• Not suitable due to high discharge rate and safety characteristics
Nickel hydrogen	40–75	• Long lifetime • Minimal self-discharge rate • Good temperature operating range	• Low specific energy and energy density compared to lithium-ion • High cost	• Too low specific energy and energy density
High-temperature sodium sulfur (NaS)	760 (Practical 140–240)	• High power • High energy density • High efficiency • Temperature stability • Low cost of raw materials • Commercially available	• Unsafe: fracture of beta alumina leads to violent reaction • High operating temperature (300°C) • Molten sodium electrode • Uses 10–14% of its own capacity to maintain the operating temperature when not in use • Expensive due to manufacturing process, insulation requirements and thermal management	• Requirements for high operating temperature, expensive and safety features
ZEBRA	788 (Practical 120)	• High voltage • Safety: no gassing • Tolerance against overcharge • Low cost of raw materials • Commercially available	• Preheating to the operating temperature • High operating temperature (300°C) • Molten sodium electrode • Uses 10–14% of its own capacity to maintain the operating temperature when not in use • Manufacturing process, insulation requirements and thermal management make the batteries expensive	• Requirements for high operating temperature, expensive
Super capacitors	0.01–15	• Very high specific power • Commercially available • Safe	• Very low specific energy and energy density	• Suitable for peak shaving applications, where the need for energy storage capacity is low
Flow batteries	20–35	• Can decouple energy and power characteristics • Easy to scale up energy and power capabilities • Low flammable risk	• Very low specific energy and energy density • Toxic fluids	• Too low energy density and specific energy

TABLE 5.3[45]

Table 5.3 summarizes an assessment of future technology. Solid-state, particularly combined with metal-air, is regarded as the most exciting future technology. This combination significantly improves specific energy, energy density, and safety aspects. The assessment is evaluated as follows:

Types of batteries	Specific energy (Wh/kg)	Advantages	Disadvantages	Applicable for maritime
Solid state	200–400	• Safety: non-flammable electrolyte and no dendrite formation • Potential for higher specific energy and energy density	• Low conductivity and high interface resistance • Low lifetime • High production cost • Bad in cold weather	• Most promising technology for both increasing safety, specific energy, and practical energy density in marine applications
Zinc-ion	75–85	• Safety: non-flammable electrolyte and no dendrite formation • Cheap to produce • Environmentally friendly	• Low specific energy and energy density (comparable to LTO) • Not commercialized yet	• Might be suitable for peak shaving applications if performance is improved
Sodium-ion	90–115	• High access to raw materials • Low raw material cost • High redox potential (however lower compared to lithium)	• Lower energy density compared to lithium • Structural stability in the electrodes needs to be improved • Need to operate at low temperature • Not commercially available	• Since it seems that no safety benefits are gained and the energy density is lower, it will be hard to compete with state-of-the-art lithium-ion batteries
Calcium-ion	-	• High access to raw materials • Low raw material cost • High redox potential (however lower compared to lithium)	• Lower energy density compared to lithium • Proof of concept cell is not developed • Not commercially available in decades	• Too early to determine if this has potential • Seems no benefits are gained other than raw material costs
Potassium-ion	-	• High access to raw materials • Low raw material cost • High redox potential (however lower compared to lithium) • Conventional, proven, and low-cost electrolyte, and electrode materials can be used	• Lower energy density compared to lithium • Structural stability in the electrodes needs to be improved • Not commercially available	• Too early to determine if this has potential • Seems no benefits are gained other than raw material costs
Magnesium batteries	-	• High access to raw materials • Potentially low raw material cost • No dendrite formation on low c-rates for magnesium-metal anodes	• Only non-rechargeable cells are commercially available • Energy density of rechargeable cells are low (magnesium-ion) • Rechargeable batteries will lose energy and power capability rapidly (magnesium-metal)	• Too early to determine if this has potential • Seems no benefits are gained other than raw material costs
Fluoride-ion	-	• Raw materials highly available • Low cost at refining raw material • Potential of both high specific energy and high energy density	• Early research stage • Particle formation in electrodes • Fading capacity for HTFIB and incapable of cycling for RTFIB • Low conductivity	• Too early to determine if this has potential • Seems no benefits are gained other than raw material costs

Types of batteries	Specific energy (Wh/kg)	Advantages	Disadvantages	Applicable for maritime
Rechargeable metal-air	• Al-air, 2791 • Li-air, 3463 • Mg-air, 2843 • K-air, 935 • Na-air, 1105–1600 • Zn-air, 1085	• Very high specific energy potential	• Early research stage • No suitable electrolyte solving, ensuring both safety and performance requirements • The cathode is vulnerable for moisture and CO_2 in the air	• Still has severe challenges to overcome to meet performance and safety requirements, but the potential for high specific energy and energy density combined with solid state safety features makes it very interesting for maritime applications
Lithium-sulphur	2,500	• Higher theoretical capacity compared to conventional lithium-ion battery • High theoretical energy density compared to conventional lithium-ion battery • Low environmental impact	• High cost of lithium • Volume expansion and particle formation of sulphur • Low electrical conductivity • Shuttle effects • Not expected to be commercially available for decades	• Still has severe challenges to overcome to meet performance and safety requirements, but the potential for high specific energy and energy density combined with solid state safety features makes it very interesting for maritime applications
Room-temperature sodium-sulphur	450	• High theoretical capacity and energy density compared to conventional lithium-ion battery • Low environmental impact	• Shuttle effect for liquid electrolytes • High risk for internal short circuit (dendrite formation) • Low columbic efficiency (electrical conductivity) • Rapid capacity fading • Not expected to be commercially available for decades	• Still has severe challenges to overcome to meet performance and safety requirements
Aluminium-sulphur	650	• High theoretical specific energy and energy density compared to conventional lithium-ion battery • Potentially low cost • Low environmental impact • Safety: no dendrite formation, which lowers the risk for internal short circuit	• Sluggish electrochemical kinetics and poor reversibility • Shuttle effect for liquid electrolytes • Not expected to be commercially available for decades	• Still has severe challenges to overcome to meet performance and safety requirements
Magnesium-sulphur	-	• High theoretical specific energy and energy density compared to conventional lithium-ion battery • Low raw material cost • High global abundant raw material • Low environmental impact • Safety: no dendrite formation, which lowers the risk for internal short circuit • High negative reduction potential	• Sluggish electrochemical kinetics and poor reversibility • Shuttle effect for liquid electrolytes • No appropriate electrolytes found • Not expected to be commercially available for decades	• Still has severe challenges to overcome to meet performance and safety requirements
Dual-ion	20-200	• May utilize cheaper raw materials in future • May utilize globally abundant available raw materials in future	• Early research stage • Low specific energy and energy density compared to lithium-ion • Electrolytes not mass produced and still expensive	• Still have severe challenges to overcome to meet performance and safety requirements

Nuclear

Several compact nuclear reactor ideas are being researched with power outputs ranging from 30 to 200 MWe and a service life of more than 10 years. The safe storage and recycling of wasted fuel is a significant hurdle that must be addressed.

Thorium as nuclear fuel (rather than uranium or plutonium, which are currently used) has several advantages, including increased fuel availability, increased efficiency and reduced nuclear waste output. Thorium oxide can be combined with 10% plutonium oxide, which allows plutonium to be recycled. The combination of thorium and plutonium oxide raises the melting point and thermal conductivity of the reactor, making it safer. In order to assess the practicality of this technology, an experimental thorium reactor is now being tested in Norway. Nuclear power is one of the most divisive power-generating and propulsion technologies. Despite the fact that safety standards are extremely rigorous, and accidents are extremely rare, the effects of an accident can be disastrous. Three recent incidents (Three Mile Island in 1979, Chernobyl in 1986 and Fukushima in 2011) demonstrate the impact of an accident on public perception and policy actions. The most recent example of this is Germany's dramatic shift in direction following the Fukushima disaster in 2011, with a drastic reduction in nuclear power generation.

Given popular hostility to nuclear power in most nations and concerns about the potential repercussions of accidents, nuclear propulsion in ships appears unlikely to be used in the next 10 to 20 years. Because of developments in China, nuclear power generation on land will remain at current levels. This picture may alter after 2030 if societal acceptance improves and other initiatives to reduce greenhouse gases do not prove to be as effective as hoped.

Technological maturity

The term 'technological maturity' refers to the degree to which engine technology and systems have matured. A technical maturity level is ascribed to each converter (containing all necessary components). A maturity level of 1 denotes high maturity and commercially accessible technology, whereas a maturity level of 4 denotes low maturity and technology that is not even in the pilot stage. The level of technical maturity is determined based on the current situation. Technical maturity levels are interpreted as follows:

1. Off-the-shelf measures that are regularly utilized on new ships
2. Commercially available but not yet fully mature measures
3. Measures that are in the early stages of development and/or have only a few practical applications
4. Measures that have not been fully tested, with no piloting or full-scale testing currently occurring.

Table 5.4 shows that most fuel cell systems are still in their infancy. In addition, hydrogen and ammonia systems have a low level of technical maturity.

TABLE 5.4

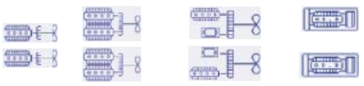
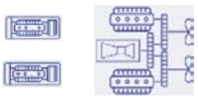
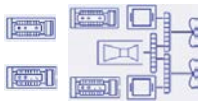
Technical maturity levels[17]

Fuel	Converter	Components	Maturity
LNG	ICE 4-stroke lean-burn spark ignition / dual fuel low pressure (4S LBSI/LPDF)	Engine storage tanks, process system	1
	ICE 2-stroke dual fuel low pressure (2S LPDF)	Engine storage tanks, process system	1
	ICE 2-stroke dual fuel high pressure (2S HPDF)	Engine storage tanks, process system, NOx reduction system (EGR/SCR)	1
	FC	Fuel cell, storage tanks, electric motor and reformer battery	3
Hydrogen	FC	Fuel cell, storage tanks, electric motor and reformer battery	3
	ICE	Engine storage tanks, process system	4
Ammonia	FC	Fuel cell, storage tanks, process system, electric motor and reformer battery	3–4
	ICE	Engine storage tanks, process system, NOx reduction system (EGR/SCR)	3–4
Methanol	FC	Fuel cell, storage tanks, electric motor and reformer battery	3
	ICE 2-stroke dual fuel high pressure	Engine storage tanks, process system, NOx reduction system (EGR/SCR)	2
	ICE 4-stroke	Engine Storage tanks, Process system	2
LPG	ICE 2-stroke	Engine storage tanks, process system, NOx reduction system (EGR/SCR)	2–3
	ICE 4-stroke	Engine storage tanks, process system	4
Battery-electric	Battery	Electric motor battery, battery management system	1

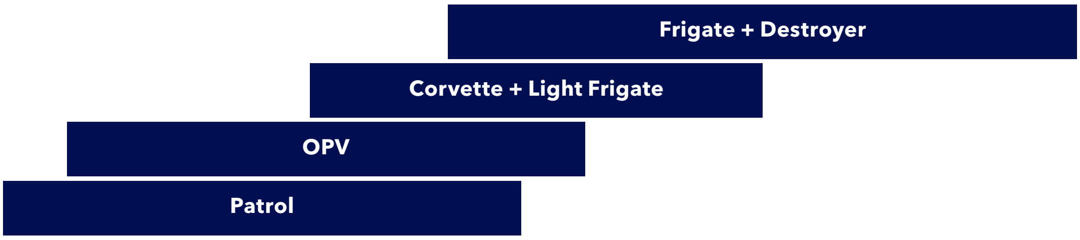
FIGURE 5.1

Propulsion system variants, per vessel[46]

The naval market is highly driven by proven propulsion concepts

Propulsion system	SiSO + CODAD Optional E-Drive (300kW-1,000kW)	CODAG GT+Diesel	CODELAG GT + E-Drive
Drivetrain arrangement			

Vesel type



Propulsion power	4–32 MW (+ 300–1,000kWe)	25–60MW	30–60 MW (2–5MWe)
Genset power	<1–8MW	2–8 MW	6–12 MW
Ship speed	20 to>40 knots	22 to >30 knots	22 to >30 knots
Naval requirements	ILS, acoustics, shock, system integration genset and driving modules		
Years of service	15–30	>30	>30

Genset Prop. Diesel E-Motor Gas Turbine

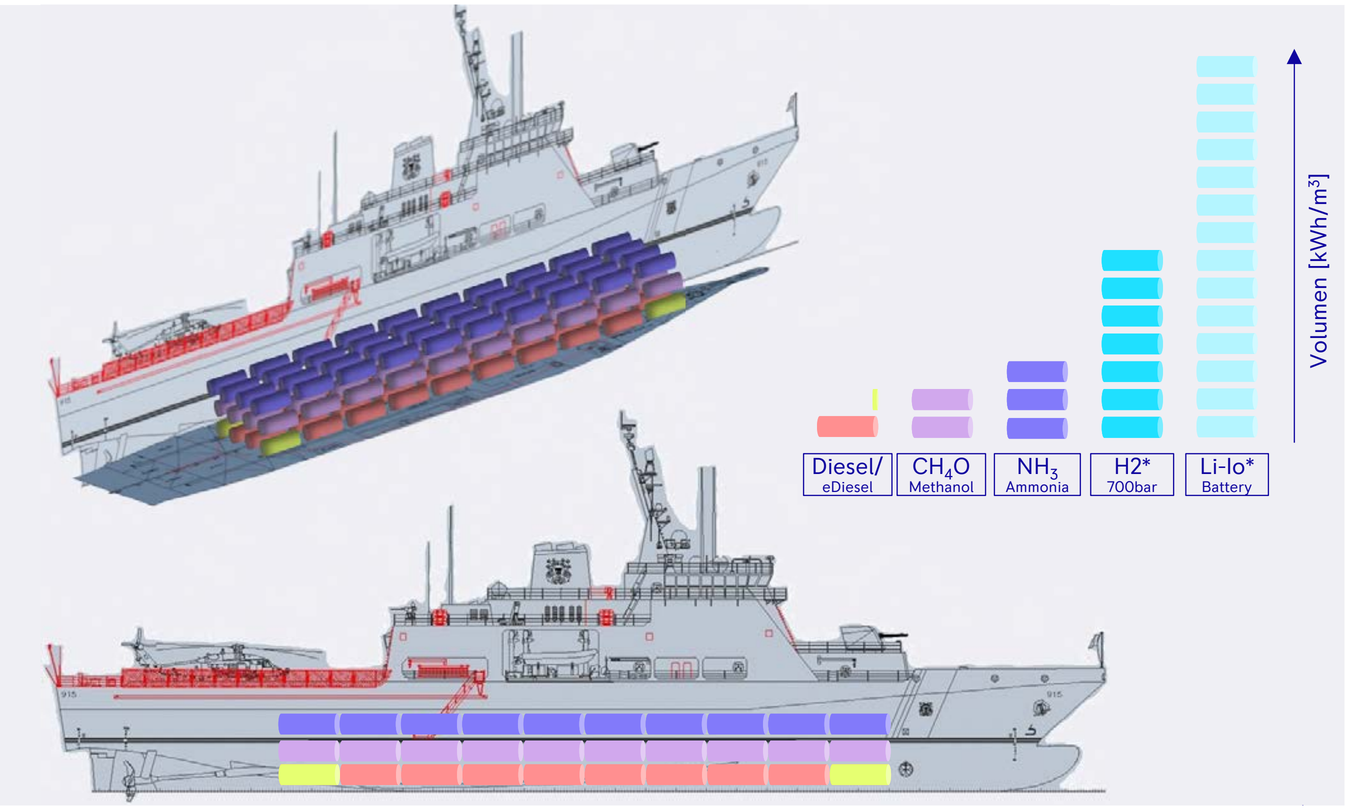
Specifically to the naval market, Figure 5.1 shows proven propulsive concepts that could be applicable. Patrol vessel, offshore patrol vessel (OVP), corvette and light frigate, and frigate and destroyer are among the naval vessels featured. Different propulsion systems such as SiSO and CODAD, CODAG, and CODELAG were mentioned. The mission's goal is the driving force behind the propulsion system configuration.[46]

For the vessels mentioned in Figure 5.1, there is a need for high power demand. A comparison of the power demands of commercial and navy vessels could be made. A 40-foot container with one fuel cell, for example, can produce up to 1 MW. The propulsion systems installed in the naval sector, however, range from 4 to 60 MW per vessel. As can be observed, each vessel type has a different propulsion power range, with patrol vessels ranging from 4 to 32 MW and frigates and destroyers ranging from 30 to 60 MW. Modern naval vessels should be able to operate from one to 760 days (about two years) at sea without returning to their home base. Apart from having an adequate maintenance and spare part concept for long periods of operation, there must also be a strategy for regular refuelling. As refuelling will need to take place either at a port or through Replenishment at Sea (RAS), the accessibility and safe handling of the selected alternative fuel need to be taken into consideration and require a well-proven and sound logistics approach. This undoubtedly will also have implications regarding the design of the naval vessel. As a result, around 15 to 35% of the vessel's weight has already been employed for energy storage in today's vessel design. This combination is essentially the force behind larger vessels' decision to only travel in one direction. The e-drive trend, in which mission-critical or overall efficiency increases, for example in governmental growth, smaller vessels such as coastal patrol vessels are able to control and the alternative fuel can be readily stored. All of these requirements, however, must take into account the ship's speed.

FIGURE 5.2

Key design and influence factor[43]

Fuel storage needed for an OPV with various energy sources (18 MW main engine /~4,000t)



*Hydrogen (H_2) and batteries not reasonably presentable

As shown in Figure 5.2, when picking a fuel type, there are numerous aspects to consider:

- Mission and cargo volume of the vessel
- Adjustment of ship size and displacement
- Days at sea and range reduced
- Power demand for electrical systems (radars/weapons)

According to Figure 5.2, 15% of the OPV is fuel storage for diesel fuel, which is indicated at the bottom of the vessel below the waterline. When switching to e-diesel, it will require around 10% additional fuel storage to complete the same function. In order to maintain the same degree of fuel endurance, converting a vessel to methanol necessitates nearly double the volume of fuel tank capacity compared to diesel. However, this would result in loss of storage in a ship in terms of the engine converting the power or storage for essential needs such as food, water and the requirements that are needed for a mission. Even though it is just twice the size, it loses the same amount of volume to perform. To address this, either the vessel size must be increased, the mission must be shorter, or the vessel must be re-designed and a new mission must be considered. Ammonia, however, is three times the size; thus, the volume, as well as the weight, indicates that it is a half tank, with no further storage below the waterline. As a result, on the same vessel, this arrangement would most likely no longer work because the weight shifts too high up, causing the ship to lose stability in the sea, necessitating a whole new ship design. When it comes to hydrogen, as indicated, it is not possible to fit it into the vessel. Hydrogen would require a volume that was double the size of the original. For ammonia, it is allowed to be stored below the waterline, and the location of ammonia fuel tanks may not be at the outer shell. For methanol, it does not require cofferdams below water level, but certain rules need to be observed. The same requirements apply to NH_3 as to LNG fuel according to the IGF Code.

Rendering of the MEKO® 5.0 courtesy of thyssenkrupp Marine Systems GmbH

6. Conclusion

With an increasing decarbonization agenda set forth by the IMO, a variety of alternative fuel options is being developed. Despite the fact that the naval sector is not subjected to the same regulatory restraints as the commercial world, there is widespread acceptance that governments should set high goals for their own activities in the same way that they do for the general public.[47] This paper has presented a broad overview of the considerations, combining studies conducted for alternative fuels used for naval vessels with a survey of DNV Naval Committee members on this topic.

Referring to the increasing number of service vessels and tugs powered by alternative fuels (biofuel, batteries, LNG) in commercial shipping, the implementation of alternative fuels on non-combat vessels for decarbonization purposes is technically feasible in the near future. In the navy, support ships are not designed to participate in combat and are generally not armed. However, as of today, there are limited numbers of naval support ships, consisting of ocean tugs, research vessels and sealift vessels that are fuelled with any form of alternative fuel, despite the same vessel types in the commercial world already making the transition. Apart from battery power for those naval support ships operating near shore and/or from a mother ship, the use of LNG for those requiring a greater range is a possible option in the near future considering the advent of LNG-fuelled tugs and supply vessels in commercial shipping. The possible adopters of alternative fuels in the navy are summarized in Table 6.1. The details of assessment are presented in the Appendix (Chapter 7.2 and Table 7.1).

TABLE 6.1

Possible adopters of alternative fuels

Fuel	Benefits	Ship type
Nuclear	Speed, endurance	Large, combatant, submarine
Hydrogen	Cost, noise, hybrid systems	All
Battery	Stealth, supply chain, short sea	RHIB, harbour
Biofuel	Drop-in option for ships in operation	All
LNG	Supply chain, deep sea	All auxiliary

With regards to the need to move the policy agenda, in 2018, the U.S. Department of Defense announced formally that alternative fuels were allowed for operational use. The statement below highlights the opportunities and challenges of the widespread implementation of alternative fuels within the navy:[48]

'… It requires that alternatives be "compatible with existing equipment and infrastructure" and that producers must "provide significant volumes to support an expeditionary, globally deployed force." Beyond a pervasive bias against incorporating new energy sources into existing energy logistics, any potential implementation of a new fuel suffers from the chicken-and-egg problem where logisticians would not invest in supplying new fuels to platforms that don't exist and acquisitions officers are reluctant to procure new platforms that rely on fuel infrastructure that doesn't yet exist at scale. Without the demand from alternative fuel–powered tactical platforms, there is little incentive for logisticians to create the necessary logistics infrastructure and trained personnel to increase supply. Meanwhile, program managers are not interested in setting requirements for new tactical vehicles that run on a fuel for which there is no supply chain. Both logisticians and program managers accustomed to a single-fuel environment seem unwilling to accept the initial risk of breaking through this supply-demand trap to fund large-scale programs that use new fuels and electric powertrains.'

In a similar vein, the Ministry of Defence in the Netherlands has set itself a target to reduce dependency on fossil fuels by 20% by 2030 and 70% by 2050, in line with public pressure for Defence organizations to play a part in broader national targets. The feeling from the industry today is that in the next 10 to 20 years, there will be greater adoption of alternative fuels in the navy. Considering the need for speed and better endurance in combat vessels, nuclear propulsion could be a primary option. Hydrogen fuel cells and batteries could be equally viable alternatives to nuclear propulsion when cost and noise are the main concerns. Biofuels are usually used as drop-in fuels for both naval combat and auxiliary ships – which in itself presents a relatively seamless transition from fossil fuels. For naval auxiliary ships, the use of LNG fuels and batteries can be promising, considering the maturing supply chains in commercial shipping.

Climate change poses a wide range of risks, from the degradation of military assets to community destabilization. Defence forces may be able to help alleviate these concerns by taking substantial steps to decarbonize and reduce emissions. Any remaining emissions could be compensated for by a net-zero defensive force that would in itself provide a strong leadership role within the respective communities.

As governments elevate climate objectives and highlight the need for net-zero emissions, they have recognized the challenge posed by defence-related decarbonization.[49] Many countries may need to decarbonize their entire armed forces in order to satisfy government pledges, without relying on costly offsets.

Alternative fuel decision framework

Choosing the optimal path to incorporate alternative fuels into navy fleets is a major hurdle. For the commercial world, DNV has developed a robust methodology that would help a shipowner transit into a decarbonized setting safely and sustainably. The same methodology can be adapted into a naval setting, describing key input drivers that explore the technical and commercial viabilities.

Methodology for addressing carbon risk

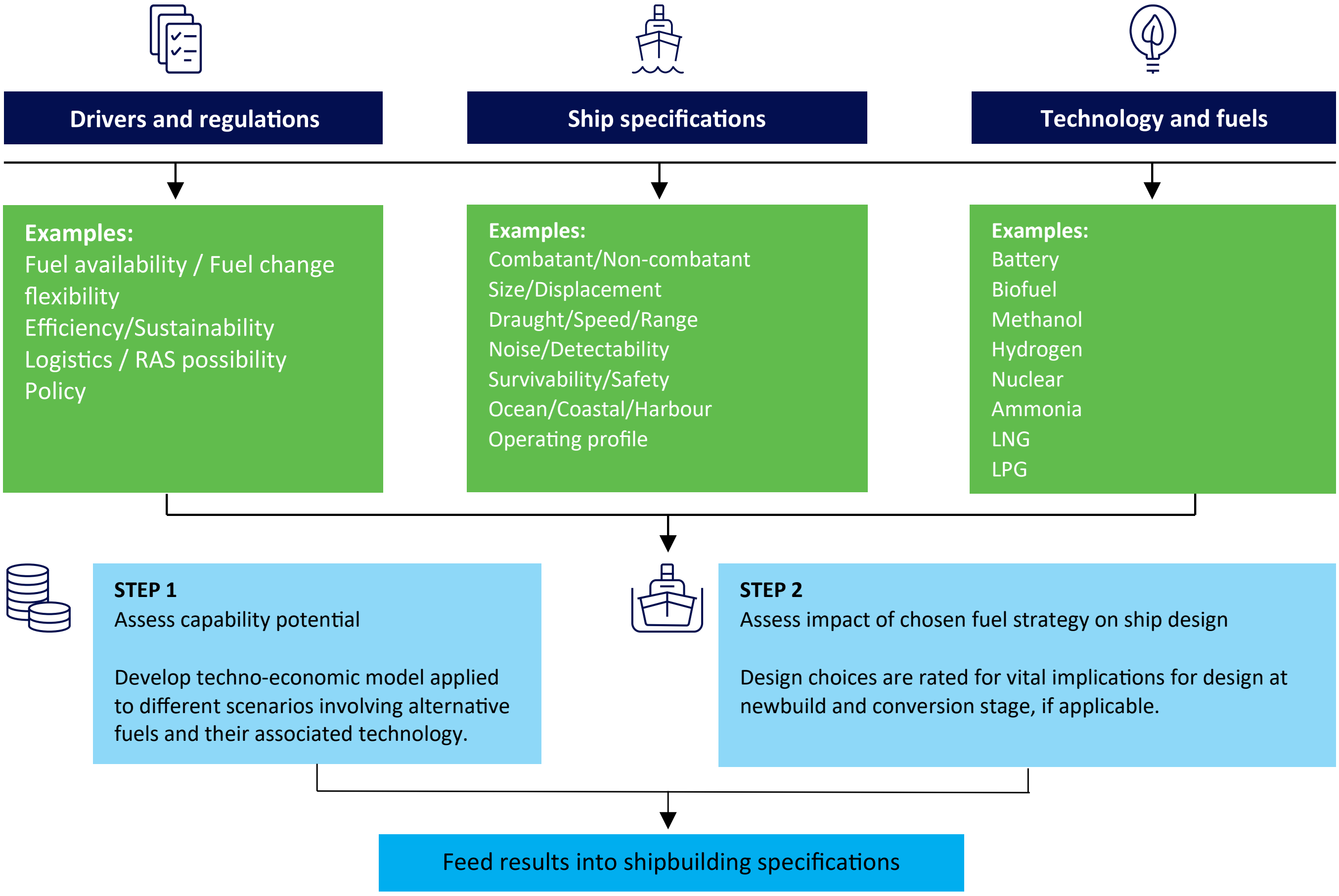
The methodology depicted in Figure 6.1 illustrates two steps in the approach. It shows that the outlook on drivers, regulations, ship technologies and fuels explored earlier in this report is vital input to the first step. When used for actual newbuild decision support, multiple fuel-price scenarios (including supply chain dynamics) and design options should be tested to identify the most robust choices for the shipowner's specific ship type and trade. The number of variables could be narrowed down depending on ship type, operation, and the shipowner's perspective of fuel availability and price.[6]

> Beyond decarbonization, the drivers for the navy to implement alternative fuels would be from an operational standpoint. Diversity in reliance from a single source, applicability to appropriate mission profiles, and overall safety of the asset are practical considerations from a naval perspective. Other factors include the availability of a robust supply chain and functions of the asset itself – combatant or auxiliary type (support type, coastal defence). In that, the latter seems to be the most viable ship type.

Using the model as-is for a civilian owner, pressure from regulators and key commercial stakeholders such as financiers and charterers will push shipowners to ensure that their ships stick to an acceptable GHG emission trajectory (such as IMO Carbon Intensity Indicator [CII] requirements). Above this trajectory, the shipowner is exposed to regulatory and commercial risk; so, for a new ship to retain its asset value throughout the next decades, taking GHG target trajectories into account in design will be critical. Worth noting as well is that the downward trajectory required by the IMO is continuous, so a shipowner will need to identify a 'decarbonization stairway' to remain below the required GHG emission trajectory. This stairway approach illustrates a chosen risk-mitigation strategy and how the introduction of new fuels and technologies at various points in time enables the emission intensity for the ship to stay below the required level. Naturally, understanding the costs associated with the stairway is vital – as is the understanding of the technical design implications of the chosen strategy. In the shorter term, energy-efficiency measures and energy harvesting combined with operational measures may be sufficient; but in the longer term, the use of alternative fuels will be necessary to meet the GHG trajectory. This also means that the ship should be designed to allow for the needed upgrades or fuel changes later in its lifetime. Thus, it is an important intervention point when a vessel is being commissioned, to influence its emissions throughout its lifetime in a cost-effective manner.[6]

FIGURE 6.1

Illustration of framework for carbon risk management (adapted from DNV Maritime Forecast to 2050[6])



Submarines as an example of successful alternative fuel implementation

The navy has been utilizing nuclear energy since the 1960s. Submarines and surface combatants (battleships, cruisers and destroyers) powered by nuclear energy have since been developed. However, independent of the nuclear option, it is submarines that have taken the lead in terms of the adoption of alternative fuels, thanks to the emergence of the air-independent propulsion (AIP) system in the mid-20th century, which offers better endurance compared to conventional non-nuclear submarines. Only after the turn of the 21st century has the use of biofuels been experimented with and subsequently utilized on surface combatants.

Thus, in general, improving operating range and operational flexibility have been the leading reasons for the widespread usage of nuclear energy, hydrogen fuel cells and biofuels on submarines and surface combatants. Furthermore, submarine operators have been able to achieve assurance around supply chains and an acceptable amount of risk, which together serves as a useful case study when considering the adoption of alternative fuels into navy surface ships.

As has been detailed in the responses to the survey conducted as a part of this white paper, facing the greatest challenges of supply chains (Fuel availability / Fuel change flexibility) and Survivability/Safety are not easily overcome. However, considerations regarding forecasted continued availability of traditional fossil fuels, when the supply chains are firmly focused on the change to low- or zero-carbon options for the commercial world, need to be acknowledged.

Independent of advances in combat systems, submarine design is based principally on operational capability not cost, decarbonization or supply chains. This fundamental approach takes a systems approach with attention to designs requiring ‘modularity, commonality and the use of commercial technology’.

In this context, operational capability means:
- Need to operate with minimal signature
- Limited space on board
- Minimized manning
- Flexibility to direct electrical power generation to combat systems
- Survivability under water over long periods of time
- Long range from home base

FIGURE 6.2

U212A submarine of the German Navy

As previously described, the need for power has not changed much, only the source of the power (and perhaps the uses of power). This is nowhere more visible than in developments of integrated propulsion systems that pre-plan for upgrades in technology through design, construction and operation. Of course, new power needs on board require continuous and reliable power generation. Thus, any fuel source that can be reliably sourced within the operational requirements of the vessel should be considered as early as possible in any retrofit or newbuild programme.

And challenging the commercial sector to meet these expectations in relation to designs, systems and sustainment is well within the remit of navies.

7. Appendix

A survey was sent to about 130 respondents of various profiles (navies, shipyards, and fuel suppliers), originating from 12 different countries. A total of 24 responses were received, representing nearly 50% of participating nations. The insights from the survey findings are discussed and analysed in this section.

7.1 Survey

Rank critical factors in relation to alternative fuels

The results shown in Figure 7.1 suggest that top concerns are Fuel availability / Fuel change flexibility, with Noise and Detectability being the least of concerns. Although the majority of respondents did not rank Fuel availability / Fuel change flexibility as their top issue, it was ranked as one of the top four concerns by 72.9% of respondents, highlighting the importance of this element when it comes to alternative fuels.

When it comes to the utilization of alternative fuels, 37.5% of respondents ranked Combatant/Non-combatant as the most essential consideration. Survivability/Safety was placed second by 20.8% of respondents, and Fuel availability / Fuel change flexibility was ranked third by 16.7% of respondents. The following concerns were echoed in the later survey questions.

Looking at Figure 7.2, it further corroborates with the previous analysis where Logistics (Fuel availability / Fuel change flexibility), Fire safety (Survivability/Safety) and Compatibility (Combatant/Non-combatant) are the top three priorities for many industry stakeholders considering the future of alternative fuels in the navy, with 79.2%, 70.8% and 58.3% of the respondents choosing these three options respectively. Many respondents also noted that the issue of Logistics (Fuel availability / Fuel change flexibility) will have to be addressed before it can be successfully utilized in the navy, with the concepts of Standardization and Safety coming into play subsequently.

'Alternative fuels' for navy vessels

Respondents were asked, 'When the topic of "alternative fuels" for navy vessels is raised, which types spring to mind?' and 83.3% of them chose biofuels as one of their

FIGURE 7.1

Survey Question 3: 'Please rank your opinion on the following critical factors in relation to alternative fuels'.

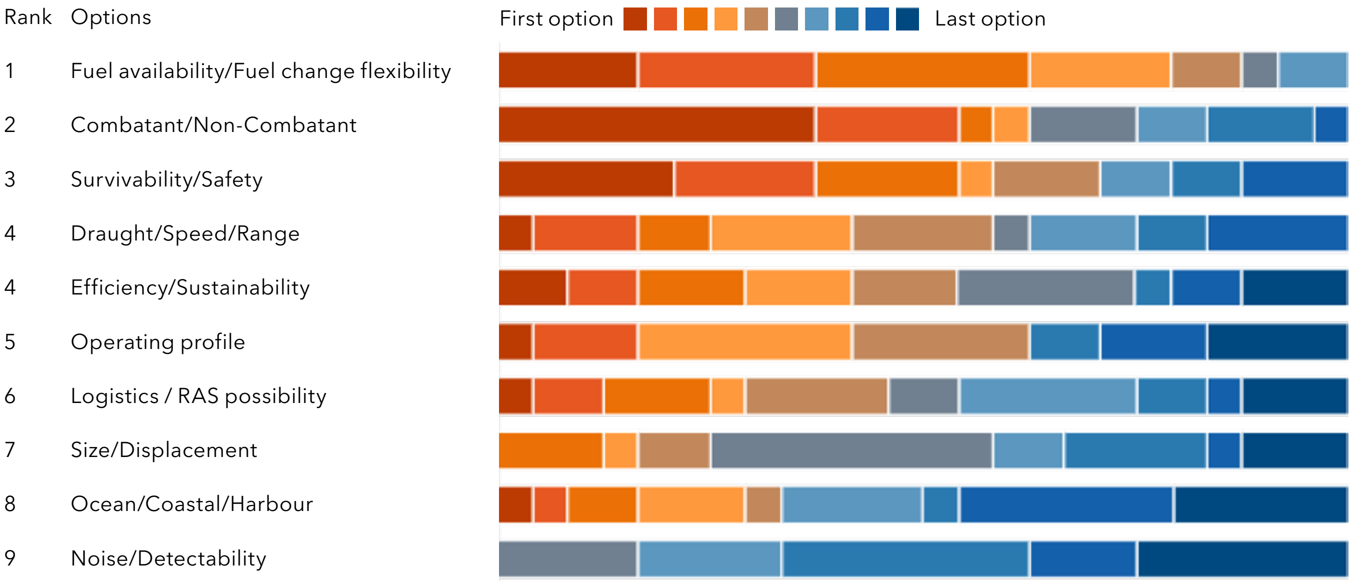
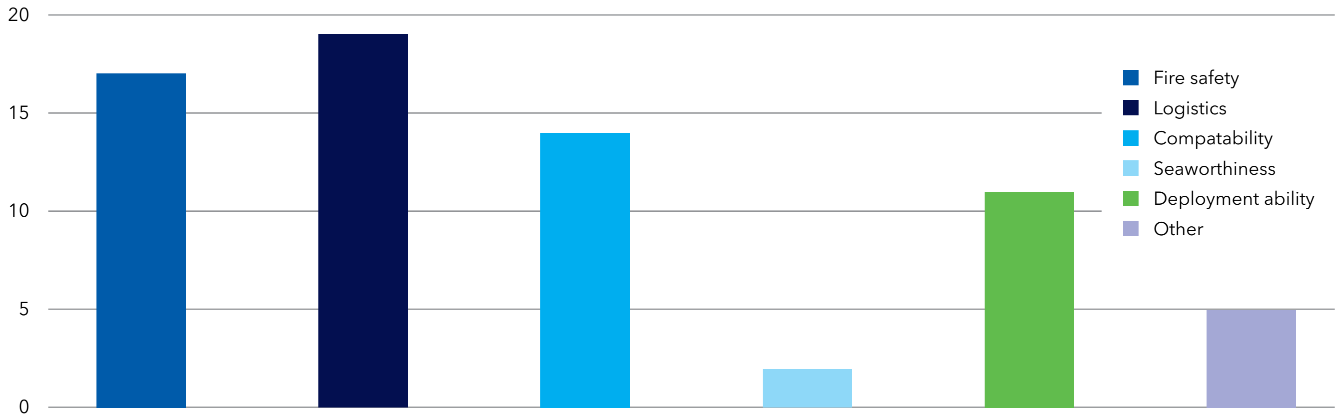


FIGURE 7.2

Survey Question 6: 'What constraints do you see in the future in relation to marine fuel for navy vessels?'



options (Figure 7.3), showing how popular and how far ahead biofuels are, relative to other alternative fuels, as the alternative fuel of choice for the navy. This is similarly observed in the case studies analysis, with a majority of them utilizing biofuels in the implementation stage.

A large majority also picked the 'Others' option and brought up many other alternative fuels such as ammonia, methanol and hydrocarbons. These are fuels that are also currently being looked at in the maritime industry and show great potential in being the future of decarbonization in shipping. One survey response mentioned that 'Synthetic diesel manufactured using renewable energy and a net-zero carbon cycle is the ideal, but likely to be expensive'. This response encapsulates perfectly the challenges of decarbonization in the industry today, with the ideal end goal being able to develop a fuel that has a net-zero carbon footprint but is also relatively cheap to produce.

FIGURE 7.3

Survey Question 4: 'When the topic of "alternative fuels" for navy vessels is raised, which types spring to mind?'

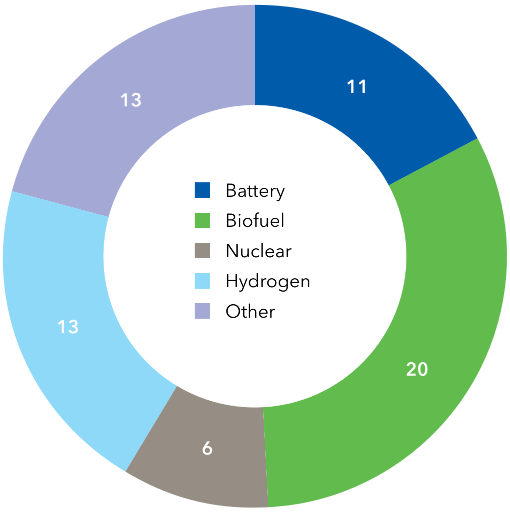
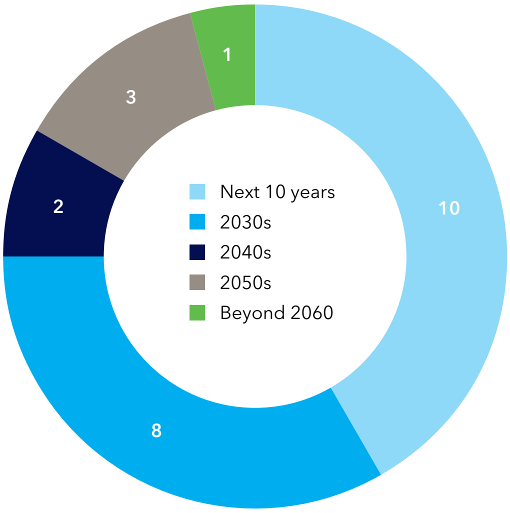


FIGURE 7.4

Survey Question 7: 'When do you think naval vessels will be spec'd with alternative fuels?'



When will naval vessels be spec'd with alternative fuels

Based on Figure 7.4, the consensus in the industry today would be that in the next 10 to 20 years, there will be a greater adoption of alternative fuels in the navy. As mentioned by a respondent, 'Driven by government policy to cut down GHG emissions by 30% by 2030, we will see fast movement and adoption starting with the use of biofuels and hybrid solutions initially with OPVs and small crafts used for day operations near coastlines.' With the IMO guideline of cutting greenhouse gases (GHG) down by 30% by 2030 and by 50% by 2050, research and development into alternative fuels will be sped up by the increased government support and funding. Looking at the many case studies, this has already started with many forays by governments and the industry into utilizing biofuels and hybrid solutions on small craft first before looking at ways to shift the know-how to deep-sea vessels.

In newbuilds, existing vessels or both

As seen from Figure 7.5, when respondents were asked whether alternative fuels are exclusive to newbuilds or existing assets, 58.3% said newbuilds and 41.7% said both. This means that 100% of the respondents agreed that alternative fuels will be a part of any newbuild and is the future of the navy, with many respondents agreeing that adopting alternative fuels in new vessels should be considered.

Adopters of alternative fuels

The respondents' perspective on the types of naval vessels most likely to embrace alternative fuels in the future is depicted in Figure 7.6. Although, in comparison to other categories, the choices given to respondents are primarily categorized as support vessel with vessels such as depot and repair vessel (6), tender/support unit (10), cargo vessel (9), tug and salvage vessel (7), research vessel (14), hospital vessel (4) and dock ship (3). This results in 53 counts for support vessel as the most likely type of naval vessel to use alternative fuels. In addition, three voted for all the ship types, bringing the total to 56; with the majority picking research vessel, tender/support unit, and cargo vessel as the top three. The second most popular type of vessel was a coastal defence vessel, with 50 counts.

This response backs up Figure 7.1, whereby the majority of respondents believe that non-combat boats will be the first to embrace alternative fuels, rather than combat vessels such as frigates and destroyers.

FIGURE 7.5

Survey Question 10: 'Is the implementation of alternative fuels an exclusive focus on newbuilds, existing assets or both?'

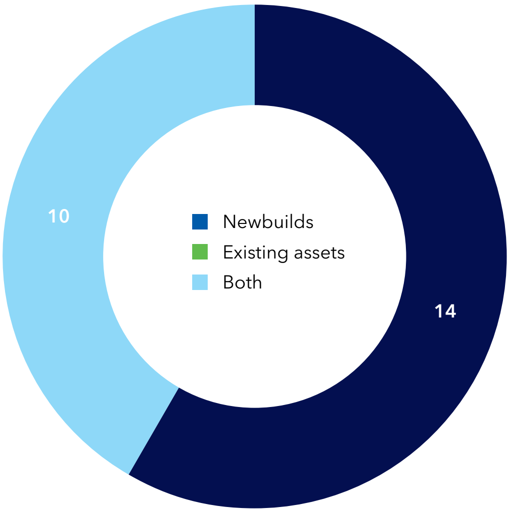


FIGURE 7.6

Survey Question 10: 'What vessel types are most likely to be adopters of alternative fuels?'

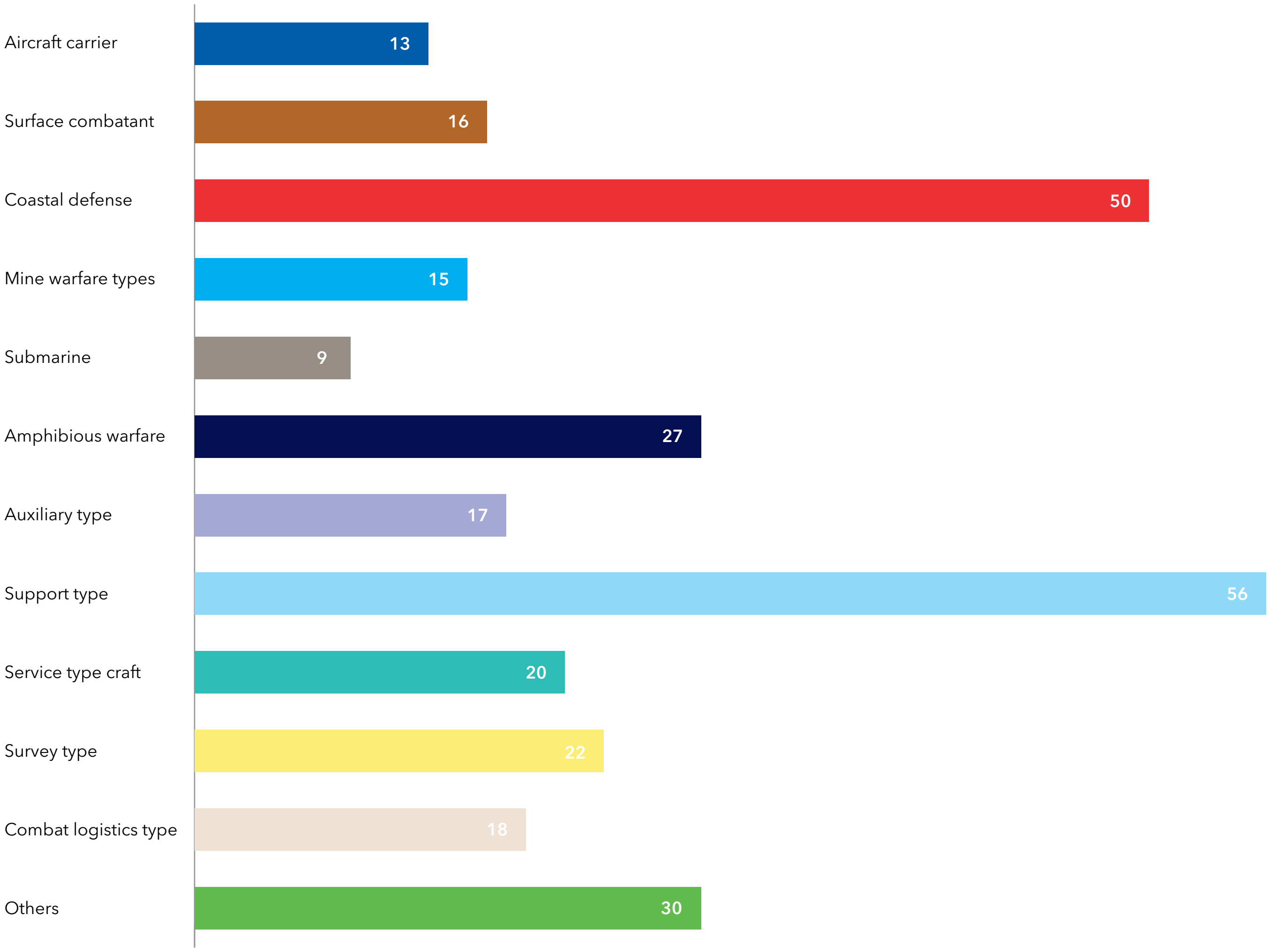


TABLE 7.1

Summary of findings of the white paper

Naval vessel type	Purpose	Mission requirement
LNG		
All auxiliary vessels	Designed to support combatant ships and other naval operations. Auxiliary ships are not primary combatant vessels, though they may have some limited combat capacity, usually for purposes of self-defence. Classification of Naval Ships and Craft (fas.org)	There are many auxiliary ship designations with many different designs and primary functions. Oilers and tenders replenish other ships with fuel, ammunition, supplies and food. Tankers transport fuel to other locations, while other auxiliaries transport other ships and navy personnel. Salvage ships rescue and tow ships damaged during battle. Repair vessels serve as on-the-sea hubs for ship repairs. Tugboats and other ships provide harbour support, and some ships research the navy's operating environment and test future technology advances. https://www.asbestos.com/navy/auxiliary-vessels/
Support ships	Support ships provide the provisions needed to keep the navy operating. There are combat stores on board with supplies, food, repair parts, post and other goods. There are ammunition ships, fast combat support ships, cargo, pre-positioned supply ships, as well as rescue and salvage, tankers, tugboats and hospital ships. https://www.thoughtco.com/types-of-navy-ships-1052445	Designed to operate in the open ocean in a variety of sea states to provide general support to either combatant forces or shore-based establishments. Conduct back-to-back patrols without returning to home bases. Support ships have specialized berthing facilities, battery-charging capabilities, battery and mast workshops, an air supply for submarine escape systems, and the ability to embark and support. Not designed to participate in combat and are generally not armed. The Royal Australian Navy needs a support ship, not a fixed base at Manus Island | The Strategist (aspistrategist.org.au)
Harbour craft	Categorized under service type craft, harbour craft is designed to provide general support to either combatant forces or shore-based establishments. Classification of Naval Ships and Craft (fas.org)	Critical support by assisting vessel docking/undocking, providing firefighting and salvage services, and providing personnel transfer platforms. A failure to smoothly provide harbour tug services during peacetime or wartime could critically impair the operational effectiveness of the port. https://www.globalsecurity.org/military/systems/ship/ytb.htm
Hydrogen		
Submarines	Submarines travel underwater and carry an array of weapons. Submarines are stealthy navy assets for attacking enemy ships and deploying missiles. A submarine may stay underwater on patrol for six months. https://www.thoughtco.com/types-of-navy-ships-1052445	**Speed** Increased speed requires increased power. Since the resistance a submarine encounters is a function of its surface area, the ideal was to achieve greater power without increasing the volume or weight of the power plant and, therefore, the size of the submarine. A more powerful (and therefore noisier) engine could be silenced, but only by increasing the size of the submarine, which in turn would lower its speed. High sustained speed also makes it possible for submarines to deploy more efficiently to distant patrol stations. Higher speed is also valued for evasion after an attack. **Depth** Deeper diving is valued for several reasons. It can be combined with higher speed for better evasion. In addition, a deep-diving submarine can make better use of its own sonar, partly because it can operate in several quite different layers of the sea. Greater maximum operating depth becomes particularly important at high speed, when there is always a possibility that a submarine could accidentally tip down and descend below a safe operating depth before the downward motion can be corrected. Greater depth requires a stronger (and heavier) hull, and increased power requires a stronger power plant. Attempts to combine the two requires a larger hull (to provide enough buoyancy); that, in turn, with added underwater resistance can cut the speed advantage gained from the more powerful engine. **Silencing** Pumps of pressurized-water reactors were redesigned to be quieter, and in many submarines the machinery is carried clear of the hull on sound-absorbing mounts. All of this adds to the size and weight of the machinery and to the expense of construction; it also adds to the attraction of natural-circulation plants. As a further step in silencing, hulls are coated with sound-absorbing material. Even relatively simple coatings can drastically reduce the effectiveness of homing torpedoes. https://www.britannica.com/technology/submarine-naval-vessel/Nuclear-propulsion#ref57478

Pros (relative to diesel fuels)	Cons (relative to diesel fuels)	Safety considerations	Bunkering

• Widely available supply chain
• Range
• Technological maturity
• Expected to be less costly than MGO
• Reduces emissions by up to 90%
• Low energy cost
• Low local and GHG emissions
• Safer:
  • It only burns if it comes in contact with oxygen in concentrations of 5 to 15%
  • Natural gas is lighter than air; in case of leakage, it disperses
DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)
	• Low energy density
	• Requires larger tank capacity
	• Requires maintaining to 163°C
	• Carries 5% more energy per unit volume
	• Doe not require heating or purification, saving cost and maintenance on existing ships and also installation costs on new ships
	DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)
	Stolt-Nielsen Limited: Low Sulphur – Advantages and Challenges | Stolt-Nielsen :..: https://bit.ly/3g2xyej
		Safety research shows that after leakage, LNG tends to accumulate in lower sections due to its high density; and the heat flux from burning LNG clouds reaches levels sufficient for third-level burns.
		https://energsustainsoc.biomedcentral.com/articles/10.1186/s13705-021-00301-9
			LNG bunkering infrastructure for ships is currently limited but improving rapidly.
			DNV 2019: Comparison of Alternative Marine Fuels - SEA-LNG)

Production from electrolysis is well-known and a commercially available technology suitable for local production of hydrogen. Can be produced from natural gas, which is globally available. DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)	• High investment cost • Low maturity of technology • Availability and price of hydrogen • On-board storage requirement • Lack of safety and approval requirements DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)	Highly combustible and explosive, giving rise to safety issues; combustion produces nitrous oxides. https://www.mondaq.com/uk/renewables/1094108/decarbonisation-and-shipping-alternative-fuels	Currently, infrastructure and bunkering facilities are not developed. DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)

Naval vessel type	Purpose	Mission requirement
Ammonia		
All auxiliary vessels	Designed to support combatant ships and other naval operations. Auxiliary ships are not primary combatant vessels, though they may have some limited combat capacity, usually for purposes of self-defence. Classification of Naval Ships and Craft (fas.org)	There are many auxiliary ship designations with many different designs and primary functions. Oilers and tenders replenish other ships with fuel, ammunition, supplies and food. Tankers transport fuel to other locations, while other auxiliaries transport other ships and navy personnel. Salvage ships rescue and tow ships damaged during battle. Repair vessels serve as on-the-sea hubs for ship repairs. Tugboats and other ships provide harbour support, and some ships research the navy's operating environment and test future technology advances. https://www.asbestos.com/navy/auxiliary-vessels/
Support ships	Support ships provide the provisions needed to keep the navy operating. There are combat stores on board with supplies, food, repair parts, post and other goods. There are ammunition ships, fast combat support ships, cargo, pre-positioned supply ships, as well as rescue and salvage, tankers, tugboats and hospital ships. www.thoughtco.com/types-of-navy-ships-1052445	Designed to operate in the open ocean in a variety of sea states to provide general support to either combatant forces or shore-based establishments. Conduct back-to-back patrols without returning to home bases. Support ships have specialized berthing facilities, battery-charging capabilities, battery and mast workshops, an air supply for submarine escape systems, and the ability to embark and support. Not designed to participate in combat and are generally not armed. The Royal Australian Navy needs a support ship, not a fixed base at Manus Island | The Strategist (aspistrategist.org.au)
Harbour craft	Categorized under service type craft, harbour craft is designed to provide general support to either combatant forces or shore-based establishments. Classification of Naval Ships and Craft (fas.org)	Critical support by assisting vessel docking/undocking, providing firefighting and salvage services, and providing personnel transfer platforms. A failure to smoothly provide harbour tug services during peacetime or wartime could critically impair the operational effectiveness of the port. https://www.globalsecurity.org/military/systems/ship/ytb.htm
Methanol		
All auxiliary vessels	Designed to support combatant ships and other naval operations. Auxiliary ships are not primary combatant vessels, though they may have some limited combat capacity, usually for purposes of self-defence. Classification of Naval Ships and Craft (fas.org)	There are many auxiliary ship designations with many different designs and primary functions. Oilers and tenders replenish other ships with fuel, ammunition, supplies and food. Tankers transport fuel to other locations, while other auxiliaries transport other ships and navy personnel. Salvage ships rescue and tow ships damaged during battle. Repair vessels serve as on-the-sea hubs for ship repairs. Tugboats and other ships provide harbour support, and some ships research the navy's operating environment and test future technology advances. https://www.asbestos.com/navy/auxiliary-vessels/
Support ships	Support ships provide the necessary provisions that keep the navy operating. There are combat stores on board with supplies, food, repair parts, mail and other goods. There are ammunition ships, fast combat support ships, cargo, pre-positioned supply ships, as well as rescue and salvage, tankers, tugboats and hospital ships. www.thoughtco.com/types-of-navy-ships-1052445	Designed to operate in the open ocean in a variety of sea states to provide general support to either combatant forces or shore-based establishments. Conduct back-to-back patrols without returning to home bases. Support ships have specialized berthing facilities, battery-charging capabilities, battery and mast workshops, an air supply for submarine escape systems, and the ability to embark and support. Not designed to participate in combat and are generally not armed. The Royal Australian Navy needs a support ship, not a fixed base at Manus Island | The Strategist (aspistrategist.org.au)
Harbour craft	Categorized under service type craft, harbour craft is designed to provide general support to either combatant forces or shore-based establishments. Classification of Naval Ships and Craft (fas.org)	Critical support by assisting vessel docking/undocking, providing firefighting and salvage services, and providing personnel transfer platforms. A failure to smoothly provide harbour tug services during peacetime or wartime could critically impair the operational effectiveness of the port. https://www.globalsecurity.org/military/systems/ship/ytb.htm
LPG		
All auxiliary vessels	Designed to support combatant ships and other naval operations. Auxiliary ships are not primary combatant vessels, though they may have some limited combat capacity, usually for purposes of self-defence. Classification of Naval Ships and Craft (fas.org)	There are many auxiliary ship designations with many different designs and primary functions. Oilers and tenders replenish other ships with fuel, ammunition, supplies and food. Tankers transport fuel to other locations, while other auxiliaries transport other ships and navy personnel. Salvage ships rescue and tow ships damaged during battle. Repair vessels serve as on-the-sea hubs for ship repairs. Tugboats and other ships provide harbour support, and some ships research the navy's operating environment and test future technology advances. https://www.asbestos.com/navy/auxiliary-vessels/
Support ships	Support ships provide the provisions needed to keep the navy operating. There are combat stores on board with supplies, food, repair parts, post and other goods. There are ammunition ships, fast combat support ships, cargo, pre-positioned supply ships, as well as rescue and salvage, tankers, tugboats and hospital ships. www.thoughtco.com/types-of-navy-ships-1052445	Designed to operate in the open ocean in a variety of sea states to provide general support to either combatant forces or shore-based establishments. Conduct back-to-back patrols without returning to home bases. Support ships have specialized berthing facilities, battery-charging capabilities, battery and mast workshops, an air supply for submarine escape systems, and the ability to embark and support. Not designed to participate in combat and are generally not armed. The Royal Australian Navy needs a support ship, not a fixed base at Manus Island | The Strategist (aspistrategist.org.au)
Harbour craft	Categorized under service type craft, harbor craft is designed to provide general support to either combatant forces or shore-based establishments. Classification of Naval Ships and Craft (fas.org)	Critical support by assisting vessel docking/undocking, providing firefighting and salvage services, and providing personnel transfer platforms. A failure to smoothly provide harbour tug services during peacetime or wartime could critically impair the operational effectiveness of the port. https://www.globalsecurity.org/military/systems/ship/ytb.htm

Pros (relative to diesel fuels)	Cons (relative to diesel fuels)	Safety considerations	Bunkering
• Has existing infrastructure for transport and handling. • Can be produced from natural gas, which is globally available. • Production from hydrogen and nitrogen is a well-known and commercially available technology suitable for local production of ammonia, which eliminates the need for a long-distance distribution infrastructure. DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)	• Development of a bunkering infrastructure • Very high auto-ignition temperature • Low flame speed • High heat of vaporization • Narrow flammability limits • Toxicity DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)	• Highly toxic https://www.mondaq.com/uk/renewables/1094108/decarbonisation-and-shipping-alternative-fuels • Exposure to gaseous anhydrous ammonia can cause caustic burns, lung damage and death. https://www.ammoniaenergy.org/articles/ammonia-as-a-renewable-fuel-for-the-maritime-industry/#:~:text=With%20ammonia%2C%20the%20primary%20risk%20is%20clear%3A%20%E2%80%9CExposure,using%20ammonia%20as%20a%20marine%20fuel%20is%20safety.%E2%80%9D	Ammonia has existing infrastructure for transport and handling, since it is used in large quantities as fertilizer. However, the development of a bunkering infrastructure remains a barrier for the use as ship fuel. DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)
Can be produced from several different feedstock resources, like natural gas or coal, or from renewable resources, such as biomass, CO_2 and hydrogen. Readily available through existing global terminal infrastructure and well positioned to reliably supply the global marine industry. DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)	• Low-flashpoint properties • Dedicated bunkering infrastructure is currently limited DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)	• Low flashpoint represents a fire risk • Toxic when inhaled, ingested or handled • Increased corrosion risks https://www.mondaq.com/uk/renewables/1094108/decarbonisation-and-shipping-alternative-fuels	It is readily available through existing global terminal infrastructure and well positioned to reliably supply the global marine industry. However, dedicated bunkering infrastructure for ships is currently limited. Distribution to ships can be accomplished either by truck or by bunker vessel. DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)
A large network of LPG import and export terminals is available around the world and has been prevalent due to the maturing of the technologies and supply chains. DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)	The development of a bunkering infrastructure for ships. DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)	Propane and butane are heavier than air and this causes different risks than, for example, methane, which is lighter than air. Both propane and butanes will burn (or explode) if an ignition source is introduced in a concentration range of about 2 to 9% in air. As a gas, it burns quickly with a high energy content. In addition to this, and like LNG, liquid propane or butane in a pressure vessel constitutes a risk when the pressure vessel is heated, such as by a leak catching fire. https://www.smartmaritime.no/documentation/publications/external-publications/lpg-as-a-marine-fuel-dnv-gl-2017/	Bunkering can be made available by truck or bunker vessels, from LPG terminals. DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)

Naval vessel type	Purpose	Mission requirement
Nuclear		
Aircraft carriers	Aircraft carriers carry fighter aircraft and have runways allowing the aircraft to take off and land. A carrier has about 80 aircraft on board – a powerful force when deployed. All current aircraft carriers are nuclear-powered. https://www.thoughtco.com/types-of-navy-ships-1052445	Speed is an important asset for aircraft carriers, as they need to be deployed anywhere in the world quickly and must be fast enough to evade detection and targeting by enemy forces. High speed provides additional 'wind over the deck', increasing the lift available for fixed-wing aircraft to carry fuel and munitions. To avoid nuclear submarines, they should be faster than 30 knots. Aircraft carriers are among the largest warships, as much deck room is needed. An aircraft carrier must be able to perform increasingly diverse mission sets. Diplomacy, power projection, quick crisis response force, land attack from the sea, sea base for helicopter and amphibious assault forces, Anti-Surface Warfare (ASUW), Defensive Counter Air (DCA), and Humanitarian Aid Disaster Relief (HADR) are some of the missions the aircraft carrier is expected to accomplish. Traditionally, an aircraft carrier is one ship that can perform power projection and sea control missions at the least. An aircraft carrier must be able to efficiently operate an air combat group. This means it should handle fixed-wing jets as well as helicopters. This includes ships designed to support operations of short-take-off/vertical-landing (STOVL) jets. AİRCRAFT CARRİER | Aviation and Airplane Crashes, Air Disasters (planefilms.com) Features include catapults on the flight deck to assist in launching aircraft; for braking while landing, aircraft are fitted with retractable hooks that engage wires on the deck. https://www.britannica.com/technology/aircraft-carrier
Surface combatants	Designed for warfare on the surface of the water, with their own weapons and armed forces. They are generally ships built to fight other ships, submarines, aircraft or land targets, and can carry out several other missions including counter-narcotics operations and maritime interdiction. Their primary purpose is to engage space, air, surface and submerged targets with weapons deployed from the ship itself, rather than by manned carried craft. Classification of Naval Ships and Craft (fas.org)	• **Anti-submarine warfare** Anti-submarine warfare (ASW) is an important role for surface combatants, as submarines present a serious threat to navies and civilian vessels. Many surface combatants carry weapons and sensors to engage submarines, but increasingly an on-board helicopter is used as the primary anti-submarine asset. • **Anti-surface warfare** Anti-surface warfare (attacking enemy ships) is typically carried out using anti-ship missiles, often from the ship but also from helicopters – particularly against small ships such as fast attack craft. Naval guns may also be used in an anti-surface role. • **Anti-aircraft warfare** Anti-aircraft warfare (AAW) is typically defensive in nature, protecting the ship and other friendly ships against both aircraft and incoming missiles (which may be fired from aircraft, but also from other ships, submarines or land platforms). Some surface combatants are developing anti-ballistic missile and/or anti-satellite missile capabilities. SURFACE COMBATANT FORCE REQUIREMENT STUDY – Navy Ships (fas.org) Wayback Machine (archive.org)
Submarines	Submarines travel underwater and carry an array of weapons. Submarines are stealthy navy assets for attacking enemy ships and deploying missiles. A submarine may stay underwater on patrol for six months. https://www.thoughtco.com/types-of-navy-ships-1052445	**Speed** Increased speed requires increased power. Since the resistance a submarine encounters is a function of its surface area, the ideal was to achieve greater power without increasing the volume or weight of the power plant and, therefore, the size of the submarine. A more powerful (and therefore noisier) engine could be silenced, but only by increasing the size of the submarine, which in turn would lower its speed. High sustained speed also makes it possible for submarines to deploy more efficiently to distant patrol stations. Higher speed is also valued for evasion after an attack. **Depth** Deeper diving is valued for several reasons. It can be combined with higher speed for better evasion. In addition, a deep-diving submarine can make better use of its own sonar, partly because it can operate in several quite different layers of the sea. Greater maximum operating depth becomes particularly important at high speed, when there is always a possibility that a submarine could accidentally tip down and descend below a safe operating depth before the downward motion can be corrected. Greater depth requires a stronger (and heavier) hull, and increased power requires a stronger power plant. Attempts to combine the two requires a larger hull (to provide enough buoyancy); that, in turn, with added underwater resistance can cut the speed advantage gained from the more powerful engine. **Silencing** Pumps of pressurized-water reactors were redesigned to be quieter, and in many submarines the machinery is carried clear of the hull on sound-absorbing mounts. All of this adds to the size and weight of the machinery and to the expense of construction; it also adds to the attraction of natural-circulation plants. As a further step in silencing, hulls are coated with sound-absorbing material. Even relatively simple coatings can drastically reduce the effectiveness of homing torpedoes. https://www.britannica.com/technology/submarine-naval-vessel/Nuclear-propulsion#ref57478

Pros (relative to diesel fuels)	Cons (relative to diesel fuels)	Safety considerations	Bunkering
• No hot exhaust gases that contribute to the infrared detectability of fossil-fuelled ships. • Produces fewer or no emissions during operation, which prevents detection as nothing is discharged when underwater, thereby making detection more difficult due to the absence of rising bubbles. • Superior option to conventional fuels in terms of surge ability, moving from one theatre to another, and staying on station. DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)	• Radioactive waste coming from nuclear power is a great caution and peril to the environment. • In terms of operating cost, challenging market conditions have left the nuclear industry struggling to compete. • Strict regulations on maintenance, staffing levels, operator training, and plant inspections have become a burden for sustenance. DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)	• Protecting the nuclear reactor • A nuclear reactor can be one of the most dangerous things on Earth. The nuclear material must be kept shielded and contained at all costs, and the nuclear reaction needs to have a failsafe in place to prevent any meltdown scenarios. https://busbymetals.com/key-considerations-nuclear-submarine-safety/	

Naval vessel type	Purpose	Mission requirement
Battery		
RHIBs	A Rigid Inflatable Boat (RIB), also Rigid-Hull Inflatable Boat or Rigid-Hulled Inflatable Boat (RHIB), is a lightweight, high-performance and high-capacity unsinkable boat constructed with a rigid hull bottom joined to side-forming air tubes that are inflated with air to a high pressure so as to give the sides resilient rigidity along the boat's top sides. The design is stable, light, fast and seaworthy. The inflated collar acts as a life jacket, ensuring that the vessel retains its buoyancy, even if the boat is taking on water. Classification of Naval Ships and Craft (fas.org)	• High manoeuvrability • High speed • Relative immunity to damage in low-speed collisions • Protective Coatings for Rigid Hulled Inflatable Boats – Rhino Linings Premium Protection
Harbour craft	Categorized under service type craft, harbour craft is designed to provide general support to either combatant forces or shore-based establishments. Classification of Naval Ships and Craft (fas.org)	Critical support by assisting vessel docking/undocking, providing firefighting and salvage services, and providing personnel transfer platforms. A failure to smoothly provide harbour tug services during peacetime or wartime could critically impair the operational effectiveness of the port. https://www.globalsecurity.org/military/systems/ship/ytb.htm
Support ships	Support ships provide the provisions needed to keep the navy operating. There are combat stores on board with supplies, food, repair parts, post and other goods. There are ammunition ships, fast combat support ships, cargo, pre-positioned supply ships, as well as rescue and salvage, tankers, tugboats and hospital ships. https://www.thoughtco.com/types-of-navy-ships-1052445	Designed to operate in the open ocean in a variety of sea states to provide general support to either combatant forces or shore-based establishments. Conduct back-to-back patrols without returning to home bases. Support ships have specialized berthing facilities, battery-charging capabilities, battery and mast workshops, an air supply for submarine escape systems, and the ability to embark and support. Not designed to participate in combat and are generally not armed. The Royal Australian Navy needs a support ship, not a fixed base at Manus Island | The Strategist (aspistrategist.org.au)
Biofuel		
Surface combatants	Designed for warfare on the surface of the water, with their own weapons and armed forces. They are generally ships built to fight other ships, submarines, aircraft or land targets, and can carry out several other missions including counter-narcotics operations and maritime interdiction. Their primary purpose is to engage space, air, surface and submerged targets with weapons deployed from the ship itself, rather than by manned carried craft. Classification of Naval Ships and Craft (fas.org)	• **Anti-submarine warfare** Anti-submarine warfare (ASW) is an important role for surface combatants, as submarines present a serious threat to navies and civilian vessels. Many surface combatants carry weapons and sensors to engage submarines, but increasingly an on-board helicopter is used as the primary anti-submarine asset. • **Anti-surface warfare** Anti-surface warfare (attacking enemy ships) is typically carried out using anti-ship missiles, often from the ship but also from helicopters – particularly against small ships such as fast attack craft. Naval guns may also be used in an anti-surface role. • **Anti-aircraft warfare** Anti-aircraft warfare (AAW) is typically defensive in nature, protecting the ship and other friendly ships against both aircraft and incoming missiles (which may be fired from aircraft, but also from other ships, submarines or land platforms). Some surface combatants are developing anti-ballistic missile and/or anti-satellite missile capabilities. SURFACE COMBATANT FORCE REQUIREMENT STUDY – Navy Ships (fas.org) Wayback Machine (archive.org)

Pros (relative to diesel fuels)	Cons (relative to diesel fuels)	Safety considerations	Bunkering
• Has been prevalent due to the maturing of both technologies and supply chains. • Has the best efficiency at low power, but as power increases, the efficiency decreases. • Might greatly increase combat capability as well as decarbonization. DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)	• At present, the size of the necessary battery pack would preclude their use as the sole means of propulsion in all but the smallest of ships on short sea voyages. • Full battery propulsion must await further technical development and even then it is likely to be confined to the smaller ship end of the market. • The battery pack requires replacement when it reaches its life as determined by the total number of charge/discharge cycles. https://www.raeng.org.uk/publications/reports/future-ship-powering-options	An increasing use of Lithium-ion batteries leads to an increased risk for fire, which leads to a high concentration of poisonous smoke. A Lithium-ion battery fire is one of the most dangerous and difficult fires to control and extinguish. The hull of a vessel is slammed with waves, sometimes at very high frequency when the weather is rough. The shock and vibration effects can eventually lead to structural damage of the battery encasing, potentially triggering a short circuit. And above all, it takes much more time for the emergency services to reach a burning ship. http://www.lithiumsafe.com/battery-fire-safety-marine/#:~:text=The%20safety%20approach%20for%20batteries%20on%20sea%20is,damage%20of%20the%20battery%20encasing%2C%20potentially%20triggering%20short-circuit.	
• Can directly replace petroleum-based gasoline and distillate fuels, as these fuels would not require modifications to the ship infrastructure and regular operation procedures. • Improves its operational flexibility and combat capability. DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)	Present compatibility issues in the marine sector owing to their physical and chemical properties that make them hard to mix with fossil fuel, and difficult for long-term on-board storage. DNV 2019: Comparison of Alternative Marine Fuels – SEA-LNG)	Biofuels are cleaner in terms of greenhouse gas and toxic emissions if we compare them with petroleum-based fuels. However, biofuels still produce a reduced amount of carbon emissions while burning, and this could increase the greenhouse effect on our planet. https://www.alternative-energies.net/biofuels-advantages-and-disadvantages/	

TABLE 7.2

Table 7.2 shows the case studies of the different countries, types of alternative fuels used, the classification, vessel type and status. These case studies were conducted to provide an overview of the current use of naval vessels that have adopted alternative fuels.

No.	Country	Fuel type	Vessel name	Classification	Vessel type	Status
1	USA	Nuclear	Long Beach	Surface combatant	Cruiser	Decommissioned
2	USA	Nuclear	Bainbridge	Surface combatant	Cruiser	Decommissioned
3	USA	Nuclear	Truxtun	Surface combatant	Cruiser	Decommissioned
4	USA	Nuclear	California	Surface combatant	Cruiser	Decommissioned
5	USA	Nuclear	South Carolina	Surface combatant	Cruiser	Decommissioned
6	USA	Nuclear	Virginia	Surface combatant	Cruiser	Decommissioned
7	USA	Nuclear	Texas	Surface combatant	Cruiser	Decommissioned
8	USA	Nuclear	Mississippi	Surface combatant	Cruiser	Decommissioned
9	USA	Nuclear	Arkansas	Surface combatant	Cruiser	Decommissioned
10	USA	Nuclear	USS John C. Stennis	Aircraft carrier	Aircraft carrier	In operation
11	USA	Biofuel	USS William P. Lawrence	Surface combatant	Missile destroyer	In operation
12	USA	Biofuel	USS Chung-Hoon	Surface combatant	Destroyer	In operation
13	USA	Biofuel	USS Mobile Bay	Surface combatant	Guided-missile cruiser	In operation
14	USA	Biofuel	USS Stockdale	Surface combatant	Missile destroyer	In operation
15	USA	Biofuel	USS Makin Island	Amphibious warfare	Amphibious assault ship	In operation
16	USA	Biofuel	Ex-Paul F. Foster	Support type	Self Defense Test Ship	In operation
17	Italy	Biofuel	FOSCARI	Patrol combatant	Offshore patrol vessel	In operation
18	Italy	Hydrogen	212A Salvatore Todaro	Submarine	212A submarine	In operation
19	Italy	Hydrogen	212A Scire	Submarine	212A submarine	In operation
20	Italy	Hydrogen	212A Pietro Venuti	Submarine	212A submarine	In operation
21	Italy	Hydrogen	212A Romeo Romei	Submarine	212A submarine	In operation
22	Germany	Hydrogen	212A U31	Submarine	212A submarine	In operation
23	Germany	Hydrogen	212A U32	Submarine	212A submarine	In operation
24	Germany	Hydrogen	212A U33	Submarine	212A submarine	In operation
25	Germany	Hydrogen	212A U34	Submarine	212A submarine	In operation
26	Germany	Hydrogen	212A U35	Submarine	212A submarine	In operation
27	Germany	Hydrogen	212A U36	Submarine	212A submarine	In operation
28	Germany	Hydrogen	212A U37	Submarine	212A submarine	On order
29	Germany	Hydrogen	212A U38	Submarine	212A Submarine	On order
30	Greece	Hydrogen	214 Papanikois	Submarine	214 submarine	In operation
31	Greece	Hydrogen	214 Pipinos	Submarine	214 submarine	In operation
32	Greece	Hydrogen	214 Matrozos	Submarine	214 submarine	In operation
33	Greece	Hydrogen	214 Katsonis	Submarine	214 submarine	In operation
34	South Korea	Hydrogen	214 ROKS Sohn Won-yil	Submarine	214 submarine	In operation
35	South Korea	Hydrogen	214 ROKS Jeong Ji	Submarine	214 submarine	In operation
36	South Korea	Hydrogen	214 ROKS An Jung-geun	Submarine	214 submarine	In operation
37	South Korea	Hydrogen	214 ROKS Kim Jwa-jin	Submarine	214 submarine	In operation
38	South Korea	Hydrogen	214 ROKS Yun Bong-gil	Submarine	214 submarine	In operation
39	South Korea	Hydrogen	214 ROKS Yu Gwan-sun	Submarine	214 submarine	In operation
40	South Korea	Hydrogen	214 ROKS Hong Beom-do	Submarine	214 submarine	In operation
41	South Korea	Hydrogen	214 ROKS Lee Beom-seok	Submarine	214 submarine	In operation
42	South Korea	Hydrogen	214 ROKS Shin Dol-seok	Submarine	214 submarine	In operation
43	Portugal	Hydrogen	214 NRP Tridente	Submarine	214 submarine	In operation
44	Portugal	Hydrogen	214 NRP Arpao	Submarine	214 submarine	In operation
45	Turkey	Hydrogen	214 TCG Pirireis	Submarine	214 submarine	On order

No.	Country	Fuel type	Vessel name	Classification	Vessel type	Status
46	Turkey	Hydrogen	214 TCG Murat Reis	Submarine	214 submarine	On order
47	Turkey	Hydrogen	214 TCG Seydi Ali Reis	Submarine	214 submarine	On order
48	Turkey	Hydrogen	214 TCG Aydin Reis	Submarine	214 submarine	On order
49	Turkey	Hydrogen	214 TCG Hizirreis	Submarine	214 submarine	On order
50	Turkey	Hydrogen	214 TCG Selman Reis	Submarine	214 submarine	On order
51	Spain	Bioethanol	S-80 Isaac Peral	Submarine	S-80 submarine	On order
52	Spain	Bioethanol	S-80 Narciso Monturiol	Submarine	S-80 submarine	On order
53	Spain	Bioethanol	S-80 Cosme Garcia	Submarine	S-80 submarine	On order
54	Spain	Bioethanol	S-80 Mateo Garcia de los Reyes	Submarine	S-80 submarine	On order
55	USA	Biofuel	USS Ford	Surface combatant	Frigate	In operation
56	USA	Nuclear	USS Dallas	Submarine	SSN-700 submarine	Decommissioned
57	Russia	Nuclear	Daniil Moskovsky (B-414)	Submarine	Victor III submarine	In operation
58	Russia	Nuclear	K-448 Tambov	Submarine	Victor III submarine	In operation
59	Russia	Nuclear	B-138 Obninsk	Submarine	Victor III submarine	In operation
60	China	Nuclear	401 Changzheng 1	Submarine	Han class type 091 submarine	Decommissioned
61	China	Nuclear	402 Changzheng 2	Submarine	Han class type 091 submarine	Decommissioned
62	China	Nuclear	403 Changzheng 3	Submarine	Han class type 091 submarine	In operation
63	China	Nuclear	404 Changzheng 4	Submarine	Han class type 091 submarine	In operation
64	China	Nuclear	405 Changzheng 5	Submarine	Han class type 091 submarine	In operation
65	China	Nuclear	406 Changzheng 6	Submarine	Xia class type 092 submarine	In operation
66	China	Nuclear		Submarine	Jin class type 094 / 094A submarine	In operation
67	China	Nuclear	410 Changzheng 10	Submarine	Jin class type 094 / 094A submarine	In operation
68	China	Nuclear	411 Changzheng 11	Submarine	Jin class type 094 / 094A submarine	In operation
69	China	Nuclear	412 Changzheng 18	Submarine	Jin class type 094 / 094A submarine	In operation
70	China	Nuclear		Submarine	Jin class type 094 / 094A submarine	In operation
71	China	Nuclear		Submarine	Jin class type 094 / 094A submarine	In operation
72	Russia	Nuclear	Project 1910	Submarine	Kashalot class submarine	In operation
73	Russia	Nuclear	Arkhangelsk	Submarine	Oscar class II submarine	Decommissioned
74	Russia	Nuclear	Murmansk	Submarine	Oscar class II submarine	Decommissioned
75	Russia	Nuclear	Krasnodar	Submarine	Oscar class II submarine	Decommissioned
76	Russia	Nuclear	Krasnoyarsk	Submarine	Oscar class II submarine	Decommissioned
77	Russia	Nuclear	Irkutsk	Submarine	Oscar class II submarine	On order
78	Russia	Nuclear	Voronezh	Submarine	Oscar class II submarine	In operation
79	Russia	Nuclear	Smolensk	Submarine	Oscar class II submarine	In operation
80	Russia	Nuclear	Chelyabinsk	Submarine	Oscar class II submarine	On order
81	Russia	Nuclear	Orel	Submarine	Oscar class II submarine	In operation
82	Russia	Nuclear	Tver	Submarine	Oscar class II submarine	In operation
83	Russia	Nuclear	Omsk	Submarine	Oscar class II submarine	In operation
84	Russia	Nuclear	Tomsk	Submarine	Oscar class II submarine	In operation

No.	Country	Fuel type	Vessel name	Classification	Vessel type	Status
85	Russia	Nuclear	Kursk	Submarine	Oscar class II submarine	Decommissioned
86	Russia	Nuclear	Belgorod	Submarine	Oscar class II submarine	On order
87	Russia	Nuclear	Volgograd	Submarine	Oscar class II submarine	On order
88	Russia	Nuclear	Barnaul	Submarine	Oscar class II submarine	On order
89	Russia	Nuclear	Severodvinsk	Submarine	Yasen class submarine	In operation
90	Russia	Nuclear	Kazan	Submarine	Yasen class submarine	In operation
91	Russia	Nuclear	Novosibirsk	Submarine	Yasen class submarine	On order
92	Russia	Nuclear	Krasnoyarsk	Submarine	Yasen class submarine	On order
93	Russia	Nuclear	Arkhangelsk	Submarine	Yasen class submarine	On order
94	Russia	Nuclear	Perm	Submarine	Yasen class submarine	On order
95	Russia	Nuclear	Ulyanovsk	Submarine	Yasen class submarine	On order
96	Russia	Nuclear	Voronezh	Submarine	Yasen class submarine	On order
97	Russia	Nuclear	Vladivostok	Submarine	Yasen class submarine	On order
98	Russia	Nuclear	Yury Dolgorukiy	Submarine	Borey class	In operation
99	Russia	Nuclear	Alexander Nevsky	Submarine	Borey class	In operation
100	Russia	Nuclear	Vladimir Monomakh	Submarine	Borey class	In operation
101	Russia	Nuclear	Knyaz Vladimir	Submarine	Borey class	In operation
102	Russia	Nuclear	Knyaz Oleg	Submarine	Borey class	On order
103	Russia	Nuclear	Generalissimus Suvorov	Submarine	Borey class	On order
104	Russia	Nuclear	Imperator Aleksandr III	Submarine	Borey class	On order
105	Russia	Nuclear	Knyaz Pozharskiy	Submarine	Borey class	On order
106	Russia	Nuclear	Dmitry Donskoy	Submarine	Borey class	On order
107	Russia	Nuclear	Knyaz Potyomkin	Submarine	Borey class	On order
108	South Korea	Hydrogen	ROKS Dosan Ahn Changho	Submarine	Dosan Ahn Changho class	In operation
109	South Korea	Hydrogen	ROKS Ahn Mu	Submarine	Dosan Ahn Changho class	On order
110	South Korea	Hydrogen	ROKS Yi Dong-nyeong	Submarine	Dosan Ahn Changho class	On order
111	South Korea	Hydrogen	ROKS Lee Bong-chang	Submarine	Dosan Ahn Changho class	On order
112	Singapore	Hydrogen	RSS Invincible	Submarine	Type 218SG	On order
113	Singapore	Hydrogen	RSS Impeccable	Submarine	Type 218SG	On order
114	Singapore	Hydrogen	RSS Illustrious	Submarine	Type 218SG	On order
115	Singapore	Hydrogen	RSS Inimitable	Submarine	Type 218SG	On order
116	Israel	Hydrogen	INS Tannin	Submarine	Dolphin II	In operation
117	Israel	Hydrogen	INS Rahav	Submarine	Dolphin II	In operation
118	Israel	Hydrogen	INS Dakar	Submarine	Dolphin II	On order
119	India	Hydrogen	INS Kalvari	Submarine	Kalvari class	On order
120	India	Hydrogen	INS Khanderi	Submarine	Kalvari class	On order
121	India	Hydrogen	INS Karanj	Submarine	Kalvari class	On order
122	India	Hydrogen	INS Vela	Submarine	Kalvari class	On order
123	India	Hydrogen	INS Vagir	Submarine	Kalvari class	On order
124	India	Hydrogen	INS Vagsheer	Submarine	Kalvari class	On order
125	USA	Nuclear	Providence	Submarine	Los Angeles class	In operation
126	USA	Nuclear	Chicago	Submarine	Los Angeles class	In operation
127	USA	Nuclear	Key West	Submarine	Los Angeles class	In operation
128	USA	Nuclear	Oklahoma City	Submarine	Los Angeles class	In operation
129	USA	Nuclear	Helena	Submarine	Los Angeles class	In operation
130	USA	Nuclear	Newport News	Submarine	Los Angeles class	In operation
131	USA	Nuclear	San Juan	Submarine	Los Angeles class	In operation
132	USA	Nuclear	Pasadena	Submarine	Los Angeles class	In operation
133	USA	Nuclear	Albany	Submarine	Los Angeles class	In operation

No.	Country	Fuel type	Vessel name	Classification	Vessel type	Status
134	USA	Nuclear	Topeka	Submarine	Los Angeles class	In operation
135	USA	Nuclear	Scranton	Submarine	Los Angeles class	In operation
136	USA	Nuclear	Alexandria	Submarine	Los Angeles class	In operation
137	USA	Nuclear	Asheville	Submarine	Los Angeles class	In operation
138	USA	Nuclear	Jefferson City	Submarine	Los Angeles class	In operation
139	USA	Nuclear	Annapolis	Submarine	Los Angeles class	In operation
140	USA	Nuclear	Springfield	Submarine	Los Angeles class	In operation
141	USA	Nuclear	Columbus	Submarine	Los Angeles class	In operation
142	USA	Nuclear	Santa Fe	Submarine	Los Angeles class	In operation
143	USA	Nuclear	Boise	Submarine	Los Angeles class	In operation
144	USA	Nuclear	Montpellier	Submarine	Los Angeles class	In operation
145	USA	Nuclear	Charlotte	Submarine	Los Angeles class	In operation
146	USA	Nuclear	Hampton	Submarine	Los Angeles class	In operation
147	USA	Nuclear	Hartford	Submarine	Los Angeles class	In operation
148	USA	Nuclear	Toledo	Submarine	Los Angeles class	In operation
149	USA	Nuclear	Tucson	Submarine	Los Angeles class	In operation
150	USA	Nuclear	Columbia	Submarine	Los Angeles class	In operation
151	USA	Nuclear	Greeneville	Submarine	Los Angeles class	In operation
152	USA	Nuclear	Cheyenne	Submarine	Los Angeles class	In operation
153	USA	Nuclear	Ohio	Submarine	Ohio class	In operation
154	USA	Nuclear	Michigan	Submarine	Ohio class	In operation
155	USA	Nuclear	Florida	Submarine	Ohio class	In operation
156	USA	Nuclear	Georgia	Submarine	Ohio class	In operation
157	USA	Nuclear	Henry M. Jackson	Submarine	Ohio class	In operation
158	USA	Nuclear	Alabama	Submarine	Ohio class	In operation
159	USA	Nuclear	Alaska	Submarine	Ohio class	In operation
160	USA	Nuclear	Nevada	Submarine	Ohio class	In operation
161	USA	Nuclear	Tennessee	Submarine	Ohio class	In operation
162	USA	Nuclear	Pennsylvania	Submarine	Ohio class	In operation
163	USA	Nuclear	West Virginia	Submarine	Ohio class	In operation
164	USA	Nuclear	Kentucky	Submarine	Ohio class	In operation
165	USA	Nuclear	Maryland	Submarine	Ohio class	In operation
166	USA	Nuclear	Nebraska	Submarine	Ohio class	In operation
167	USA	Nuclear	Rhode Island	Submarine	Ohio class	In operation
168	USA	Nuclear	Maine	Submarine	Ohio class	In operation
169	USA	Nuclear	Wyoming	Submarine	Ohio class	In operation
170	USA	Nuclear	Louisiana	Submarine	Ohio class	In operation
171	USA	Nuclear	Seawolf	Submarine	Seawolf class	In operation
172	USA	Nuclear	Connecticut	Submarine	Seawolf class	In operation
173	USA	Nuclear	Jimmy Carter	Submarine	Seawolf class	In operation
174	USA	Nuclear	Virginia	Submarine	Virginia class	In operation
175	USA	Nuclear	Texas	Submarine	Virginia class	In operation
176	USA	Nuclear	Hawaii	Submarine	Virginia class	In operation
177	USA	Nuclear	North Carolina	Submarine	Virginia class	In operation
178	USA	Nuclear	New Hampshire	Submarine	Virginia class	In operation
179	USA	Nuclear	New Mexico	Submarine	Virginia class	In operation
180	USA	Nuclear	Missouri	Submarine	Virginia class	In operation
181	USA	Nuclear	California	Submarine	Virginia class	In operation
182	USA	Nuclear	Mississippi	Submarine	Virginia class	In operation

No.	Country	Fuel type	Vessel name	Classification	Vessel type	Status
183	USA	Nuclear	Minnesota	Submarine	Virginia class	In operation
184	USA	Nuclear	North Dakota	Submarine	Virginia class	In operation
185	USA	Nuclear	John Warner	Submarine	Virginia class	In operation
186	USA	Nuclear	Illinois	Submarine	Virginia class	In operation
187	USA	Nuclear	Washington	Submarine	Virginia class	In operation
188	USA	Nuclear	Colorado	Submarine	Virginia class	In operation
189	USA	Nuclear	Indiana	Submarine	Virginia class	In operation
190	USA	Nuclear	South Dakota	Submarine	Virginia class	In operation
191	USA	Nuclear	Delaware	Submarine	Virginia class	In operation
192	USA	Nuclear	Vermont	Submarine	Virginia class	In operation
193	USA	Nuclear	Oregon	Submarine	Virginia class	On order
194	USA	Nuclear	Montana	Submarine	Virginia class	On order
195	USA	Nuclear	Hyman G. Rickover	Submarine	Virginia class	On order
196	USA	Nuclear	New Jersey	Submarine	Virginia class	On order
197	USA	Nuclear	Iowa	Submarine	Virginia class	On order
198	USA	Nuclear	Massachusetts	Submarine	Virginia class	On order
199	USA	Nuclear	Idaho	Submarine	Virginia class	On order
200	USA	Nuclear	Arkansas	Submarine	Virginia class	On order
201	USA	Nuclear	Utah	Submarine	Virginia class	On order
202	USA	Nuclear	Oklahoma City	Submarine	Virginia class	On order
203	USA	Nuclear	Arizona	Submarine	Virginia class	On order
204	USA	Nuclear	Columbia	Submarine	Columbia class	On order
205	USA	Nuclear	Wisconsin	Submarine	Columbia class	On order
206	Russia	Nuclear	Orenburg	Submarine	Delta III class	In operation
207	Russia	Nuclear	Ryazan	Submarine	Delta III class	In operation
208	Russia	Nuclear	Verkhoturye	Submarine	Delta IV class	In operation
209	Russia	Nuclear	Ekaterinburg	Submarine	Delta IV class	In operation
210	Russia	Nuclear	Podmoskovye	Submarine	Delta IV class	In operation
211	Russia	Nuclear	Tula	Submarine	Delta IV class	In operation
212	Russia	Nuclear	Bryansk	Submarine	Delta IV class	In operation
213	Russia	Nuclear	Karelia	Submarine	Delta IV class	In operation
214	Russia	Nuclear	Novomoskovsk	Submarine	Delta IV class	In operation
215	Russia	Nuclear	Dmitriy Donskoy	Submarine	Typhoon class	In operation
216	Russia	Nuclear	Nizhniy	Submarine	Sierra class	In operation
217	Russia	Nuclear	Pskov	Submarine	Sierra class	On order
218	Russia	Nuclear	Pantera	Submarine	Akula class	On order
219	Russia	Nuclear	Volk	Submarine	Akula class	On order
220	Russia	Nuclear	Bratsk	Submarine	Akula class	On order
221	Russia	Nuclear	Leopard	Submarine	Akula class	On order
222	Russia	Nuclear	Tigr	Submarine	Akula class	On order
223	Russia	Nuclear	Magadan	Submarine	Akula class	On order
224	Russia	Nuclear	Vepr	Submarine	Akula class	In operation
225	Russia	Nuclear	Kuzbass	Submarine	Akula class	In operation
226	Russia	Nuclear	Gepard	Submarine	Akula class	In operation
227	Russia	Nuclear	Samara	Submarine	Akula class	On order
228	Russia	Nuclear	Chakra	Submarine	Akula class	In operation
229	UK	Nuclear	Talent	Submarine	Trafalgar class	In operation
230	UK	Nuclear	Triumph	Submarine	Trafalgar class	In operation
231	UK	Nuclear	Vanguard	Submarine	Vanguard class	In operation

No.	Country	Fuel type	Vessel name	Classification	Vessel type	Status
232	UK	Nuclear	Victorious	Submarine	Vanguard class	In operation
233	UK	Nuclear	Vigilant	Submarine	Vanguard class	In operation
234	UK	Nuclear	Vengeance	Submarine	Vanguard class	In operation
235	UK	Nuclear	Astute	Submarine	Astute class	In operation
236	UK	Nuclear	Ambush	Submarine	Astute class	In operation
237	UK	Nuclear	Artful	Submarine	Astute class	In operation
238	UK	Nuclear	Audacious	Submarine	Astute class	On order
239	UK	Nuclear	Anson	Submarine	Astute class	On order
240	UK	Nuclear	Agamemnon	Submarine	Astute class	On order
241	UK	Nuclear	Agincourt	Submarine	Astute class	On order
242	UK	Nuclear	Dreadnought	Submarine	Dreadnought class	On order
243	UK	Nuclear	Valiant	Submarine	Dreadnought class	On order
244	UK	Nuclear	Warspite	Submarine	Dreadnought class	On order
245	UK	Nuclear	King George VI	Submarine	Dreadnought class	On order
246	France	Nuclear	Rubis	Submarine	Rubis class	In operation
247	France	Nuclear	Casabianca	Submarine	Rubis class	In operation
248	France	Nuclear	Emeraude	Submarine	Rubis class	In operation
249	France	Nuclear	Amethyste	Submarine	Rubis class	In operation
250	France	Nuclear	Perle	Submarine	Rubis class	In operation
251	France	Nuclear	Le Triomphant	Submarine	Triomphant class	In operation
252	France	Nuclear	Le Temeraire	Submarine	Triomphant class	In operation
253	France	Nuclear	Le Vigilant	Submarine	Triomphant class	In operation
254	France	Nuclear	Le Terrible	Submarine	Triomphant class	In operation
255	France	Nuclear	Suffren	Submarine	Barracuda class	On order
256	France	Nuclear	Duguay-Trouin	Submarine	Barracuda class	On order
257	France	Nuclear	Tourville	Submarine	Barracuda class	On order
258	France	Nuclear	De Grasse	Submarine	Barracuda class	On order
259	France	Nuclear	Rubis	Submarine	Barracuda class	On order
260	France	Nuclear	Casabianca	Submarine	Barracuda class	On order
261	India	Nuclear	INS Arihant	Submarine	Arihant class	In operation
262	India	Nuclear	INS Arighat	Submarine	Arihant class	On order
263	India	Nuclear	-	Submarine	Arihant class	On order
264	India	Nuclear	-	Submarine	Arihant class	On order
265	Brazil	Nuclear	Alvaro Alberto	Submarine	Alvaro Alberto class	On order
266	USA	Biofuel	Robert Gordon Sproul	Support type	Research vessel	In operation
267	USA	Hydrogen	US Vindicator	Coast guard	Coast guard	In operation
268	USA	Hydrogen	-	Support type	Research vessel	Feasibility study
269	USA	Hydrogen	-	Support type	Sealist vessel	Feasibility study
270	Sweden	Hydrogen	-	Support type	Rescue boat	Feasibility study
271	USA	Battery	eWolf	Support type	Ocean-going tug	On order
272	Turkey	Battery	Zeetug	Support type	Ocean-going tug	On order
273	China	Battery	Yungang	Support type	Ocean-going tug	In operation
274	Italy	Hydrogen	ZEUS	Support type	Research vessel	On order

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