Alternative Fuels, Propulsion and Power Systems for the Future Navy
A Route Towards Reduced Emissions and Signatures, and Fossil Fuel Independence

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CHAPTER 14

Alternative Fuels, Propulsion and Power Systems for the Future Navy – A Route Towards Reduced Emissions and Signatures, and Fossil Fuel Independence

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Abstract

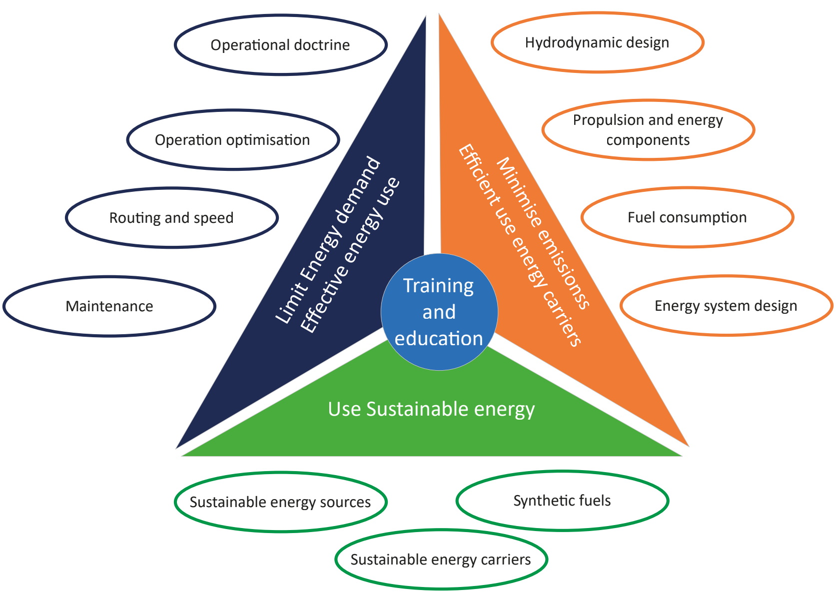
The sustainability policy requires the Netherlands Ministry of Defense (MoD) to become largely independent of fossil fuels in the coming decades, while at the same time the geopolitical situation requires the Armed Forces to operate globally. Therefore, the Royal Netherlands Navy needs to reconsider its fuel strategy, to gradually change to energy carriers from renewable sources, and to redesign its power and propulsion system, both to improve efficiency and to reduce its emissions and signatures. The aim of this chapter is to provide a critical review of the challenges and opportunities of the transition to alternative energy carriers and energy systems and to provide a direction for the required research and development towards the future Navy fleet that can operate independently of fossil fuels and with minimal signature. First, the chapter reviews production, expected availability and projected development of cost of the various alternative fuels, with a specific focus on hydrogen, methanol, and renewable drop-in alternatives for naval distillate fuels, according to NATO F-76 specifications. Subsequently, the chapter will discuss the impact of these three fuels on three differently sized navy vessels, that are currently considered for replacement: diving vessels, seagoing support vessels, and future surface combatants. For these three use cases, the chapter also discusses the potential power and propulsion system configurations and the opportunities to reduce signatures by alternative power supplies, such as fuel cells and batteries. Based on this analysis, the chapter will propose a fuel selection strategy for future navy vessels and will discuss the required research and development that is required to achieve the identified opportunities. The chapter closes with conclusions and recommendations on the route towards a future fleet that can operate globally independent of fossil fuels.

Keywords: military, ships, energy, power systems, fuel, emissions

14.1 Introduction

The fourth International Maritime Organisation (IMO) Greenhouse gas (GHG) Study 2020 (Faber, et al., 2021) concludes that shipping greenhouse gas emissions have grown from 2012 to 2018 due to a growth in shipping activity and that the IMO's GHG reduction ambition of 50% by 2050 (International Maritime Organisation, 2018) can only be achieved using low-carbon fuels. At the same time, the Netherlands Ministry of Defense (NL MoD) also strategically wants to reduce its dependency on fossil fuel, according to its energy and environment strategy (Bijleveld-Schouten, & Visser, 2019) and the subsequent sustainability policy (Maat, van der, 2023). Concurrently, it aims to minimise signatures, such as noise and infrared, for operational reasons. Because of this strategy, the Royal Netherlands Navy must become progressively independent of fossil fuels, while maintaining its operational autonomy and reducing its signature. The 'Roadmap Energietransitie Operationeel Materieel' (Gales, 2022) describes how the Netherlands MoD aims to reduce its dependency on fossil fuels by three courses of action, the so-called '*trias energetica*' illustrated in Figure 14.1: limiting the energy demand by effective use of energy, minimising emissions by efficient use of energy carriers and use of sustainable energy sources.

Figure 14.1. 'Trias Energetica' of the MoD – three lines of reducing the MOD's dependency on fossil fuels supported by training and education, adapted from (Gales, 2022).



The first course of action to reduce the dependency on fossil fuel is to reduce the energy demand of naval vessels. Optimal operations planning (Laan, Barros, Boucherie, Monsuur, & Noordkamp, 2020), ship weather routing (Zis, Psaraftis, & Ding, 2020), improved maintenance (Valchev, et al., 2018; Kartatug, Arslanoglu, & Guedes Soares, 2023) and hull optimisation and Energy Saving Devices (Schuilinga, & Terwisga, 2017) can contribute to significant reductions of the required propulsion power. Therefore, during fleet planning, operational doctrines and tactics need to be developed, during ship design, the hull form needs to be optimised and during the lifetime of naval vessels, maintenance strategies and energy saving devices should be considered, such as the hull vane for the Holland class OPV's (Bouckaert, Uithof, Moerke, & Oossanen, 2016). Unfortunately, the reductions resulting from these measures are insufficient to reach the goals of the IMO GHG strategy and Defence Operational Energy Strategy (Faber, et al., 2021). Therefore, this work focuses on minimising the emissions and using energy carriers efficiently through the power plant design with hybrid propulsion and power generation (Geertsma, Negenborn, Visser, & Hopman, 2017) and the possibilities and limitations of using sustainable energy carriers (Pothaar, Geertsma, & Reurings, 2022).

14.1.1 Literature review

Figure 14.2 shows the possible pathways from energy source to use in the energy system of the ship (Pothaar, Geertsma, & Reurings, 2022). Every conversion step from energy source to energy carrier costs energy, as will be covered in Section 14.2. It is practically possible to convert sustainable energy sources to drop-in fuels as energy carriers like e-diesel, which also is the aim for aviation with Sustainable Aviation Fuels (SAF) (Juan, Hoang, & Cheng, 2023). The Well-To-Tank (WTT) efficiency of these so-called *electro fuels* is significantly higher when using short chain energy carriers such as hydrogen or methanol (Brynolf, Taljegard, Grahn, & Hansson, 2018) (Table 14.3). On the other hand, large surface combatants, one of the types of naval ship considered in this article, have a very challenging typical autonomy requirement of 30 days of independent operation at sea and a range of 5000 NM at 18 kts. With a typical fuel capacity of 600 m3 or 530 tons for a Large Surface Combatant, replacing diesel oil with lower density hydrogen or methanol fuels directly adds 1200 or 600 tons displacement, respectively (Pothaar, Geertsma, & Reurings, 2022), as shown in Figure 14.3 (Van Kranenburg et al., 2020). Moreover, operations take place worldwide in international NATO fleets and refuelling from any NATO partner is a requirement when operating in a NATO context. Therefore, when establishing the future fuel strategy, the trade-off between production cost and the impact on the ship design and its global operation needs to be considered.

Figure 14.2. Possible fuel production pathways from energy source to biofuel and e-fuel (Pothaar, Geertsma, & Reurings, 2022).

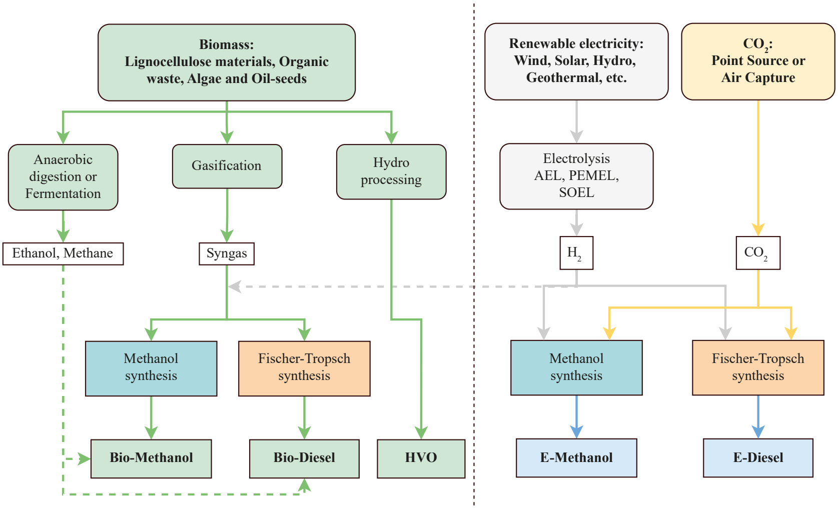
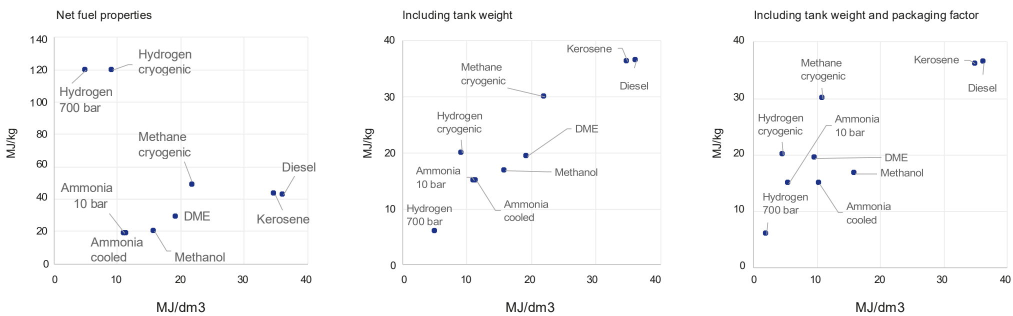


Figure 14.3. Energy density and specific energy of fuels with and without the tank weight and volume (Kranenburg, et al., 2020).



The choice of fuels considered for maritime application is extensive and ranges from hydrogen, alcohol fuels, such as methanol, ethanol and butanol, other carbon-based fuels, such as dimethyl ether, methane, liquefied natural gas (LNG) and liquefied petroleum gas (LPG) to ammonia, which contains no carbon, like hydrogen. Methanol is a liquid fuel that is representative of other alcohol fuels and dimethyl ether, which are more energy intensive to produce (Brynolf, Taljegard, Grahn, & Hansson, 2018). Gaseous fuels, such as methane LNG and LPG, are fossil fuels, are more difficult to store, and cannot be produced more efficiently from sustainable feedstock then methanol. Therefore, this study considers hydrogen as a fuel which can be applied for small assets as the starting point for all green fuels, methanol as the most easily produced green fuel that is liquid in ambient conditions and biodiesel and e-diesel, as a sustainably produced drop-in-fuel for distillate fuel oil. The biggest impact of alternative fuels on the ship design is determined by the energy density of the fuel as shown in Figure 14.3 (Kranenburg, et al., 2020). The fuel choice also drives other design aspects, such as safety measures as cofferdams and separated fuel treatment or pump rooms, the choice of propulsion and power system architecture and the choice of power sources.

14.1.2 Aim and contribution

This chapter aims to discuss the impact of fuel choice and propulsion and power system architecture on the design of several typical naval vessels, to provide a strategy for research and development towards sustainable power systems with minimal emissions and sufficient autonomy for the future Navy. First, the chapter reviews the production, expected availability and projected development of cost of the various alternative fuels, with a specific focus on hydrogen, methanol, and renewable drop-in alternatives for naval distillate fuels, according to NATO F-76 specifications, based on an extensive literature review. Subsequently, the chapter discusses the impact of these three fuels on three differently sized navy vessels, that are currently considered for replacement: diving vessels, seagoing support vessels and future surface combatants. For these three use cases, the chapter also discusses the potential power and propulsion system configurations and the opportunities to reduce signatures by alternative power supplies, such as fuel cells and batteries, and assesses these configurations qualitatively. Based on this analysis, the chapter will propose a strategy for fuel selection for future naval vessels and will discuss the required research and development to achieve the identified opportunities. The chapter closes with conclusions and recommendations on the route towards a future fleet that can operate globally independent of fossil fuels.

14.2. Production, Availability and Cost of Sustainable Fuels

The fuel choice has a major impact on the ship design, the power system design and operation of the ship. Table 14.1 (van de Ketterij, 2018; Verhelst, Turner, Sileghem, & Vancoille, 2019; Moirangthem & Baxter, 2016; Ryste, Wold, & Sverud, 2019; Ellis & Tanneberger, 2015) reveals the most important fuel characteristics of the different fuels discussed in this chapter. Energy density, usually described by the Lower Heating Value (LHV) of the fuel, together with gravimetric density and boiling point, determine required mass and volume for storage of the energy required for the operation. Toxicity, flash point and explosion limits directly follow from the chemical composition of the fuel and determine required safety precautions and safe zones around the fuel system.

Fuels with a boiling point well below atmospheric conditions are stored on board of a ship mostly as a liquid at low temperatures. For hydrogen, this would require a storage temperature of around 20 Kelvin, which is hard to obtain, so storage at a pressure of 700 bar is also considered. This leads to considerable weight and volume costs for storage. Storage of 1 ton of hydrogen typically requires 10 to 15 tons of storage system, and 30 to 40 m³ of volume. Table 14.2 lists the resulting volumetric requirements for the storage of different fuels, compared to diesel.

Table 14.1. Properties of the fuels considered in this study.

		Diesel*	Hydrogen	Methane	Gasoline***	Methanol	Ethanol	Dimethyl ether	Ammonia
Chemical composition		$C_{14}H_{30}$	H_2	CH_4	C_8H_{18}	CH_3OH	C_2H_5OH	CH_3OCH_3	NH_3
liquid density	kg/m³	847	708,5	426	750	792	789	660	683
density (gas)	kg/Nm³		0,083**	0,66				1,62	0,77
LHV	MJ/kg	42,6	119,9	50	44,5	20,3	22	28,4	18
energy density	MJ/NL	37,2	1,45	0,076	43,6	14,3	17,5	18,7	0,024
flash point	°C	70,5	-253	-188	-42,8	11,1	13	-41	NA
boiling point	°C	180 – 280	-253	-162	150	65	78,1	-24	-33,2
cetane number	-	38-53	-	-	18	5	12	60	-
octane number	RON	15-25	135	120	90-98	108,7	110	15	130
auto ignition temp	°C	255	560	595	460	464	363	350	650,9
flame speed	m/s	0,8	3,25	0,4	0,41 – 0,58	0,56	0,58	0,45	0,18
Flammability limits (vol)	%	1,85-8,2	4-75	5-15	1,4-7,6	6,7-36	3,3-19	2-50	15-28
heat of vaporisation	kJ/kg**	250	224,5	512	375	1089	841	467	1371

** ranges from C_9H_{20} to $C_{25}H_{52}$*
*** at a pressure of 1 bar, excluding construction weight; at 700 bars, density is 42 kg/m³*
**** content is a mixture ranging from C_6H_6 to $C_{10}H_{22}$*

Table 14.2. Volumetric and mass requirements (only energy carrier, excluding constructional weight) for energy storage of different fuels compared to diesel.

		Diesel	Hydrogen**	Methane	Gasoline	Methanol	Ethanol	Dimethyl ether	Ammonia
Storage capacity	m^3	200	1460	677	216	449	416	423	680
Volume compared to diesel	(-)	1	7,2	3,4	1,1	2,2	2,1	2,1	3,4*
Storage capacity	ton	169	62	288	162	356	328	279	464
Mass compared to diesel	(-)	1	0,36	0,9	1	2,1	1,9	1,5	2,4
Weight of fuel and storage	ton	330	1200***	382	316	693	640	496	781
Total mass compared to diesel		1	3,3	1,2	0,96	2,1	1,94	1,5	2,4

** when stored as a liquid*
*** when stored at a pressure of 700 bar, excluding construction volume*
**** reference: (Hoecke van, et al., 2021)*

14.2.1 Production process and production efficiency

The production efficiency of a bio-, or e-fuel is an important parameter when assessing the overall impact of the fuel chosen on potential independence of fossil fuels. The efficiency represents the ratio between the energy requirement of the production process and the resulting energy in terms of Lower Heating Value (LHV) stored in the fuel resulting from the production process. Table 14.3 shows the production efficiency typical for the different fuels. Hydrogen appears to be the most promising fuel from a production perspective, with ammonia the second best. Production efficiency of e-diesel is slightly lower than of e-methanol. This is the result of additional production steps required to produce the longer molecule chain of diesel. E-hydrogen can be produced at quite high efficiency. The process is rather simple and can easily be scaled-up. Ammonia requires nitrogen to combine with hydrogen. Nitrogen is abundantly available in the atmosphere, whereas carbon dioxide – required to produce e-methanol and e-diesel – is less abundant in the atmosphere. This explains the higher efficiency of e-ammonia compared to e-methanol or e-diesel.

Production efficiency of biofuels is generally higher than that of e-fuels, and shows a large variation. The higher efficiency is caused by the fact that energy for the feedstock production is not accounted for, as nature delivers this energy. The large variation is caused by the production process. Bio-methanol and biodiesel can be produced through various production processes. The process depends on the desired fuel and the used feedstock. Organic waste from food processing or crops is typically used for anaerobic processes such as fermentation or digestion, resulting in ethanol and biogas (consisting mainly of CH_4 and CO_2), respectively. Lignocellulose feedstocks are considered suitable for gasification. This is a process that converts biomass by endothermic reaction without combustion to synthesis gas, consisting of H_2, CO, CO_2, H_2O and CH_4. If desirable, the resulting products, hydrogen, and synthesis gas, can be further synthesised into other fuels. Vegetable oils are commonly used to produce FAME biodiesel and HVO biodiesel through transesterification and catalytic hydro processing, respectively. To increase the production yields of biomass, H_2 can be added to the excess CO and CO_2 generated in the biomass-to-fuel conversion process. This will generate additional fuel without the need for energy intensive carbon capture. Huang & Zhang (2011) estimated the biomass-to-fuel efficiency for bio-methanol around 54% and around 51% for biodiesel, by dividing the energy in the resulting fuel and the energy content in the biomass, without significant inputs or outputs of other energy.

Table 14.3. Overall production efficiency of methanol and diesel for two different production options (table extracted from Pothaar, 2023; Jepma, Kok, Renz, Schot, & Wouters, 2018; Fasihidi & Breyer, 2018; IRENA & Methanol Institute, 2021; van de Ketterij, 2018; Prussi, yugo, & Prada, 2020).

Fuel Type	**Overall production efficiency %**
Bio-methanol	54 – 75 %
Biodiesel	51 – 83 %
E-methanol	41 – 62 %
E-diesel	37 – 60 %
E-hydrogen	73 %
E-ammonia	66 %

14.2.2 Future availability

Methanol is a readily available product worldwide, with a production of around 100Mt per annum. Most of the produced methanol originates from fossil sources, natural gas and coal (Methanol Institute, 2021), leading to more GHG emission than diesel in a life-cycle analysis under equal circumstances (Balcombe, et al., 2019). The availability of sustainable methanol is limited: currently the production capacity is below 1% of the yearly produced methanol volume. For future availability of sustainably produced methanol, the Methanol Institute (International Energy Agency, 2021) in 2021 and DNV in 2023 analysed the market development of sustainable methanol production facilities. DNV expects that 11 million tons of oil equivalent (Mtoe) will be produced worldwide, and that this worldwide production can grow gradually to between 500 and 1200 Mtoe in 2050 (Sekkesaeter, Ovrum, Horschig, Henriksen, & Heggen, 2023). However, this production capacity needs to be shared between all sectors.

The Methanol Institute (Methanol institute, 2023) gives an overview of the bio-methanol and e-methanol production increase based on 80 renewable methanol projects and expects renewable bio-methanol production to increase sharply from 0,16 MT year to over 8 MT / year in 2027. This increase is much steeper than the expected growth of all biofuels of 7% per year for the period up to 2027 (Univdatos, 2023). The increase is fed by both an increase in energy needs and increasing government regulations for cleaner and more sustainable fuels.

Due to the limited availability of feedstock for bio-methanol production, in the energy mix e-methanol would also be required. The disadvantage for e-methanol is that it requires large amounts of renewable energy. If e-fuels will be fully deployed in shipping, it might double or even triple the maritime sector's energy consumption on a well-to-wake basis, due to the inherent thermodynamic conversion inefficiency that occurs when producing e-fuels (Lindstad, Lageman, Rialland, Gamlem, & Valland, 2021). Therefore, the feedstock for future production of sustainable fuels for shipping should consist of a combination of sustainably obtained biomass supplemented with sustainably produced hydrogen and CO_2.

For the future availability of e-diesel for maritime use, there are no concrete plans yet for large scale production facilities. Aviation is dependent on sustainable aviation fuels (SAFs) for making aviation more sustainable (Holladay, Abdullah, & Heyne, 2020). SAFs are longer chain sustainable fuels, such as e-kerosene and bio-kerosine. The production process of SAFs has many similarities with the production process of sustainable diesel and its upscaling could therefore play a crucial role in the pathway to sustainable diesel for maritime use. However, the energy consumption for the production significantly increases with increasing molecule chain sizes, as more conversion steps are required and each step reduces well-to-tank efficiency, as shown in Table 14.3.

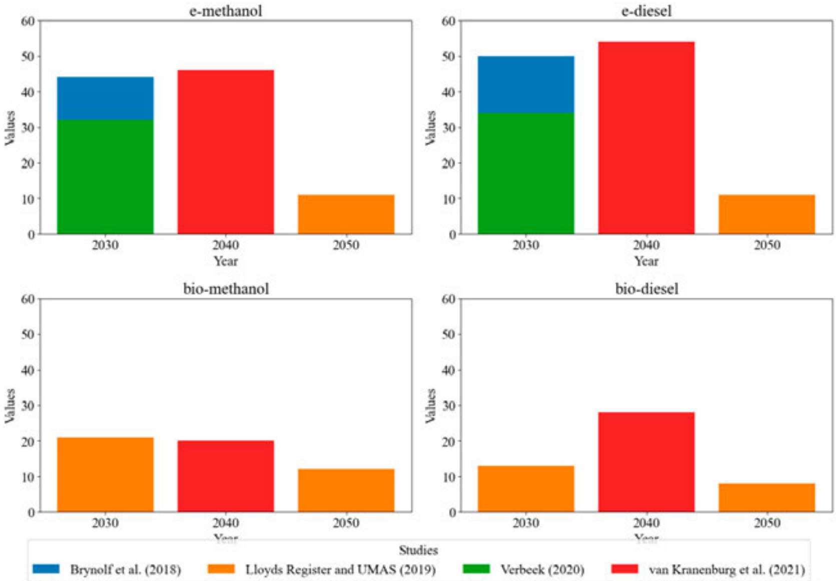
14.2.3 Fuel production cost estimates and assumptions

Decarbonisation of the shipping industry is strongly driven by cost evolution of sustainable fuels. Figure 14.4 and Table 14.4 provide an overview of cost estimates from various studies that have been performed over the past years (Brynolf, Taljegard, Grahn, & Hansson, 2018; Lloyds Register and UMAS, 2019; Verbeek, 2020; Kranenburg, et al., 2021). At first glance, it seems to indicate a huge uncertainty and disagreement in cost estimates, which is caused by different assumptions and is a confirmation of the volatility of the fuel market. This is confirmed by the study of (Brynolf, Taljegard, Grahn, & Hansson, 2018), shown in Figure 14.4. This study indicates a large uncertainty range.

Table 14.4. E-fuel cost estimates (€/GJ) (Brynolf, Taljegard, Grahn, & Hansson, 2018; Lloyds Register and UMAS, 2019; Verbeek, 2020; Kranenburg, et al., 2021).

Fuel	**Source**	**2030**	**2040**	**2050**
e-methanol	Brynolf et al. (2018)	44	-	-
	Lloyds Register and UMAS (2019)	23	18	11
	Verbeek (2020)	32	-	-
	Kranenburg et al. (2021)	-	46	-
e-Diesel	Brynolf et al. (2018)	50	-	-
	Lloyds Register and UMAS (2019)	25	17	11
	Verbeek (2020)	34	-	-
	Kranenburg, et al. (2021)	-	54	-
Bio-Methanol	Brynolf et al. (2018)	-	-	-
	Lloyds Register and UMAS (2019)	21	16	12
	Verbeek (2020)	-	-	-
	Kranenburg et al. (2021)	-	20	-
Bio-Diesel	Brynolf et al. (2018)	-	-	-
	Lloyds Register and UMAS (2019)	13	10	8
	Verbeek (2020)	-	-	-
	Kranenburg et al. (2021)	-	28	-

Figure 14.4. E-fuel cost estimates (€/GJ) (Brynolf, Taljegard, Grahn, & Hansson, 2018; Lloyds Register and UMAS, 2019; Verbeek, 2020; Kranenburg, et al., 2021).



In the study of Brynolf, Taljegard, Grahn & Hansson(2108), the authors reviewed literature to analyse the factors affecting production costs of the e-fuels and collected production costs and efficiencies associated with e-fuel synthesis. Then, they established the total production cost of the e-fuels in a consistent manner. Most other studies do seem to fit in the uncertainty range provided by Brynolf, Taljegard, Grahn, & Hansson, (2018), except the study from Lloyd's Register and UMAS (Lloyds Register and UMAS, 2019), which appears to have used more positive assumptions. This last study does provide a useful trend for the development of the cost of various fuels and solidly justifies this but does not address uncertainty. All studies agree that the difference between biodiesel and bio-methanol and between e-diesel and e-methanol is only a limited percentage of the estimated cost of the fuels, in the range of 5% to 30% depending on the assumptions of the cost of sustainable electricity and feedstock, due to the lower efficiency of the production process of bio- or e-diesel. Concluding, the studies agree on a 5% to 30% increase in price from bio- or e-methanol to bio- or e-diesel and a reducing trend in the cost of sustainable fuels as production capacity and technological readiness increases.

14.3 Introduction of Three Example Naval Vessels

The impact of hydrogen, e-methanol and e-diesel is analysed on three differently sized and different types of naval vessels, that are currently considered for replacement. The vessels have different tasks, from full scale warfare to peacetime operations, different operational autonomy, from months at sea to operations of typically one single working day, different operating environments, from open ocean and coastal operations to inland shipping and ports, and very different displacements from 6000 tons to 200 tons. These typical vessels are: the Air defence and Command Frigates (ACF) of the *'Zeven Provinciën'* class, for which the replacement is currently in the study phase (Netherlands Ministry of Defence, 2022); the hydrographic survey vessels, which will be replaced in the period from 2026 to 2030 (Maat, van der, 2022); and the inland diving vessels of the *'Cerberus'* class, which will also be replaced in the period from 2026 to 2030 (Maat, van der, 2022). The evaluation of the different fuels for these various types of vessels against its diverse operations, results in development of a strategy for evaluating and selecting fuels and the associated power system for future naval vessels and a strategy to progress from current fossil fuels to biofuels and e-fuels progressively over time, while maintaining effectiveness and improving military performance.

The vessels of the *'Cerberus'* class are diving vessels that divers use as a platform for their diving operations in coastal waters, inland waters and seaports. These divers perform several tasks, such as clearing explosives, executing underwater maintenance on naval vessels and recovering wrecks from under water. As these tasks are performed in the Dutch inland and coastal waters, they typically need to perform operations that can last up to 5 days. The typical operation of these vessels consists of a transit to an operating area within the Netherlands inland or coastal waters, a diving operation while berthed or at anchor and subsequently a transit either to a next diving operation location or return to a port or the home port. The main particulars of Hydra and Nautilus, which have been enlarged in length to provide space for additional accommodation, are listed below in Table 14.5 and diving vessel *Nautilus* is illustrated in Figure 14.5.

- Displacement: 332 tons
- Length: 38 m
- Beam: 8.8 m
- Draught: 1.5 m
- Propulsion power: 560 kW (diesel mechanical – 2 propellers)
- Installed generator power: 100 kW
- Maximum speed: 10.5 knots
- Crew: 8 base crew and 22 additional crew

Table 14.5. Typical operating profile for inland diving vessels during a training week of 6 days.

Operation	Relative power in % of nominal	Average speed in kts	Operating time in %
Diving operations at anchor or berth	96	0	30
Hotel facilities (day) for maximum crew at anchor or berth	28	0	32
Hotel facilities (night) for maximum crew at anchor or berth	18	0	32
Economic cruising	210	7	3
Fast cruising	398	8.5	1
Manoeuvring	134	5	1
Slow speed sailing	98	3	1
Total operation 12MWh effective energy	56		

Figure 14.5. Diving vessels MV Nautilus, left, and MV Argus, right, (Picture NL MoD).

The hydrographic survey vessels Zr.Ms. Snellius (2003) (Figure 14.6) and Zr.Ms. Luymes (2004) perform hydrographic surveys for civil and military tasks. To perform their tasks, they have been designed to operate at sea for 210 days per year with resupply in port every two to three weeks, with an extra fuel storage capacity for refueling the vessels at sea. As the ships have a relatively low operating speed of 8 kts, their energy requirement is limited for the three-week operating schedule (Guns, 2004). Zr.Ms. Snellius is shown in Figure 14.33 and the main particulars of this hydrographic survey vessel are:

- Displacement: 1865 tons
- Length: 81.4 m
- Beam: 13.1 m
- Draught: 4.0 m
- Propulsion: 1150 kW (diesel electric – 1 propeller)
- Total installed power 1860 kW (3 generators)
- Maximum speed: 12 knots
- Crew: 23 Persons

Figure 14.6. Zr.Ms. Snellius (Picture NL MoD.)

The Air defence and Command frigates (ACF) of the *'Zeven Provinciën'* class can defend a fleet of vessels with Smart-L radar, the APAR multifunction and fire control radar, an Mk-41 vertical launch for Evolved Sea Sparrow Missile and Standard Missile 2 and goalkeeper and Oto Breda gun systems. Air defence frigates, such as the ACF, have typical autonomy requirements to operate independently at sea for 30 days or longer and a typical range of 5000 NM at 18 knots, sailing on direct geared drive diesel engines. For these types of vessels, the autonomy and the signatures, such as underwater noise and infrared, which are mainly determined by the propulsion and power system, are very important characteristics. Air defence and

Command Frigate *'Zr.Ms. Evertsen'* is shown in Figure 14.7 and its main particulars are:

- Displacement: 6050 ton
- Length: 144 m
- Beam: 17 m
- Draught: 7 m
- Propulsion:
  - 2 x 5000 kW (diesel mechanical geared) or
  - 2 x 19000 kW (gas turbine mechanical geared)
- Maximum speed: 30 knots (on gas turbines)
- Crew: 174 Persons (plus 28 staff members)

Figure 14.7. Zr.Ms. Evertsen at sea (picture NL MoD).

14.4 Impact of Fuel Choice on Ship Design

The choice of fuel significantly affects the design of a ship, particularly concerning the vessel's tank volume and deadweight as shown in Table 14.2 and covered in (Biert, van, 2020). Fuel choice influences the options for power sources (Nguyen, et al., 2021)*;* the static and dynamic behaviour of these power sources (Geertsma, Negenborn, Visser, Loonstijn, & Hopman, 2017), the subsequent choice of propulsion and electric power system architecture (Geertsma, Negenborn, Visser, & Hopman, 2017) and the required safety measures to deal with fire and explosion risk and toxicity (Inal, Zincir, & Deniz, 2022; Verhelst, Turner, Sileghem, & Vancoille, 2019). Safety can require additional systems to mitigate fire, explosion, and toxicity risks, and can influence the best positioning of the fuel storage and power sources. While the fuel choice mainly influences energy density, the power source strongly determines power density, which is of particular interest for high-speed vessels, such as frigates. The static and dynamic behaviour limit the possibilities of applying certain power sources, such as Solid Oxide Fuel Cells, for propulsion and power systems with highly dynamic load, such as electric propulsion (Biert, van, 2020). This can be resolved with selecting a hybrid power system architecture or adding energy storage, such as batteries (Geertsma, Negenborn, Visser, & Hopman, 2017).

The choice of fuel has its most significant effect on the design of a ship due to the resulting tank volume and deadweight. Diesel is the most favourable option. Based on the required mass of the fuel only, hydrogen seems a good choice, but storage of hydrogen requires significant additional construction weight and volume compared to the fuels stored as liquid under atmospheric conditions. When including the construction weight and volume of the storage system, the weight and volume increases by a factor 2.1 and 2.2 for methanol, 2.4 and 3.4 for ammonia and 3.3 and 5.3 for hydrogen, all compared to diesel. For ammonia and hydrogen additional volume might be lost as these fuels are mostly stored under pressure in cylinders, which lead to a volume loss compared to storage in a rectangular tank. The required energy carried with the ship and the required power delivered by the ships' systems, is directly linked to the required autonomy and propulsion-, mission-, and auxiliary power. This determines the suitability of a fuel for certain types of naval vessels.

14.4.1 Impact of fuel choice on inland diving vessels

The evaluation of the feasibility of alternative energy carriers considers electric propulsion with full battery electric, hydrogen fuel cell or methanol combustion engine power generation. These alternatives could be feasible as the ship often sails at low power or is anchored, and the propulsion power for transit mode is no more than 3 times the auxiliary power. In the study, the diving vessel Nautilus (Figure 14.5) was used as a baseline vessel. First, the impact of the fuel on the weight and volume of the energy storage was established based on the energy requirement of the typical operating profile of these vessels with the Ship Power and Energy Concept tool (SPEC) as introduced in Astley, Grasman, & Stroeve (2020) and used in Streng, Kana, Verbaan, Barendregt, & Hopman (2022) and Streng J. (2021). Subsequently, a high-level cost analysis was performed to compare the cost of the three options. Then, a basic design for the vessel with a hydrogen fuel cell power generation was established. The basic design was then evaluated to establish the main risks of hydrogen. In a Hazard Identification Process with stakeholders these risks were identified, and the applicable regulations and design intent that could be used to mitigate these main risks were evaluated. This Section discusses the main risks, possible mitigation, the future work to address these risks, the cost evaluation and the conclusions established from this analysis, with all quantitative aspects based on public sources.

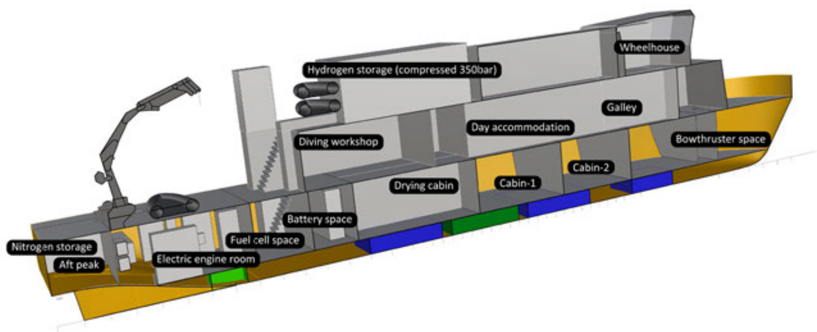
Table 14.6 shows the results of the weight, volume and cost of the stored energy and the power system power sources for the various means of energy storage. The required battery capacity for full battery electric propulsion considers a maximum depth of discharge of 80% and 20% loss of capacity over the lifetime of the battery (Tang, Roman, Dickie, Robu, & Flynn, 2020). The consequential weight and cost estimates are based on Romanovsky, Nikiforov, & Avramenko (2021). The ship weight increased by some 150 tonnes, which is half the weight of the original ship and thus considered not feasible. When using methanol, the required storage capacity easily fits in the current volume of the tanks. Therefore, methanol is considered feasible. The impact of methanol on naval vessels is discussed in the section on the impact for the seagoing support vessels. The required capacity of hydrogen can be stored in two 20 ft containers. Thus, from the high-level impact analysis, hydrogen appears potentially feasible. Therefore, a potential design for the existing inland vessels with hydrogen fuel cell power generation system was evaluated to establish whether and how a safe design could be achieved.

Table 14.6. Power system main component weights, volumes and cost for battery electric, hydrogen fuel cell electric and methanol combustion engine electric power system, based on parametric design evaluation with open-source parameters from (MARIN, 2023).

Operation		**Battery electric**	**Hydrogen Fuel cell electric**		**Methanol combustion engine electric**	
			Hydrogen	Battery	Engine	Battery
Effective energy per trip	MWh	12	12	0,45	12	0,255
Stored energy	MWh	18	32	0,7	36	0,4
Stored energy volume	m³	244	64	9	10	5
Stored energy weight	t	149	35	6	9	3
Energy weight fraction		0.31	0.09	0.02	0.03	0.01
Stored energy CAPEX	M€	11.56	0.7	0.4	0.01	0.2
Power of components	kW/t	600	600	600	600	600
Power intensity	kW/t	1.8	1.8	1.8	1.8	1.8

Operation		**Battery electric**	**Hydrogen Fuel cell electric**		**Methanol combustion engine electric**	
			Hydrogen	Battery	Engine	Battery
Power system volume	m^3	7	31	7	13	7
Power system weight	t	5	25	5	15	5
Power system CAPEX	M€	0.8	2.0	0.8	1.1	0.8
Total system volume	m^3	251	95	16	22	12
Total system weight	t	154	60	10	24	8
Total system CAPEX	M€	12.3	2.7	1.2	1.2	1.0

Figure 14.8. Side view of the Zr.Ms. Nautilus.



On the baseline concept design in Figure 14.8, a Hazard Identification process (HAZID) was performed. The key risks were primarily related to the flammability and explosivity hazards of hydrogen and secondarily to the asphyxiation hazard due to the use of nitrogen as an inerting gas and the exhaust gas of the fuel cell. In the hydrogen design of the converted diving vessel, the design intent was to limit the risks for personnel by positioning the hydrogen storage in exchangeable containers on the upper deck, like previous projects in the Netherlands such as MV Antonie and the inland containerships of Future Proof Shipping. This led to a safety zone within the container, within the double walled hydrogen piping and within the fuel cell, which are designed to contain potential leakage within its cabinet.

All risks of leakage outside these areas should be mitigated by hydrogen sensors, fast cut-off valves, ATEX certified equipment to prevent explosion initiation and sufficient ventilation to prevent explosion levels in the fuel cell space and the trunks leading to the fuel cell space. The fast cut-off valves limit the quantity of hydrogen in the fuel cell space as the storage is on the upper deck. The risk of hydrogen leakage can be retained to a minimum by applying double-walled piping and an intrinsically safe fuel cell. In case of leakage, the ship can return to port on battery power. The exhaust in the chimneys is used both for the fuel cell exhaust, which is dangerously depleted of oxygen, and for the emergency venting of the hydrogen, for example in the case of fire. This leads to a safety zone 1 with a 6 m radius around the venting mast according to the IGF-code and safety zone 2 that extends 4 m beyond zone 1. With this design and associated safety measures a safe design can be achieved, while exact sizing of safety zones and ventilation requirements for the machinery spaces should be further investigated to subsequently improve design guidelines from the used regulations such as ESTRIN 2021 (CESNI, 2021/1), ABS guidance notes on risk assessment (ABS, 2020), the IMO IGF-code (International Maritime Organisation, 2015) and DNV rules, part 6 Additional class notations (DNV, Edition July 2020).

14.4.2 Impact of fuel choice on seagoing support vessel

The feasibility study into methanol as an alternative energy source than diesel considered electric propulsion with methanol combustion engine power generation. In the study, the hydrographic survey vessel Zr.Ms. Snellius (Figure 14.6) was used as a baseline vessel. First, a basic design for the vessel with electrical propulsion and methanol combustion engine power generation was established. The basic design was then evaluated to establish the main risks of methanol as a fuel. In a Hazard Identification Process with stakeholders these risks were identified, and the applicable regulations and design intent that could be used to mitigate these main risks were evaluated. Subsequently, a high-level cost analysis was performed to compare the cost of the three options. This Section discusses the main risks, the possible mitigation, the future work to address these risks, the cost evaluation and the conclusion established from this analysis, with all quantitative aspects based on public sources.

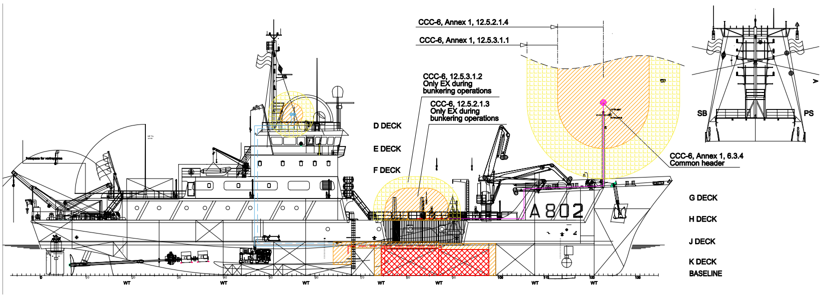
Within the Green Maritime Methanol (GMM2.0) project the Defence Materiel Organisation (DMO – now COMMIT) studied the impact that use of methanol would have on the existing ship (Alkemade & Astley, 2020). The study identifies three hazardous zone types (Hulsbosch-Dam & Deul, 2022).

- Zone 1: “area in which an explosive gas atmosphere is likely to occur occasionally in normal operation”.
- Zone 2: “area in which an explosive gas atmosphere is not likely (less than 10 hours per year) to occur in normal operation, but, if it does occur, will exist for a short period only”.
- Zone 3: “area in which an explosive gas atmosphere will not occur in normal operation”.

Methanol tanks are considered zone 1, and the area immediately outside a methanol tank is considered zone 2. To avoid identification of accommodation spaces or engine rooms as zone 2, a cofferdam is required between methanol tanks and engine rooms or accommodation spaces. Small tanks could be double walled with the same purpose. This is different from conventional diesel tanks, which usually do not have cofferdams when adjacent to engine rooms or accommodation spaces. Instead, sufficient insulation to contain a fire for more than 60 minutes is considered sufficient. For the same reason – limitation of zone 2 areas – double walled piping is applied for transportation of methanol within the ship. This has some consequences for required space, but this is limited.

Figure 14.9 shows the side view of the general arrangement plan of the Snellius, adapted for methanol. The energy capacity of the fuel tanks was reduced by 60% compared to diesel tanks, which was acceptable as the refueling capability of the ship was skipped. Thus, the energy weight fraction of the original vessel of 0.05 was reduced to 0.04 instead of increased to 0.11, for a vessel with a power intensity of 1 kW/t. Moreover, a safety area around venting pipes of 3 metres is to be kept free around venting pipes, and around bunkering stations during bunkering. Around this area a zone of 2 metres is reserved, where dangerous concentrations of methanol are not likely, but possible during short periods.

Figure 14.9. Side view of the Zr.Ms. Snellius – with methanol tanks. CCC-6 referring to legislation of the IMO subcommittee on carriage of cargoes and containers, adopted on its 6th session in September 2019.



On a relatively large vessel like the Snellius these extra space requirements are inconvenient, but do not require very large adaptations to the vessel. For small vessels these additional space requirements have a significant impact on ship design, and adaptation of existing vessels is severely hampered. Future work should thus be focused on limiting the technical impact of the safety measures, by considering alternative solutions for fire ingress and leakage to cofferdams, and investigating alternative venting solutions, such as venting under the waterline.

14.4.3 Impact of fuel choice on future frigates

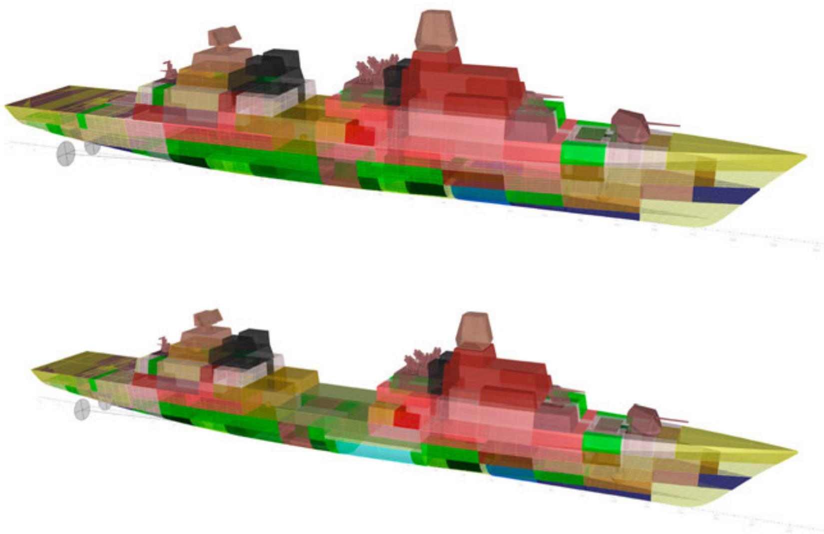
The impact of fuel choice on future frigates has recently been studied with three different approaches, using a parametric design (Streng, Kana, Verbaan, Barendregt, & Hopman, 2022), using a fixed hull design with varying draft (Pawling, Bucknall, & Greig, 2022) and using a fixed design that is lengthened (Pothaar, Geertsma, & Reurings, 2022). Streng et al. (2022) use a parametric design approach with the Ship Power and Energy Concept tool (SPEC) as introduced in Astley, Grasman, & Stroeve (2020). This assumes the ship is resized maintaining its hull form with increasing displacement, thus leading to increasing ship resistance. Pawling et al. (2022) use an approach that includes a high-level zonal layout design. Within certain displacement limits the hull form does not change and additional space for energy storage leads to an increased draft. Finally, Pothaar et al. (2022) use an approach that maintains the hull form but lengthens the hull when additional volume for energy storage is required. The advantage of this approach is that the resistance does not increase considerably, but the lengthening does have a limitation for damage stability and manoeuvrability. These three different approaches lead to different impacts of methanol as a fuel compared to diesel, as the impact additional displacement has on ship resistance is different, as shown in Table 14.7.

Table 14.7. Impact of methanol as a fuel compared to diesel for frigate design with parametric design approach (Streng, Kana, Verbaan, Barendregt, & Hopman, 2022) for frigate with combined diesel or gas turbine propulsion plant (CODOG), fixed hull design with varying draft approach (Pawling, Bucknall, & Greig, 2022) for frigate with combined diesel electric and diesel propulsion plant (CODLAD) and fixed hull shape with varying ship length approach (Pothaar, Geertsma, & Reurings, 2022) for frigate with combined diesel electric or gas turbine (CODLOG) and combined diesel and diesel (CODAD) propulsion plants.

Design approach	**Displacement baseline**	**Fuel weight fraction baseline**	**Propulsion layout and power**	**Displacement methanol**	**Relative increase**	**Fuel weight fraction methanol**
Parametric design	6050 t	0.100	CODOG 6.2 kW/t	9600 t	0.58	0.23
Fixed hull design with varying draft	3862 t	0.104	CODLAD 8.5 kW/t	4817 t	0.247	0.248
Fixed hull shape with varying ship length	6050 t	0.092	CODLOG 6.0 kW/t	6936 t	0.146	0.147
Fixed hull shape with varying ship length	6420 t	0.085	CODAD 6.0 kW/t	7267 t	0.135	0.135

Figure 14.10 shows a 3-D plot of a study into a notional Future Air Defence and Command Frigate (FUADEF) performed by Pothaar (2023). The upper plot shows the original configuration of the FUADEF, whilst the lower plot gives an impression of the required overall dimensions of the vessel to accommodate for the additional fuel volume when using methanol, in light blue, as its only energy carrier, by lengthening the design. Based on this study, the conclusion was that, although technically possible, use of methanol as an energy carrier would lead to either halving the range, or an extension of the tank volume to around 900 m^3 (Pothaar, Geertsma, & Reurings, Energy transition for the replacement Air Defense and Command Frigate, 2022). This volume increase would in turn also lead to an increase of 20 metres in ship length and 900 tonne displacement, marginal damage stability and a single point of failure with one tank location, while splitting would require additional cofferdams and thus ship length. Also, at this moment, there are no gas turbines available running on methanol. As a compromise, the Navy could consider a dual fuel option. In peace time, the Navy could run on methanol with limited autonomy and use (bio-)diesel in war time, which would significantly reduce the impact of methanol and enable alternative engine combustion strategies, such as RCCI, which could lead to reduced noise, emission, and signatures.

Figure 14.10. 3-D render plot of the baseline concept design (top) for a study into Future Air Defence and Command Frigate and the impact of methanol as a fuel (bottom). (Pothaar, Assessing the impact of sustainable fuels for large surface combatants, 2023).



The differences between the impact of methanol as a fuel with the three different design approaches demonstrate that the impact is very much determined by specific choices in the ship design approach and that more detailed design studies are required to establish the true impact. All studies confirm that the impact of the choice for methanol as a fuel has huge implications on the ship size or range. Three different approaches should therefore be considered as well. First, we could consider fuels that are a trade-off between ease of sustainable production and energy density, such as butanol, as evaluated in Streng, Kana, Verbaan, Barendregt, & Hopman (2022). Secondly, the ship could be designed with a fuel flexible approach, which allows operation on fuels that can be more efficiently produced in peacetime, such as methanol, and a switch to operation on energy dense fuels such as e-diesel in wartime. This fuel flexible approach could also be used to increase engine efficiency and reduce emissions and signature by using advanced combustion strategies and a combination of low and high reactivity fuels. Finally, when fuel cell technology becomes mature and its cost reduces due to increased scale of production, hybrid power system architectures utilising a combination of fuel cells and combustion engines can be used, which can also contribute to reduced emissions and signatures (Sapra, et al., 2021). Continued investigations are required to follow developments and establish the moment when the benefits of alternative fuels and power sources on efficiency, emissions and signatures outweigh the increased risk and cost for future frigates.

14.4.4 Future fuels strategy

This work reviewed the impact of energy storage and alternative fuels such as hydrogen, methanol, and bio- or e-diesel based on three case studies. The maritime industry's transition towards sustainable and clean energy solutions has been gaining significant momentum. A strategic shift from conventional fossil fuels to biofuels and ultimately to e-fuels is gradually occurring. This progression is driven by the impact of alternative fuels on vessel autonomy, environmental implications, as well as economic and logistical considerations. The autonomy of a vessel, especially those operating over extended distances or periods, is greatly influenced by the energy density of the chosen fuel. Long-chain fossil fuels like F-76 diesel offer high energy density, providing extended autonomy but also releasing significant carbon emissions. A feasible strategy for reducing emissions while maintaining vessel autonomy is the progressive introduction of biofuels. These fuels can replace a growing portion of fossil fuels over time without requiring major alterations to existing infrastructure (Doss, Ramos, & Atkins, 2009). It is crucial to establish a strategic alliance at an international level to support the transition to cleaner fuels. Organisations such as NATO can play a key role in fostering the development of production facilities for alternative fuels, improving logistics for distribution, and promoting the end-use of these fuels in naval operations.

The main limitations of batteries are the limited energy density and high initial purchase cost for its energy storage capacity. The analysis and results have shown that batteries can provide a zero-emission propulsion and power generation, but only for a very limited time. Typical examples are operations up to a few hours, such as entering a port or loitering, and operations up to one day for low power applications, such as diving vessels. Extending the operational range of battery-powered vessels will be a key focus for research and development. This will involve improving the energy density and efficiency of batteries, but also managing heat development and mitigating the risk of thermal runaway of lithium-ion batteries and its propagation from cell-to-cell, or the development of more energy dense battery chemistries that are inherently safe for thermal runaway. As the capability of methanol engines to deal with dynamic loads might be low due to knock and misfire limits, batteries can also be used for load levelling. In high-end warfare vessels, such as future air defence frigates, battery energy storage could be used to provide a very silent and zero-emission operating mode for a short period of time, provide fault ride through during failures of generators while reconfiguring the electrical distribution and for load levelling. Therefore, the main opportunity for battery application in naval vessels is in hybrid power supply, for which further development of advanced control concepts is required to realise these opportunities.

The two main limitations of hydrogen are its limited energy density and the high risk due to its explosivity and flammability. To mitigate the risk of harm to personnel in manned vessels, hydrogen is best stored high in the superstructure of a vessel, at a location where no personnel is regularly performing work. Alternatively, it can be stored in a well-protected space inside the vessel, with sufficient ventilation to prevent explosive mixtures and with ventilation exits at the highest point in the space due to the low density of hydrogen. This would enable safe and feasible application of hydrogen on support vessels with sufficient space in the superstructure, such as the diving vessels. However, for most naval vessels the superstructure is the most valuable space for mission systems, either for sensor, weapon, and communication equipment on high end warfare vessels, such as frigates, or for cranes, boats, easily accessible storage, for example with containers, and deck handling equipment on seagoing support vessels. Also, for naval vessels the ventilation requirements to prevent explosive hydrogen mixtures when stored low in the vessels, would require significant additional volume, on top of the already poor energy density of hydrogen compared to methanol. Moreover, both the cost of the fuel cells, its storage and distribution system and the cost and limited availability of green hydrogen currently means that other alternative fuels, such as sustainably produced methanol and diesel, can provide a larger impact on reducing fossil fuel dependency and well-to-wake greenhouse gas emissions at lower cost. Therefore, hydrogen in the short term is mainly applicable to small unmanned assets that have sufficient space for its fuel, such as unmanned drones and possibly unmanned surface vehicles or submarines. When used in combination with fuel cells, hydrogen has the added benefit of no emissions and reduced noise and infrared signatures.

Sustainably produced methanol is fluid at ambient conditions, which enables easier handling. Methanol can be produced from various non-food biomass and can lead to an 83% to 89% greenhouse gas emissions saving when produced from biomass feedback (European Parliament, 2018) and 100% when produced from sustainable electricity and captured CO_2. The use of methanol directly leads to a reduction of the autonomy of 62% for the same tank volume. For ships with a limited autonomy or sufficient volume in the vessels, such as support vessels and the hydrographic survey vessels, this impact is limited. On small ships, the required additional space for cofferdams may be problematic for ship design. Therefore, further research is required in establishing an alternative safety barrier between tanks and machinery or accommodation spaces against leakage and heat ingress during fires, that requires less space than cofferdams.

The extra safety requirements due to the toxicity and flammability of methanol lead to extra safety considerations of hazardous areas in the ship and therefore extra safety systems with consequential additional cost. Methanol storage has more restrictions than diesel. In between a methanol storage tank and an engine room or crew accommodation spaces, cofferdams are required. For naval vessels with a high autonomy requirement, the use of methanol as a fuel leads to a significant increase in the size and thus cost of the vessel. Depending on the design approach this leads to displacement increases from 20% to 25%. An approach in which the ship sails on methanol in peacetime and during training and uses sustainably produced diesel in warfare operations deserves further research. This might also allow the possibility to improve noise and infrared signatures with advanced combustion strategies such as Reactivity Controlled Compression Ignition (RCCI). The impact on the design, when considering survivability, the impact of the additionally required cofferdams and safety systems and the limitations in using the same tanks for methanol and diesel, due to poor miscibility, require further research to establish the feasibility of this fuel flexible approach for high end naval vessels.

Ammonia seems a feasible option at first sight. The energy density is slightly higher than methanol and synthetic production of ammonia will have a slightly higher efficiency than that of methanol. Ammonia is highly toxic and is a gas under atmospheric conditions. Storage should be done under pressure or at low temperatures. Due to its toxicity, it cannot be stored in tanks directly at the outer hull of a ship. Therefore, for naval purposes, ammonia is not considered a feasible option at this moment.

For high end warfare vessels with a conventional crew size, the autonomy requirement and the need for refuelling from all NATO partners' tankers drives the need for a drop-in replacement for Marine Diesel Oil (MDO) according to F-76 or similar specifications. In the short term, this can be achieved by mixing biofuel with fossil F-76. DNV expects that 11 million tonnes of oil equivalent (Mtoe) will be produced worldwide, and that this worldwide production can grow gradually to between 500 and 1200 Mtoe in 2050 (Sekkesaeter, Ovrum, Horschig, Henriksen, & Heggen, 2023). To prevent damage to equipment or loss of power, it is important to evaluate the suitability of biofuels as a drop-in for fossil diesel, as this strongly depends on the feedstock and production process and experience from long-lasting trials is still lacking. As naval vessels often refuel from various sources, such as NATO replenishment vessels, it is necessary to perform this evaluation in the international NATO context. The most promising current biofuel in this regard is Hydrotreated Vegetable Oil (HVO) due to its high oxidation and storage stability. This fuel has a limited feedstock and production growth. In the longer term, production through gasification and Fisher Tropsch synthesis can lead to higher quantities of biodiesel (Sekkesaeter, Ovrum, Horschig, Henriksen, & Heggen, 2023). Biofuel production is expected to be insufficient to meet the full demand of the maritime sector due to competition for biofuel with other transportation sectors. Therefore, in the long run, synthetic production of fuel is required. Sustainable synthetic fuel is produced based on sustainably produced hydrogen and captured CO_2. To achieve this reduction of dependence on fossil fuels, collaboration is required in NATO to develop a NATO-wide strategy for the development of production facilities, logistics and end-use of fuel.

14.5 Conclusions and Recommendations

The selection of fuel type for naval ships is dictated by a confluence of factors including operational requirements, autonomy, safety, logistical support, and environmental impact. Biofuels and e-fuels, such as biodiesel, e-diesel, methanol and hydrogen, have emerged as viable alternatives to traditional fossil fuels.

While hydrogen is feasible for vessels such as diving vessels, the cost of the power system and sustainable produced hydrogen currently prevents its introduction on large vessels. For smaller assets and potential future autonomous vessels, hydrogen is a compelling choice. Hydrogen fuel cells can produce electricity efficiently and emit only water, making them a clean energy source with no noise and signatures, supporting undetected operations. The storage and handling of hydrogen present unique challenges due to its low energy density per unit volume and flammability. These challenges could potentially be mitigated with the development of onboard hydrogen production systems, utilising water electrolysis powered by a mother-ships power system. Such systems could offer enhanced autonomy for unmanned assets operating from mother vessels.

Methanol presents a promising option for naval vessels with a limited operating autonomy and lower threat operating environment. Given its relatively high energy density and ease of handling, methanol can support naval operations with limited power demands for weeks at sea. Furthermore, the production of methanol could be made carbon-neutral if generated from renewable energy sources, making it an environmentally sound choice for support vessels, such as the investigated survey vessels and diving vessels.

For future high-end warfare naval vessels, the range limitations of methanol and the international logistics prevent the use of alternative fuels such as methanol in the short to medium term. With the evolving landscape of maritime propulsion and a shift towards sustainable fuel sources, it becomes vital for international organisations like NATO to develop a comprehensive strategy for the adoption of sustainable drop-in alternatives for F-76 Marine Diesel Oil. As for infrastructure and Logistics, NATO could foster the establishment and expansion of production facilities for biofuels and e-fuels, streamline distribution logistics, and encourage their use in naval operations. NATO could also play a vital role in promoting collaboration among its member countries to share best practices and invest in innovative solutions for efficient and safe use of alternative fuels in naval operations.

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