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Energy transition for the replacement Air Defense and Command Frigate

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Synopsis

Progressing targets on Greenhouse Gas (GHG) emission reduction urge the Netherlands Ministry of Defense (NL MoD) to reduce GHG emissions, without sacrificing striking power. The Royal Netherlands Navy (RNLN) is investigating the replacement of the Air Defense and Command Frigate (*LCF*) between 2030 and 2040 by a Large Surface Combatant. As it will be impossible to achieve substantial reduction of GHG emissions through energy-saving technologies, sustainable fuels need to be implemented in the design. In this paper, a literature review is presented to establish possible directions for the strategy to migrate future naval combatants from current fossil fuels to future sustainable fuels. We examined the effect of short- and long-carbon chain sustainable fuels, sustainable methanol and sustainable diesel, respectively, on the replacement Large Surface Combatant; specifically their advantages, disadvantages, production routes, future production cost estimates and availability to give an understanding which pathways can help the NL MoD to achieve their stated GHG emissions reduction goals. Moreover, we present three different design concepts with respect to fuel composition and propulsion configuration on which the impact of the established fuels is qualitatively examined. Firstly, operating on methanol has a significant impact on the design of a large surface combatant: the endurance of the ship is more than halved or the tank capacity has to be increased by 700 to 900 m^3; the ship might need a longer machinery space to allow for more propulsion engines to compensate for the increased power requirement and unavailability of gas turbines on methanol; and required auxiliary and safety systems add further volume area to the engine room. Secondly, sustainable diesel is a drop-in fuel, which makes blending of sustainable diesel with fossil diesel possible in the existing infrastructure allowing a gradual transfer from fossil diesel to sustainable diesel. However, the production is less efficient in a well-to-wake approach and the cost of Bio-diesel and E-diesel is 5% to 30% more expensive with a mean estimated additional cost of 6 €/GJ compared to methanol. Finally, navies could consider a two-fuel strategy: sail on methanol during operations with limited autonomy, typically in peace time, and operate on diesel during operations with high autonomy, during war time operations. In this case the design needs to include both diesel and methanol fuel systems and additional space for methanol safety measures. To more exactly quantify the impact of methanol on the design, a concept design iteration is required, which is identified as research for future work.

Keywords: Methanol; Sustainable diesel, Future Air Defence Frigate, Large Surface Combatant, FuAD, AWWF

1 Introduction

The most recent estimates in the Fourth International Maritime Organization (IMO) Greenhouse Gas (GHG) Study 2020 show that GHG emissions of shipping have increased by 9.6% between 2012 and 2018 (IMO, 2021), while the IMO strives to reduce CO_2 emissions by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008 (IMO, 2018). At the same time, the Netherlands Ministry of Defense (NL MoD) strongly depends on energy, and the access to energy is crucial for the Royal Netherlands Navy (RNLN) to perform its operations at sea. Currently, this energy requirement is mainly met by fossil fuels. That should change, as the MoD announced to contribute to the Paris agreement by reducing its dependency on fossil fuels by at least 20% by the year 2030 and 70% by the year 2050, compared to 2010, in its Operational Energy Strategy (OES) (Netherlands MoD, 2015; Bijleveld-Schouten and Visser, 2019). Whilst further improvements of power and propulsion systems can significantly contribute to the reduction of GHG emissions (Roskilly et al., 2015), it will be impossible to achieve the 2050 IMO's and MoD's ambitions just through energy-saving technologies (IMO, 2021). Therefore, under all projected scenarios, a large share of the total amount of GHG emission reduction and use of fossil fuels will have to come from the use of sustainable fuels (Lloyd's Register and UMAS, 2019b; DNV GL, 2019).

Authors' Biographies

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Cdr (E) Rinze Geertsma currently is assistant professor at the Netherlands Defence Academy and guest researcher at Delft University of Technology with a research interest in sustainable and maintainable energy systems for ships. He previously has been Marine Engineering Officer of *HNLMS de Ruyter* and *HNLMS Tromp*. Earlier experience include system and project engineering and innovation roles.

Lt Cdr (E) Jeroen Reurings is currently working as a propulsion systems engineer for the Maritime department of the Defence Materiel Organisation. Earlier experience includes Deputy Marine Engineering Officer on board of *HNLMS Rotterdam* and *HNLMS De Zeven Provicien* and sr. instructor for *Seatraining Command* and *Royal NL Navy Tech School*.

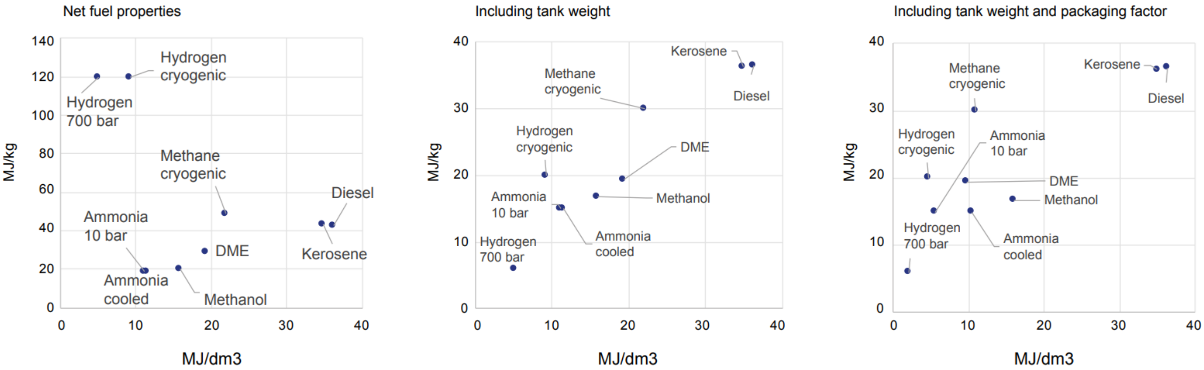

Figure 1: Energy density and specific energy of fuels with and without the tank weight and volume Van Kranenburg et al. (2020)

In the recent Defence whitepaper, the NL MoD has confirmed the replacement of its Air Defense and Command Frigates (LCF), *De Zeven Provinciën* class frigates, between 2030 and 2040 (Netherlands Ministry of Defense, 2022; Ministerie van Defensie, 2021). One of the most likely options for this replacement is a Large Surface Combatant (Ministerie van Defensie, 2021), which should be designed to operate at the high end of the violence spectrum NATO (2004). Therefore, the operational requirements are of the highest level and should be able to deal with developing Air Defence capabilities, such as hyper-sonic missiles, swarm threats and the high energy demand of modern weapon systems. Moreover, limiting the susceptibility to these threats is most important. Therefore, both the Radar and Infrared Signatures, and thus ship size and power need to be minimised. The planned lifespan of the future surface combatant is expected to be 30 years. Consequently, the IMO initial strategy and the OES must be taken into account.

The main pathways to reach IMO's low carbon-shipping goals are: (1) battery-electric propulsion with sustainable electricity , (2) zero carbon fuels like sustainable hydrogen or ammonia , (3) sustainable E-fuels or Bio-fuels, or (4) sails and wind. Despite the accumulation of literature, there is a lack of guidance on which pathway is suitable for different shipping segments, although literature agrees that the required range and autonomy are key drivers (van Biert et al., 2016). Especially for a Large Surface Combatant, with typical autonomy requirements of 30 days at sea, a range of 5000NM at 18kn and maximum speed of 29kn, energy density, specific energy, fuel weight and volume are particularly important factors in the design, as ship volume and displacement are decisive design parameters for its size, cost and signatures. With a typical fuel capacity of 600 m^3 or 530 *tonne* for a Large Surface Combatant, replacing diesel oil with lower density hydrogen or methanol fuels directly adds 1200 or 600 *tonne* displacement, respectively, as shown in Figure 1 (Van Kranenburg et al., 2020). For low density power sources, such as sails, batteries, hydrogen and ammonia, this would lead to increased ship displacement, propulsion power requirement, increased signatures, and unaffordable cost increase. To limit the size and power increase of the vessel to acceptable proportions, the most energy dense alternative fuels that can be produced sustainably are considered: methanol and sustainable diesel.

1.1 Aim and contribution

The aim of this paper is to establish an overview of the qualitative impact of the choice of alternative carbon based fuels for future naval vessels on the size, displacement, propulsion power, machinery space layout, fuel consumption, well-to-wake emissions and ultimately procurement and life cycle cost from literature. Thus, the work examines the effect of short- and long-carbon chain sustainable fuels, sustainable methanol and sustainable diesel, respectively, on the replacement Large Surface Combatant; specifically, it examines their advantages, disadvantages and production routes to give an understanding which pathways can help achieve the IMO and NL MoD sustainability goals. To assess the feasibility of the proposed fuel, we compare future production cost estimates and availability. Moreover, the impact on the design of establishing the fuels will be examined including the effect of difference in energy density; the possibilities in the power and propulsion plant concepts and related characteristics; and the impact on auxiliary systems, such as the fuel system. Finally, we present the impact for three different design concepts with respect to fuel composition: In concept one the vessels always uses sustainable diesel, in concept two the vessel always sails on sustainable methanol with the same autonomy and range, and in concept three the vessel sails on methanol in peacetime operations with a reduced autonomy and range, but sails on sustainable diesel during actual operations that require the typical autonomy of 30 days at sea with a range of 5000NM, as visualised in a schematic shown in Figure 2.

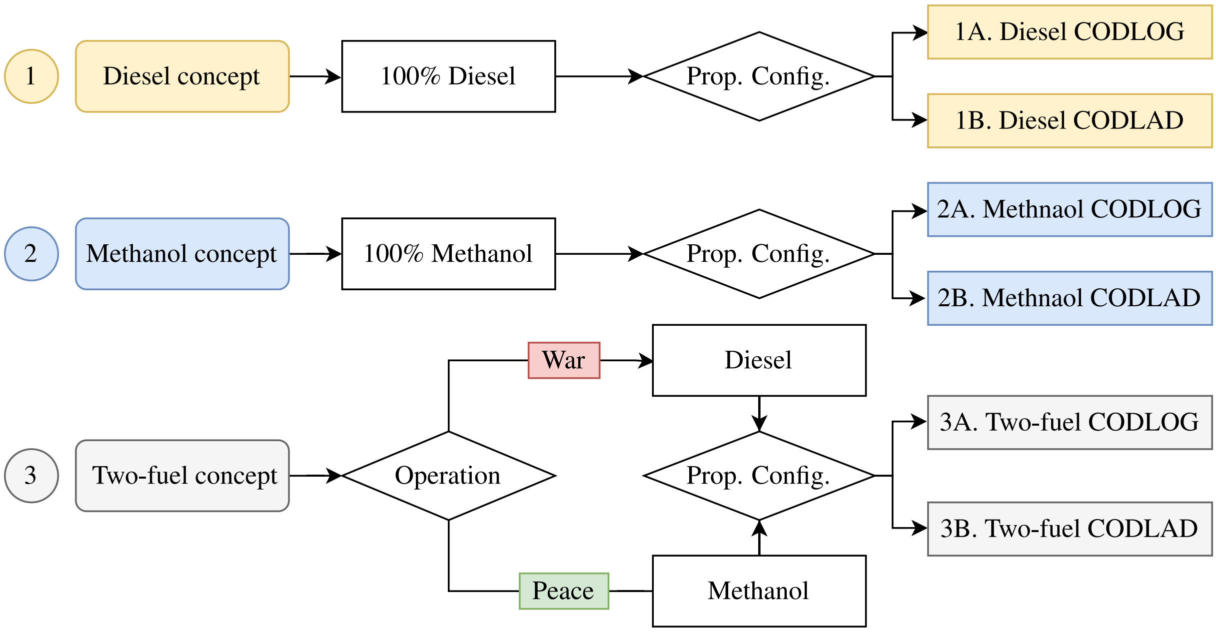

Figure 2: Design concepts

2 Fuels

For the Large Surface Combatant, short- and long-carbon chain alternative fuels, methanol and diesel, will be considered in this work. This section aims to provide an overview on methanol and diesel, and examines their advantages and disadvantages. Table 1 provides the chemical properties of marine diesel oil (F-76) and methanol.

Table 1: Fuel properties F-76 and Methanol

Parameter	**F-76**	**Methanol**	**Unit**
Lower heating value	42.8	19.9	[$MJkg^{-1}$]
Lower heating value	36.6	15.8	[$MJdm^{-3}$]
Hydrogen content	13.1	12.5	[wt.%]
Carbon content	86.6	37.5	[wt.%]
Sulfur content	0.05	0	[wt.%]
Oxygen content	0	50	[wt.%]
Density	847.4	790	[kgm^{-3}]
Flash point	69.65	11.15	[C°]
Boiling temperature	463.15-553.15	64.85	[C°]
Autoignition temperature	254.15	464.15	[C°]

2.1 Methanol

Methanol, a widely available and traded product, is seen as one of the favored contenders to decarbonise the shipping industry (Ellis and Tanneberger, 2015; Andersson and Márquez, 2015). Methanol does not have cryogenic complexity and is in liquid phase at room temperature and ambient pressure and is easier to handle than gaseous fuels such as hydrogen and ammonia (International Renewable Energy Agency and Methanol Institute, 2021). This offers the possibility to store methanol in almost any tank shape (Skov, 2015), which means no additional ship volume is lost due to inefficient tank designs. Since the methanol infrastructure for the chemical industry worldwide is already there and available in more than hundred ports globally (Ellis and Tanneberger, 2015; DNV, 2021), minimal modifications are needed to provide methanol as a fuel, in particular in comparison to the implementation of gaseous alternative fuels (Andersson and Márquez, 2015). In the early stages of implementation, truck-to-ship bunkering would be a feasible method (Van Lieshout et al., 2020).

Methanol has the highest hydrogen-to-carbon ratio of any liquid fuel. This relationship can already reduce tank-to-wake (TTW) emissions by up to 10% compared to diesel. Furthermore, methanol combusts cleanly in primarily CO2 and water, and combustion produces fewer air pollutants compared to the combustion of diesel. Due to a lower peak cylinder temperature, there is typically 60% less NO_x formation during combustion. Since methanol contains zero sulphur and has no carbon- to carbon-bonds, it emits 99% less SOX and 95-99% less particulate matter, depending on the combustion principle (Balcombe et al., 2019). In the event of a spill, it is less hazardous to the environment than heavy fuel oil or diesel, since it biodegrades rapidly in water (DNV GL, 2016). These characteristics make methanol a potential replacement to meet the policy requirements set by the IMO.

2.2 Diesel

Diesel is traditionally manufactured by refining fossil crude oil. However, nowadays sustainable diesel can be and is produced via several other alternative and sustainable production pathways, such as Fatty Acid Methyl Esters (FAME) from vegetable oils, Hydrotreated Vegatable Oil (HVO), which can also be produced from waste oil, and Fischer-Tropsch (FT) diesel, which can be produced from various bio-feedstocks or renewable electricity and captured CO_2 (Andersson et al., 2020). Sustainable diesel is attractive for a number of reasons. Most importantly, many of the sustainable diesel variants, HVO and FT-diesel for example, are backward-compatible with existing ships, distribution and infrastructure (Brynolf et al., 2022). Therefore, fossil diesel can be phased out step-by-step by blending sustainable diesel while leveraging on the existing fuel supply chain infrastructure and the well developed internal combustion engines (Zang et al., 2021). However, the additional production effort of sustainable diesel leads to a lower well-to-wake efficiency of sustainable diesel over methanol (Brynolf et al., 2022), which justifies investigating the trade-off.

3 Production and cost of sustainable fuels

3.1 Production process

The main two reasons to implement sustainable fuels are to reduce the environmental impact and dependency on fossil fuels. It is important to not just consider the impact during combustion of sustainable fuels, as they emit GHG in the same amount as conventionally produced fuels. Instead, the entire life cycle, in the shipping industry often referred to as well-to-wake (WTW), should be considered, as for sustainable hydrocarbons the difference is made in the production process. Therefore, it is essential to distinguish the different production pathways, their energy usage and efficiencies to be able to assess their viability.

In this paper, we consider diesel and methanol as sustainable when produced from sustainable feedstock, which can be a combination of sustainably obtained biomass, renewable electricity and captured CO_2. Sustainable methanol and diesel can be categorised in two production pathways: Bio-fuels and E-fuels, as shown in Figure 3. For Bio-fuels, that use biomass as the only feedstock, the prefix "Bio-" is used. For E-fuels, that combine captured CO_2 with H_2, the prefix "E-" is given.

Bio-fuels can be produced through various production processes. The process depends on the desired fuel and the available biomass. Organic waste from food processing or crops is typically used for anaerobic processes such as fermentation or digestion, resulting in ethanol and Bio-gas (consisting mainly of CH_4 and CO_2), respectively. Lignocellulose feedstocks are considered suitable for gasification. This is a process that converts biomass by reacting it endothermically without combustion to synthesis gas, consisting of H_2, CO, CO_2, H_2O and CH_4. If desirable, the resulting products, ethanol, methane and synthesis gas, can be further synthesised into other fuels. Vegetable oils are commonly used to produce FAME Bio-diesel and HVO Bio-diesel through transesterification and catalytic hydroprocessing, 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 and Zhang (2011) estimated the biomass-to-fuel efficiency for Bio-methanol around 54% and around 51% for Bio-diesel, by dividing the energy in the resulting fuel and the energy content in the biomass, without significant inputs or outputs of other energy.

Methanol synthesis can be achieved in a one or two step hydrogenation, during which synthesis gas consisting mainly of CO or CO_2 and H_2 is processed to generate methanol. Synthesis gas can be obtained by gasification of biomass or via combination of CO_2 and H_2. The composition CO:H_2 ratio of the synthesis gas can be tuned via the water-gas shift reaction. To increase the ratio, CO_2 can be added or reduced by adding more or less steam to the reactor. If desirable, methanol can further react to produce diesel. The reported synthesis efficiency of hydrogen to methanol varies between 69%-89% (Brynolf et al., 2018; Lester et al., 2020) and the overall production efficiency between 41%-72% Grahn et al. (2022).

Diesel can be produced either with synthesis gas from biomass or with captured CO_2 and hydrogen via Fischer-Tropsch synthesis, during which synthesis gas reacts to form synthetic crude. The chain growth of the synthetic crude depends on the catalysts used in the Fischer-Tropsch synthesis and the syngas stoichiometry, as well as temperature and reactor pressure. The reported efficiency of the Fischer-Tropsch synthesis at process-level ranges

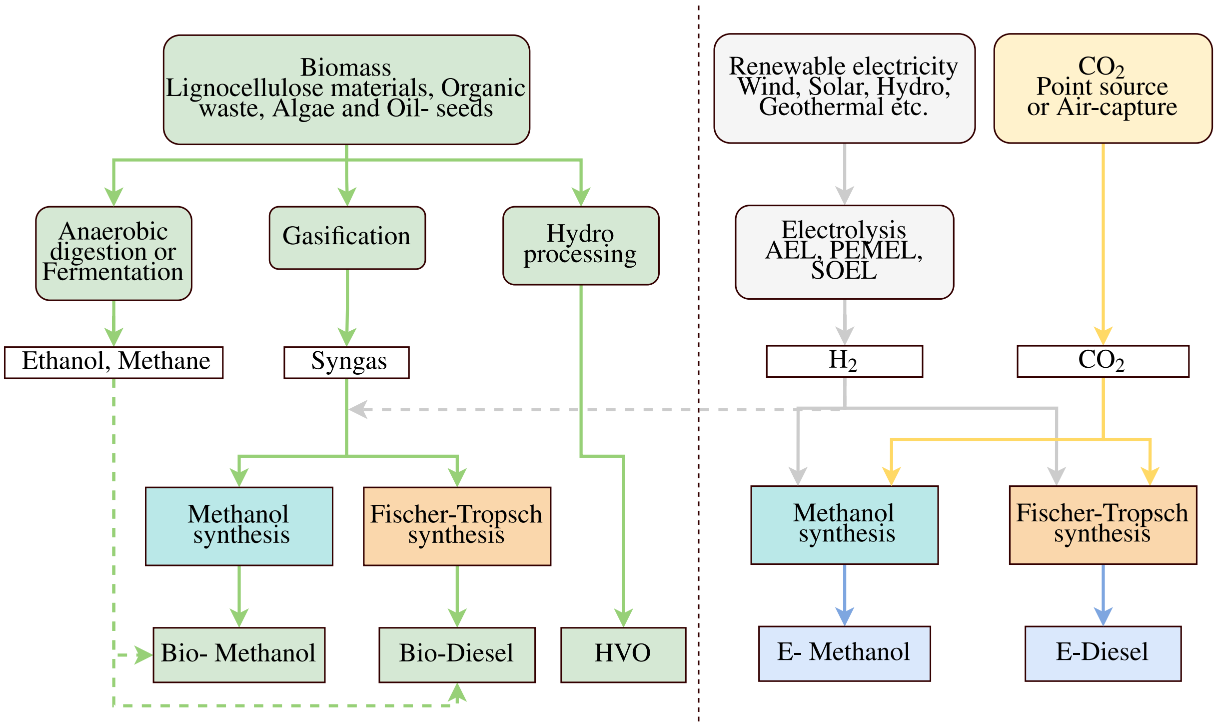

Figure 3: Simplified overview of the fuel production pathways

between 59%-78% (Blanco et al., 2018; Hänggi et al., 2019; Lester et al., 2020). And the overall production efficiency between 37%-64% Grahn et al. (2022).

Renewable CO_2 can come from Direct Air Capture (DAC), Point Source Carbon Capture (PSCC) or biomass. DAC is an energy intensive process and is not yet available on industrial scale. CO_2 from biomass is widely available and more affordable (Daniel et al., 2022). However, biomass alone can not supply sufficient CO_2 in the future for large scale production of carbon based E-fuels. Currently, CO_2 from biomass can be supplemented by PSCC, as long as significant CO_2 emission from industry is available. In the long term however, CO_2 from industry will become less. For example, the sustainable pathway for iron and steel industry could be CO_2 free. Therefore, upscaling of DAC will most likely be required. With different studies carried out on DAC developments, the range of cost estimations is wide and strongly depends on the energy price. However, DAC is expected to become more cost efficient in the future (Fasihi et al., 2019).

For the production of H_2 there are three leading technologies: Alkaline Electrolysis (AEL), Polymer Electrolyte Membrane Electrolysis (PEMEL), and Solid Oxide Electrolysis (SOEL). Electrolysis uses electricity to separate water into hydrogen and oxygen by current between two electrodes that are separated and immersed in an electrolyte to raise ionic conductivity. The efficiency of these electrolysis methods ranges between 63-71% for AEL, 58-71% for PEMEL and 75-83% for SOEL (Grahn et al., 2022). For the production of e-fuels in general, large amounts of hydrogen are required. As a result, the efficiency of the electrolysis primarily determines the total E-fuel production efficiency.

Summarising, Table 2 provides an overview of the production process, feedstock, limitations and production efficiency for Bio-methanol, Bio-diesel, E-methanol and E-diesel. While the production efficiency for the various fuels depends on the details of the production process and the potential to efficiently combine various required feedstocks, the general trend is that production of diesel is 5% to 15% less efficient than the production of methanol.

Table 2: Overview of the production process, feedstock, limitations and production efficiency for Bio-methanol, Bio-diesel, E-methanol and E-diesel.

Fuel type	Production procces	Feedstock	Dependancy/limitations	%[1]
Bio-methanol	Anaerobic digestion (Bio-gas to methanol)	Manure, food waste and sewage sludge	Biofuel feedstock can compete both direct and indirect with the world food demand.	54
	Gasification (syngas to methanol)	Biomass and municipal waste	There is insufficient biomass available to supply the total energy demand.	
	Anaerobic fermentation (ethanol - methanol)	Energy crop		
Bio-diesel	Hydroprocessing or Transesterification	Vegetable oils		51
	Anaerobic digestion (Bio-gas to diesel)	Manure, food waste and sewage sludge		
	Gasification (syngas to diesel)	Biomass and municipal waste		
	Anaerobic fermentation (ethanol to diesel)	Energy crop		
E-methanol	Methanol synthesis	CO2, hydrogen and electricity	Limited availability of renewable energy and therefore H2 and DAC. PSCC could become unavailable. Biomass can not supply sufficient CO2 for large scale production.	41-72
E-diesel	FT-synthesis	CO2, hydrogen and electricity		37-64

1. Overall production efficiency

3.2 Future availability

Methanol is a readily worldwide available product, with a production of around 100Mt per annum. The majority of the produced methanol originates from the fossil sources, natural gas and coal Methanol institute (2021). However, methanol originating from fossil sources leads to more GHG emission than diesel in a life-cycle analysis under current circumstances Balcombe et al. (2019). The availability of sustainable methanol is limited, currently the production capacity is below 1% of the total produced methanol volume yearly. For future availability of sustainable methanol production, the Methanol Institute International Renewable Energy Agency and Methanol Institute (2021) analysed the market development of sustainable methanol production facilities. In Figure 4 locations are marked where Bio- and E-methanol production facilities are projected or in operation.

Bio-Methanol provides the largest contribution to the total sustainable projected production capacity of methanol for 2025, which is around 3.1 Mt per annum versus 1.7Mt per annum of E-Methanol. A disadvantage of Bio-methanol, especially when produced from agricultural biomass, is that it competes with the world food demand. Furthermore, there is insufficient biomass available to supply the total energy demand of the shipping sector in Bio-fuels (Concawe Review, 2019). 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 et al. (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. However, aviation is dependent on sustainable aviation fuels (SAFs) for making aviation more sustainable US Department of Energy; Sustainable Aviation. SAFs are longer chain sustainable fuels, such as E-kerosene

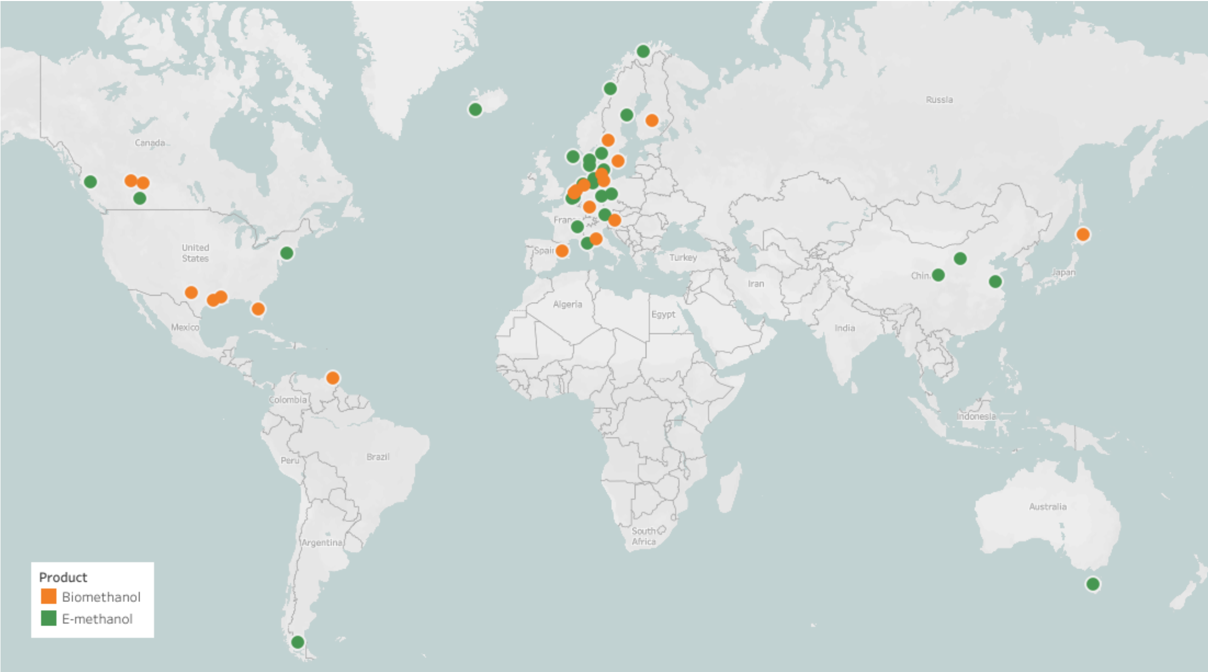

Figure 4: Renewable and Biomethanol Projects 2021 International Renewable Energy Agency and Methanol Institute (2021)

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.

3.3 Fuel production cost estimates and assumptions

Decarbonising of the shipping industry is strongly driven by cost evolution of sustainable fuels. Production, supply and storage costs are important elements. Table 3 provides an overview of studies into fuel production cost of sustainable diesel end methanol.

Figure 5 and Table 3 provide an overview of cost estimates from various studies that have been performed over the past years. (Brynolf et al., 2018; Lloyd's Register and UMAS, 2019b; Verbeek, 2020; van 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 most scientific study of Brynolf et al. (2018), which clearly provides a large uncertainty range indicated by the error bars in Figure 5. In this study, 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 et al. (2018), except the study from Lloyd's Register and UMAS (2019b), which has taken very positive assumptions. However, the study of Lloyd's Register and UMAS (2019b) does provide a useful trend for the development of the cost of various fuels which is solidly justified in Lloyd's Register and UMAS (2019a), but does not address uncertainty. All studies agree that the difference between Bio-diesel 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, again with the study of Lloyd's Register and UMAS (2019b) providing a significant outlier. 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 cost of sustainable fuels as production capacity and technological readiness increases.

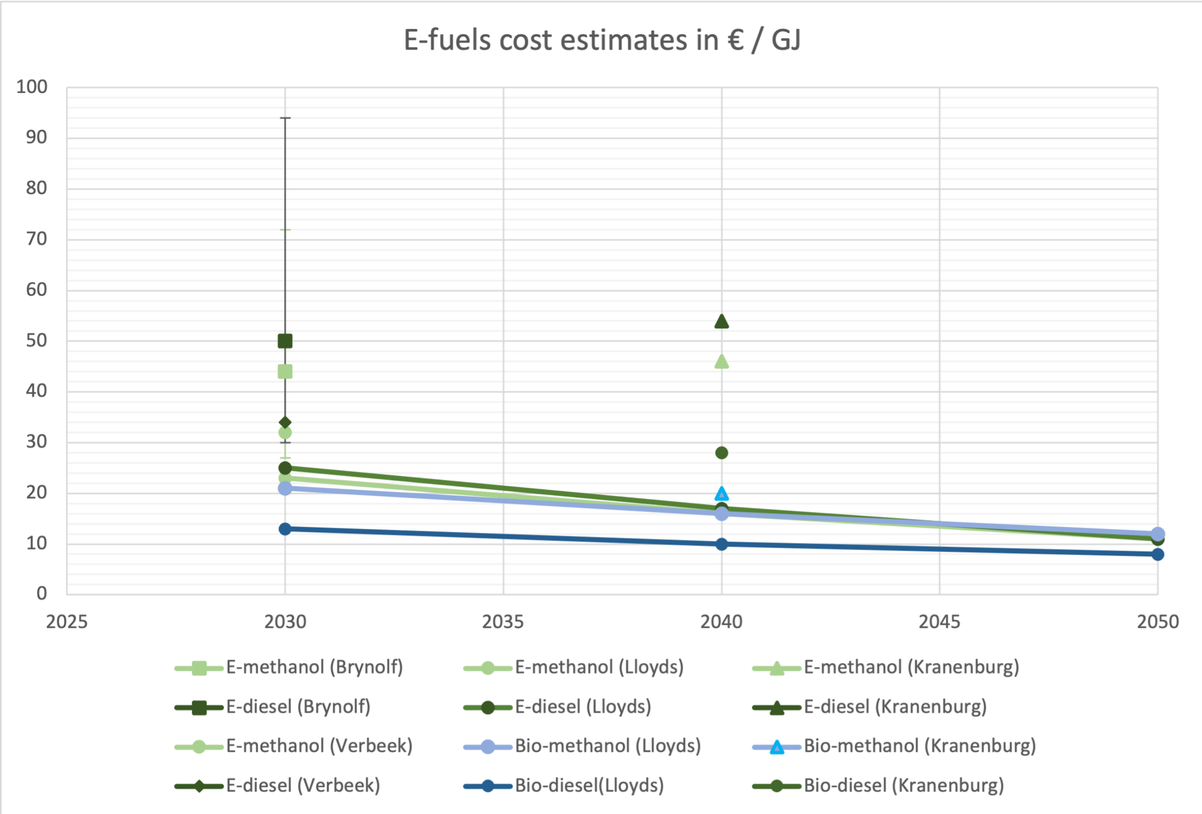

Figure 5: E-fuel cost estimates (Brynolf et al., 2018; Lloyd's Register and UMAS, 2019b; Verbeek, 2020; van Kranenburg et al., 2021)

Table 3: Overview of studies into fuel production cost of sustainable diesel and methanol

Author/Article	**Year**	**Time Horizon**	**Fuels Assessed**	**Assumptions**	**Cost range [€/GJ]**
Brynolf et al.	2018	2030	E-methanol E-diesel	Production cost including investment, operation and maintenance, electricity, water, CO2 and selling excess O2 and heat.	27-44-72[1] 30-50-94[1]
Lloyds-register and UMAS	2019	2030, 2040, 2050	Bio-methanol Bio-diesel E-methanol E-diesel	The costs composed of: total production costs, transportation, bunkering and vessel storage.	21, 16, 12 13, 10, 8 23, 16 , 11 25, 17, 11
Verbeek (TNO)	2020	2030	E-methanol E-diesel	Production cost levels are based on costs of H2, CO2, electricity and CAPEX.	25-39[2] 27-41[2]
van Kranenburg et al. (TNO)	2021	2040	Bio-methanol Bio-diesel E-methanol E-diesel	Production costs in this study are calculated with the Supply Chain Model[3].	20[4] 28[4] 36-57[5] 42-66[5]

1. Three cases: base, low and high where calculated. In the low and high cases, the most optimistic and pessimistic values were used and for the base case, the average data is used from literature.

2. Estimations are done for two assumptions of LCoE and €/tonne CO2, €30/MWh, €40/tonne and €50/MWh, €30/tonne.
3. TNO's Supply Chain Model is an economic model that calculates complete supply chain costs for import of green hydrogen and hydrogen based carriers from different countries and compares these to local production in the Netherlands. Costs are based on expected CAPEX levels for 2030.
4. The expected price development of Bio-fuels were based on extensive research done by the International Energy Agency and the U.S. Energy Information Administration. International Energy Agency (2021a,b); Brown et al. (2020); US EIA (2019).
5. Estimations are done for two assumptions of LCoE, €30/MWh and €70/MWh.

4 Impact on design

Leading parameters in the design of large surface combatant are volume and displacement. Sensor, Weapon and Command (SEWACO) systems, the power and propulsion plant, accommodation, fuel storage, and auxiliary systems all compete for volume, displacement and position on board the vessel (Van Oers et al., 2018). Consequently, the available volume and displacement determine the amount of fuel and the installed power that can be carried on board. Therefore, a direct relation between the displacement and the operational profile and autonomy of a vessel arises. This makes the energy density of a fuel a critical parameter for its applicability. Furthermore, the additional requirements and complications that come with the use of a certain fuel can be crucial for its compatibility in the design. For this paper, we assume a Future Air Defence Frigate (FuAD) with a displacement of 6000 tonnes and propulsion configurations similar to the ones presented in Geertsma et al. (2017). The key parameters are presented in Table 4 and a 3-D render plot is shown in Figure 6

Parameter	**1A. Diesel CODLOG**	**Unit**
Displacement	6000	[tonne]
Top speed	29	[kts]
Propulsion power	36	[MW]
Range at 18kts	5000	[nm]
Diesel volume	600	[m^3]

Table 4: Key parameters of a potential concept design for a notional Future Air Defence Frigate

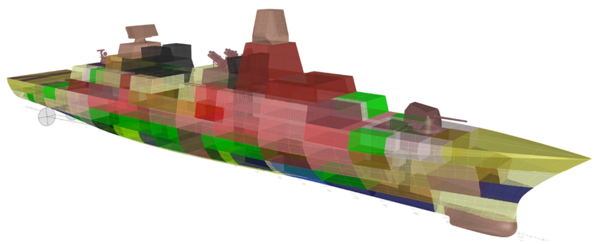

Figure 6: 3-D render plot of a potential concept design for a notional Future Air Defence Frigate

4.1 Ship/platform

According to interim guidelines from IMO (IMO, 2020), methanol tanks should be surrounded by protective cofferdams, except on those surfaces bound by shell plating below the lowest possible waterline, other fuel tanks containing methanol, or fuel preparation spaces. Cofferdams are a structural space surrounding a fuel tank which provides an added layer of gas and liquid tightness protection against external fire and leakage of toxic and flammable vapours between the fuel tank and other areas of the ship. Alternatively, diesel tanks do not have this arrangement complexity. However, alternative protection against spread of fire and leakage of methanol are investigated in various Dutch and European research projects. An equivalent safety compared to current diesel configurations needs to be demonstrated before alternative measures with less volumetric impact on the design can be accepted.

Methanol has a specific energy of 19.7 MJ/kg (16.6 MJ/L), which is a factor 2.3 lower than that of diesel, which is around 45.6 MJ/kg (38.6 MJ/L). One of the main challenges is not designing an engine to run on methanol, but finding the space to store methanol on board (Nysjö et al., 2022). While methanol has a lower energy density than diesel, its energy density and ease of storage are great advantages over other sustainable fuels, since it is liquid at ambient temperature and pressure. Two other sustainable fuels that are considered by the maritime sector, ammonia and hydrogen, have an even lower energy density and need to be stored under pressure or cryogenically, often requiring cylindrical tanks. However, for the same energy content as diesel, taking into account the extra measures required for safe storage, methanol requires up to 2.5 times more storage volume than diesel (Andersson and Márquez, 2015; Ellis and Tanneberger, 2015). On the other hand, sustainable diesel is compatible with conventional diesel, it has comparable energy density, it can be mixed with conventional diesel and it can be transported in the existing diesel infrastructure. Figure 1 shows the relative tank capacity required for different fuel options to store the same amount of energy. Concluding, the required volume for methanol storage is estimated at 1300 m^3 to 1500 m^3 compared to a typical diesel storage of 600 m^3.

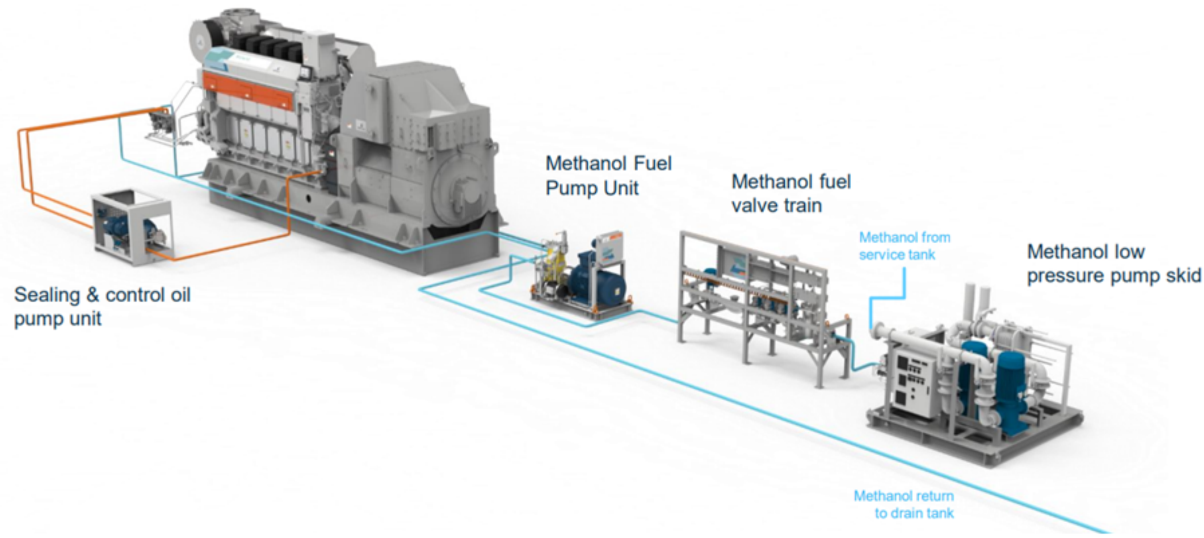

Figure 7: Wärtsilä W32 methanol engine system overview Wärtsilä (2022)

4.2 Power and propulsion plant

Methanol tests in marine engines have already been performed for a long time demonstrating good engine power and fuel consumption, and showing lower harmful emissions (Song et al., 2008). The novelty with using methanol as a fuel mainly lies in the fuel system and injection technology. Engine manufacturers have shown compatibility with several combustion principles. This concerns both spark-ignition (Otto-cycle) and compression-ignition (Diesel-cycle) engines. At the moment, MAN Energy Solutions is developing methanol retrofit solutions for its four-stroke customers which will be sales-ready from 2022 onwards, with retrofits starting in 2024 (MAN Energy Solutions). This will be a dual-fuel compression-ignition concept to provide greater flexibility. Also, Wärtsilä announced their first modern, methanol-fuelled engine, the Wärtsilä 32 Methanol (Nysjö et al., 2022). For robust operation, this engine is equipped with a full diesel and methanol fuel system. Therefore, 8% pilot fuel (diesel) is required at 85% MCR when the engine is running on methanol, allowing a seamliss switch to diesel as a back-up or for a switch during operations that require longer autonomy. In conclusion, methanol engines emerge, with dual-fuel variants in the high power four stroke range, enabling methanol to become one of the main fuels available to decarbonise shipping and as a serious option for future naval vessels.

The marine gas turbine market is small and highly dependent on developments in the aerospace industry. Methanol has three characteristics that make turbine modifications necessary (GE Power, 2001): its lower heating value results in higher fuel flow rate; the poor lubricating effect of methanol requires changes in the main fuel pump and flow divider system; and due to the low flash point of methanol, precautions to eliminate possible sources of ignition and therefore, explosion proof components are required. Rolls Royce indicates that the energy transition pathway and their solution direction is uncertain (Rolls Royce, 2022). In the development of aviation gas turbines, the focus is currently on SAFs, thus maritime gas turbines will most likely not be developed for methanol in the near future.

Therefore, a methanol fuelled vessel with gas turbine propulsion is unlikely. However, for sufficient energy density, internal combustion engines at speeds of 1000 rpm or higher are required; these are available up to 10 MW. For a future air defence frigate with top speed requirements of 30 kts or higher, four of these engines would be required. Compared to a vessel with gas turbine propulsion, this would lead to an increased length, weight and cost. This length might also provide space for the extra required methanol. To establish the full impact, a concept design needs to be performed.

4.3 Vulnerability

A Large Surface Combatant is designed to operate at the highest end of the violence spectrum (NATO, 2004). Thus, it is important to maintain the ability to accomplish the mission by avoiding or withstanding weapon effects. The vulnerability of a vessel concerns the damage that will be done by an impact or the sensitivity to impact. This damage comes in two forms, often referred to as primary and secondary damage (Habben Jansen, 2020). The first is the sensitivity of the system to primary damage. If a system is very sensitive to damage, weapon impact may easily disrupt the operation, leaving the vessel dead in the water and possibly without weapons, sensors, communication systems and propulsion. The second aspect is the possible propagation of damage if sensitive fuel systems are compromised. Fuels with higher flammability may be prone to explosion and will magnify the damage already done. Due to the lower flash point and toxicity of methanol with respect to diesel, safety measures need to be taken into account in the design. On the other hand, the lower heating value of the fuel and its good miscibility with water might ease fire suppression and fire fighting. For now, however, Lloyd's Register Lloyd's Register (2021) and the IMO introduced interim guidelines for the classification of methanol-fuelled ships and guidelines for the safety of ships using alcohol as fuel IMO (2020).

According to these guidelines, methanol fuel tanks must be filled with an inert gas to prevent an explosive gas mixture forming in the tank. To make the above possible, the tanks must be provided with a controllable pressure vacuum system. For the fuel supply system, fuel pipes must be constructed double-walled. Leak detection must be present in this double wall and it must be possible to ventilate the hollow spaces and fill them with inert gas. In the event of a leak detection, the fuel supply must be stopped and a back-up fuel supply system is necessary to maintain (minimum) propulsion and energy generation in accordance with the PSMR classification (Lloyd's Register, 2022). In the fuel supply system, that pumps methanol in the first stage at approximate 15 bar and feeds it to the high pressure pump of the common rail system, the surplus of methanol is fed back to the tank, but must be cooled to prevent heating up of the fuel tank. In the final stage, the methanol is pressurised in the common rail system up to 600 bar. An overview of the fuel systems from Wärtsilä (2022) is presented in Figure 7.

Table 5: Qualitative impact of the fuel choice on the design concepts of a future air defence frigate

Design concept	**Characteristic**	**Size**	**Cost**	**Emissions**
1A. Diesel fuel with gasturbine hybrid propulsion	High top speed with 36 MW propulsion	Most compact design	6 Eur /GJ extra fuel cost	Increased hazardous emission
1B. Diesel fuel with diesel engine propulsion	Limited top speed with up to 30 MW propulsion	Extra lenght for additional engines	6 Eur /GJ extra fuel cost	Increased hazardous emission
2A. Methanol fuel with gasturbine hybrid propulsion	Not feasible or very expensive	900 m3 extra tank space, extra fuel pump and safety system space and	Reduced fuel cost, but uncertain extra power requirement	Reduced hazardous emissions
2B. Methanol fuel with diesel hybrid propulsion	Feasible but extra ship length	900 m3 extra tank space, extra fuel pump and safety system space and extra length for additional engines	Reduced fuel cost, but uncertain extra power requirement	Reduced hazardous emissions
3A. Two fuel strategy with gasturbine hybrid propulsion	Not feasible or very expensive	Extra fuel pump and safety system space	Reduced fuel cost, but uncertain extra power requirement	Reduced hazardous emissions.
3B. Two fuel strategy with diesel hybrid propulsion	Feasible but extra systems and some ship lenght	Extra fuel pump and safety system space and extra length for additional engines	Reduced fuel cost, but uncertain extra power requirement	Reduced hazardous emissions.

4.4 Discussion

In Table 5 an overview is presented on the qualitative impact of the fuel choice on the design of a future air defence frigate.

While the implementation of methanol as a fuel for high-end naval vessels does appear technically feasible for propulsion systems based on diesel engines alone, its impact on the size of the vessel is large and its top speed might be limited unless the ship is stretched. The size increase starts with 900 m^3 extra tank space, extra fuel pump and safety system space and extra length for additional engines. To establish the full impact, including the effect of the propulsion power increase, the concept design of such vessels needs to be established and compared. To reduce the impact, navies could consider operating the vessel on a two-fuel strategy, on methanol during operations with limited autonomy, typically in peace time, and on diesel during operations with high autonomy, during (certain) peace time operations. The compatibility of the specific tank coatings suitable for methanol with long term storage of diesel would need to be investigated. Finally, navies could consider preparing for investment in production of Bio-diesel or E-diesel. The main limitation will be the availability of feedstock and the up-scaling of the required production facilities to reduce the long term cost of these fuels. The development in aviation towards SAF might be a crucial enabler for this strategy.

5 Conclusions and further research

This literature study has reviewed current and future developments of sustainable methanol and diesel. The adoption of these fuels for a Large Surface Combatant is a multi-dimensional challenge, because of the uncertainty in the development of their production process, future availability, fuel production cost and their impact on design. The production capacity of Bio-methanol and E-methanol is growing rapidly as illustrated in Figure 4. Bio-diesel is becoming more available as well, but availability of E-diesel is lagging behind. The development of SAF production facilities for aviation might prove an enabler for future availability of E-diesel.

Currently, the scarcely available proposed sustainable fuels are significantly more expensive than conventional fuels. The production cost of sustainable fuels is mostly led by renewable feedstock costs. It is expected that, due to stimulating government policies, the prices of the proposed fuels will become equal and eventually lower than conventional fuel prices, while the availability will become higher. In summary, the production cost of Bio-diesel and E-diesel is 5% to 30% more expensive with a mean estimated additional cost of 6 €/GJ compared to methanol.

Operating on methanol has a significant impact on the design of a Large Surface Combatant. The specific energy of methanol is more than twice as low as diesel and therefore the endurance of the ship is more than halved or the tank capacity has to be increased by 700 to 900 m^3, which directly adds 10% to 15% to the displacement and similar cost and signatures. Gas turbines are unlikely to become available, and therefore the ship might need a longer machinery space to allow for more propulsion engines to compensate for the increased power requirement. The required auxiliary and safety systems add further volume area to the engine room. Moreover, the safety measures make the ship design larger and less flexible, due to segregation requirements. To more exactly quantify the impact of methanol on the design, a concept design iteration is required, which the authors will undertake in future work.

Sustainable diesel is a drop-in fuel, which makes blending of sustainable diesel with fossil diesel possible in the existing infrastructure allowing a gradual transfer from fossil diesel to sustainable diesel. The main uncertainty in the feasibility of this option is the future availability of sustainable fuels, as production facilities have not yet been planned as much as sustainable methanol production facilities. Moreover, more hazardous emissions, such as particulate matter and NO_x might remain, but these could be mitigated by after treatment. During the lifetime, however, the navies should take additional cost of sustainable diesel compared to sustainable methanol into account. Whether this cost is higher than including methanol in the design needs to be established with an economic trade-off after establishing comparable concept designs, which is planned for future work.

Finally, navies could consider a two-fuel strategy, on methanol during operations with limited autonomy, typically in peace time, and on diesel during operations with high autonomy, during (certain) war time operations. In this case the design needs to include both diesel and methanol fuel systems and additional space for methanol safety measures. The feasibility of this option depends on how much this impacts the design, which can again be established through a concept design. Moreover, the compatibility of the same tanks for two fuels needs to be further investigated, but ultimately the limitation on flexibility of the navy to change operations in a short time might prove the factor that blocks this option for naval commanders.

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