German Environment Agency

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In-depth analysis 2: Technical aspects of future fuels in existing fleet and newbuilds

Technical suitability onboard of ships

The maritime transport sector significantly contributes to global GHG emissions and to EU GHG emissions, accounting for a 2-3 % share and an approx. 4 % share respectively (IMO 2020; EC 2021a). To decarbonize this sector, energy efficiency improvements, such as slow steaming or improvements to the ship design, will not be sufficient. The main lever to reduce GHG emissions in shipping is the switch to sustainable, alternative fuels, referred to as future fuels in the following (DNV GL 2019). This short paper is part of a series of in-depth analyses of future marine fuels. Based on a selection of Renewable Fuels of Non-Biological Origins (RFNBOs) and second generation or advanced biofuels[1] in a first in-depth paper[2], this paper provides an overview of technical aspects to consider onboard of ships from a tank-to-wake (TtW) perspective. The presented findings are based on a literature review and interviews with stakeholders from the maritime sector. The production and well-to-tank (WtT) aspects, lifecycle emissions, and competition around the supply of future fuels are considered in separate in-depth papers.

With a view to the ships, the suitability of a future fuel is determined by its characteristics, which have advantages and disadvantages compared to the fossil fuel reference and other future fuel options. Important aspects which are influenced by the characteristics are safety regulations and handling, storage and energy content, engine compatibility, TtW emissions as well as the resulting implications for costs. The characteristics of future fuels also determine the need for small or large retrofits or newbuilds.

Key findings

- Energy densities and safety precautions influence storage conditions, space requirements and costs for using future fuels onboard a vessel. International safety regulations are crucial for the progress of methanol or ammonia as marine fuels. It is difficult to weigh the risks and storage implications of fuels against the expected future cost.
- It is clear that most future fuels will take up more space onboard. However, depending on the ship type, size and route, the operating range can be maintained if a small loss of cargo-carrying capacity is accepted. The decision about the exact vessel design and related implications on bunkering frequency, safety and cargo-carrying capacity will vary for different ship types and sizes.
- Biofuels can be used in existing engines whereas all RFNBOs (except e-diesel) will require dedicated engines and likely the use of pilot fuels. Fuel cells are currently not competitive

[1] There is no clear definition of second generation or advanced biofuels. In this paper, these terms are used interchangeably, which also distinguishes them from biofuels made from food crops with high (indirect) land-use change emissions which might compete with food production (first generation biofuels) (see e.g. Florentinus et al. (2012)).

[2] Wissner and Cames (2023) – In-depth analysis 1: Future fuels

with marine ICE for deep-sea shipping. Depending on the cost degression and technology development, fuel cells can play an important role in the sector in the long-term.

- Ammonia and hydrogen offer the largest greenhouse gas emission reductions from a TtW perspective. Policies need to consider all relevant greenhouse gases in order to avoid the risk of an increase in non-CO_2 greenhouse gases like methane. The real climate impact of all future fuels is determined by their WtW emissions. If policies only consider TtW greenhouse gas emissions, climate benefits from carbon-based future fuels are not distinguishable from their fossil counterparts.

- From a total cost-of-ownership perspective, the choice of the future fuel will be determined by fuel costs. Studies have found that both methanol- and ammonia-fuelled vessels will have the lowest total cost of ownership in future, assuming that advanced biofuels will remain limited and expensive in the future.

1 Technical aspects onboard

From a (technical) onboard perspective, the suitability of a future fuel is determined by its characteristics, which have advantages and disadvantages compared to the fossil fuel reference and other future fuel options. Important aspects which are influenced by the characteristics are:

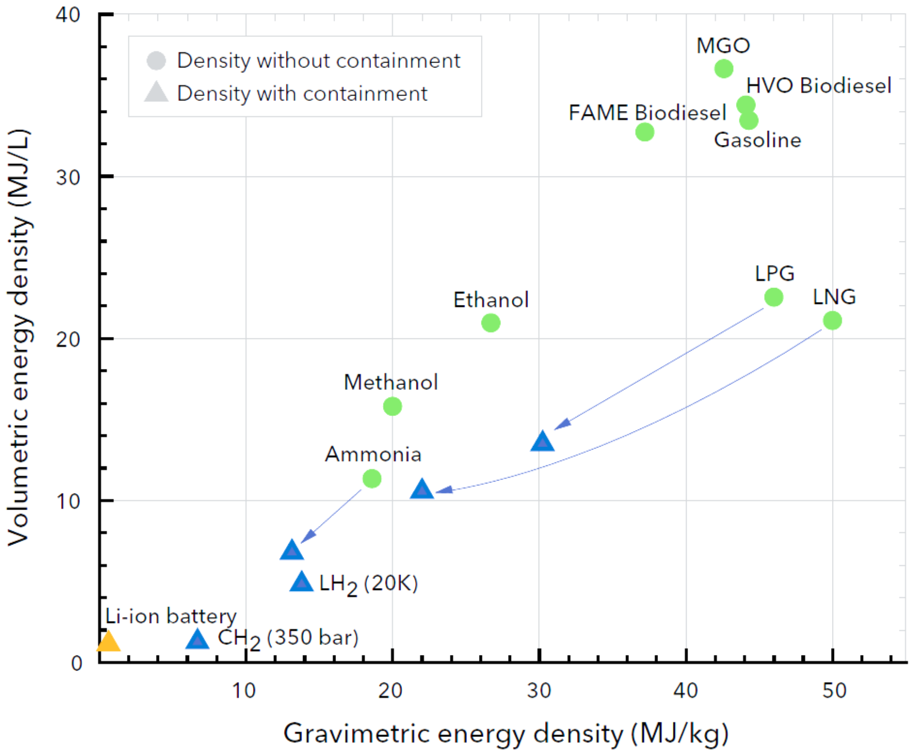
- safety regulations and handling,
- storage and energy content,
- engine and fuel system compatibility.

1.1 Storage and safety

Except diesel-like fuels, future fuels have a different energy density and characteristics to Marine Gas Oil (MGO).[3] This has an influence on the design and operation of a vessel. The lower the energy density of a future fuel, the more fuel is needed to sail the same distance compared to MGO. The efficiency of the energy converter also plays a role, but it is expected that future (dual-fuel) ICE will have a very similar conversion efficiency of about 40-45 % compared to current ICE (Stolz et al. 2022). If fuel tanks are larger (to cover the same distance), it is very likely that the additional space needed onboard of ships is compensated by carrying less cargo. If operating range is less important or more frequent bunkering is feasible, cargo-carrying capacity can be maintained or at least cargo space loss minimized. The frequency of refuelling is also determined by the amount of fuel that can be stored onboard a ship. Deriving the energy densities for the fuels including their storage system is not straightforward as they depend on the actual design of the fuel tank or the position on/within the ship. The insulation or sealing of the tank requires mass and space and thus influences the energy density of the storage system onboard a ship (Stolz et al. 2022). DNV GL (2020a) provides an overview of the volumetric and gravimetric energy densities of future fuels (including the storage system) and the fossil reference MGO, all shown in Figure 1. It can be seen that the energy density is lower for all future fuels (selection listed in Table 2) compared to MGO. Differing energy densities and storage conditions also influe nce investment and operational costs
(chapter 3).

[3] Wissner and Cames (2023) – In-depth analysis 1: Future fuels

Figure 1 - Energy densities with and without fuel storage system



Source: DNV GL (2020a)

Safety concerns regarding future fuels are mainly the result of the toxicity, flammability, explosion risk and storage conditions of each fuel. The level of toxicity is important for the workers onboard who handle the fuel and is relevant for marine life in case of accidental releases of the fuel in coastal or marine areas. High toxicity of fuels requires higher or different security requirements for storage and handling onboard (compared to MGO) and poses a larger environmental risk in case of spills or accidents. Flammability is the ability of a chemical to burn or ignite, causing fire or combustion. It is thus a safety issue; extremely flammable substances require high precautions in fuel handling and storing. Flammability is also important for the engine combustion process. Fuels with a low flammability are harder to ignite and thus require a pilot fuel for ignition during each combustion process (section 1.2). The storage condition itself might cause an additional effort as cryogenic storage comes with the risk of cryogenic burns. These safety concerns are elaborated for each future fuel in the following. Safety concerns and related additional safety precautions increase the complexity and costs of adopting a future fuel (see also chapter 3). New training of crew will be required, especially for fuels which have very different characteristics compared to conventional marine fuels. The training required will also vary depending on the shipping segment. Crews of tanker or gas carriers are more experienced with handling 'dangerous' cargo or liquids than crews in the dry bulk and container segment. Experts indicated, however, that regular trainings are always needed and that the training of crews is less of an issue than the setting of (international) safety standards. The international safety regulations for alternative fuels are laid down in the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code) of the IMO. Methanol, ammonia and hydrogen are not currently covered by the code whereas LNG (and thus bio- or e-methane) is.

However, interim guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel can be used under specific circumstances for the design process of methanol-fuelled ships (DNV 2022b). The latter and the fact that methanol-fuelled ships are already in operation make it likely that methanol will be more quickly added to the IGF Code than ammonia and hydrogen. The development of guidelines for ammonia and hydrogen are, nevertheless, already on the agenda of the IMO (DNV 2022b).

Table 1 provides a summary of relevant fuel characteristics. The table includes an assessment of safety concerns based on risks for humans and the (marine) environment in case of leakages or spills, risks for explosions and derived safety precautions.

Table 1 – Fuel characteristics and safety issues

	Storage pressure	Storage temperature	Tank size	Toxicity	Flamm-ability	Safety concerns	Propulsion system
Unit	Bar	°C	Relative to MGO tank				
E-Hydrogen (gas.)	700	20	>7.6				ICE / FC
E-Hydrogen (liqu.)	1	-253	7.6				ICE / FC
E-Ammonia	1 or 10	-34 or 20	4.1				ICE / FC
E-methane and bio-methane (liqu.)	1	-162	2.3				ICE
E-Methanol and bio-methanol	1	Ambient	2.3				ICE / FC
E-diesel	1	Ambient	1				ICE
Biodiesel	1	Ambient	1				ICE
MGO	1	Ambient	1				ICE

Sources: Own compilation based on Cames et al. (2023), Cames et al. (2021), KR (2020) and Clark et al. (2021). Colour coding: green = low, orange = medium, red = high. Safety concerns based on toxicity , flammability characteristics, explosion risk and storage conditions of fuels.

- **Bio- and e-diesel** have a very similar energy density compared to MGO (Figure 1) and can be stored at ambient temperature. It is thus reasonable that the tank volume will be comparable to a conventional MGO tank (Table 1). The MGO similarities are also advantageous for compatibility with existing ships and engines (section 1.2). However, bio- and e-diesel have a high acute toxicity - as MGO does - especially when swallowed or exposed to the skin (Cames et al. 2023). Long-term toxic effects, for example in the case of a spill, are likely to be more severe for MGO (or similar fuels) than, for example, for ammonia (Cames et al. 2021). The comparable flammability and toxicity also mean that these future fuels can be handled like MGO. Overall, this makes bio- and e-diesel a very promising future fuel from a practical perspective as they are similar to MGO. However, they do not represent an improvement when the risks for humans and the marine environment are taken into account. Standards and guidelines for biofuel use are available and different biofuels will likely be covered by the IGF Code in future (DNV GL 2018).

- **Bio- and e-methanol** have lower gravimetric and volumetric energy densities including the fuel storage system than diesel-like fuels (Figure 1). The fuel tanks are, therefore, more than twice the size of MGO tanks (Table 1**Fehler! Verweisquelle konnte nicht gefunden werden.**). While it is possible to equip ships with a methanol tank large enough to ensure full operating range, it leads to a loss of cargo-carrying capacity (DNV 2022a). Although this is a slight disadvantage, methanol is easier to handle as it is liquid at ambient temperature. While methanol is not considered as a high risk for marine environments, it can be toxic if swallowed or if it comes into contact with the skin (Clark et al. 2021). In the case of a spill, methanol dissolves quickly (ibid). Methanol is flammable like ammonia and safety measures have been developed for handling the fuel and designing methanol ships (DNV GL 2016). In contrast to ammonia, methanol tanks could be installed in areas of the ship where ammonia tanks cannot be installed because of the more complicated fuel characteristics (like toxicity).

- **Liquefied bio- and e-methane** have a higher volumetric and gravimetric energy density than methanol. Their storage conditions lead, however, to a similar gravimetric and a lower volumetric energy density than methanol (values for LNG in Figure 1). Compared to methanol and MGO, methane as a marine fuel cannot be stored at ambient temperature but is liquefied at -162 °C (Table 1). The tank size is similar overall to methanol – meaning it brings about a similar loss of cargo space. Methane is an extremely flammable gas but is not considered toxic (Clark et al. 2021). The flammability of methane and its storage at cryogenic conditions require safety precautions, but LNG ships are already operating safely and regulations like, for example, the IMO IGF Code are in place (DNV GL 2018). Risks to safety and handling of liquefied methane are not, therefore, considered an issue.

- **Ammonia** has much lower energy densities than MGO, irrespective of whether the fuel storage system is considered (Figure 1). A clear disadvantage of ammonia is hence that the fuel tanks are about 4 times the size of MGO fuel tanks (Table 1**Fehler! Verweisquelle**

konnte nicht gefunden werden.). Therefore, using ammonia for similar ranges as a fossil-fuelled ship results in a larger loss of cargo space than in the case of methanol (LR; UMAS 2020). It is possible, however, to operate a ship on its full range on ammonia: DNV (2022a) outlines options to locate ammonia tanks in the aft of the ship away from the cargo, which also reduces risks of ignition. Compared to liquefied methane, the actual storage conditions of ammonia are easier as ammonia can be stored either at ambient pressure at -34 °C or at 10 bar at ambient temperatures. However, ammonia does require more safety precautions due to its high acute toxicity (Table 1). Ammonia can be toxic for humans if inhaled or if it comes into contact with skin and can be very toxic to marine life, depending on its concentration in the water (Clark et al. 2021). Compared to MGO, long-term toxic effects, for example in the case of a spill, are likely to be less severe for ammonia because ammonia concentrations in the water column will rapidly decrease and be assimilated by algae (Cames et al. 2021). Nevertheless, any exposure to humans or the environment must be avoided. While international safety regulations are not yet in place, first safety measures have already been developed in the run-up to the first ammonia pilot projects (such as DNV GL (2021a) and Vries (2019)). Ammonia is a corrosive substance, but requirements for the materials used in fuel tanks and fuel system are known and need to be taken into account when designing ships for ammonia use (Cames et al. 2021). Ammonia is flammable, but to a lesser extent than MGO, thus explosion risks are lower (Clark et al. 2021).

- **Hydrogen** can be stored in two ways: either liquefied (at -253 °C, at normal pressure) or pressurized (e.g. at 700 or 350 bar). Consequently, hydrogen fuel tanks can be more than 7 times larger than MGO tanks (Table 1). This loss of cargo space loss is thus the most pronounced compared to other future fuels and is one of the major limitations to hydrogen's application in deep-sea shipping (LR; UMAS 2020). One substantial advantage compared to ammonia or methanol is that hydrogen is not considered toxic. It is, however, extremely flammable and therefore safety precautions are needed to avoid fire or explosions (Clark et al. 2021). As a low-flash point fuel, hydrogen would need to be covered by the IGF Code; regulations, also for its use in fuel cells, are currently being developed (DNV GL 2018).

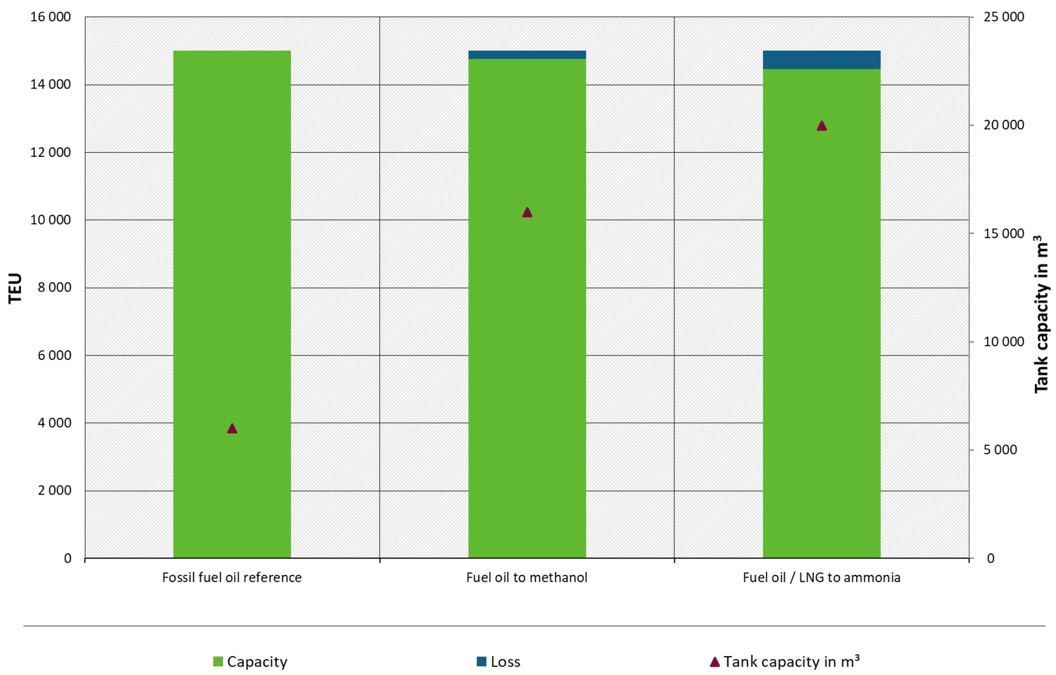
Regarding the impact on cargo-carrying capacity or sailing distance, some conclusions can be drawn based on the modelling of Stolz et al. (2022) of Europe's bulk carrier fleet. They analysed the share of transport work (= tonnes of cargo carried times the voyage length) that can be performed by the fleet with future fuels used in ICE or fuel cells:

- If the cargo-carrying capacity is maintained, liquefied hydrogen and ammonia can cover approx. 80 % to 90 % of current cargo (bulk) operations. Methanol, methane and diesel can cover 93 %, 98 % and 100 % respectively.
- If an additional refuelling stop is made, between 90 % to 100 % of the transport work can be conducted with all future fuels except compressed hydrogen.

- If a 3 % cargo loss is accepted to allow for more fuel storage, at least 93 % of the transport work can still be achieved with all future fuels.
- The longer a voyage, the higher the impact of the different energy densities of future fuels. For voyages of up to 10,000 nautical miles (nm), more than 90 % of the transport work can be performed with all future fuels, except hydrogen. For shorter distances between 2,000 and 4,000 nautical miles (nm), more than 90 % of the transport work can be conducted with liquefied hydrogen.

While Stolz et al. (2022) have studied the influence of refuelling, loss of cargo carry capacity and sailing distance on the attainment rate separately, LR; UMAS (2020) have examined the loss of cargo-carrying capacity while similarly reducing the operating range. They conducted a case study for a large bulk carrier powered with a range of future fuels either in fuel cells or ICE. An 80 % reduction in operating range was assumed. The conclusion of LR; UMAS (2020) on cargo-carrying capacity is comparable to Stolz et al. (2022): the impact on the cargo-carrying capacity is greater for carbon-free than carbon-based future fuels; and the loss of cargo-carrying capacity due to the fuels is low compared to the total carrying capacity (about 10 % for hydrogen and lower than 3-4 % for the remaining fuels) - given the assumed reduction in operating range. While these findings apply to a typical large bulk carrier, they are comparable for oil tankers due to similar technical specifications (LR; UMAS 2020). Container ships have different characteristics, which result in different suitable options (ibid). Besides the energy content of the future fuel, the loss of cargo-carrying capacity depends a lot on the tank design and its location on an individual vessel. MMKMC (2022) show the cargo loss for a 15 000 TEU container vessel operating on a 22 500 nautical mile route: although tanks require more space if the ship runs on methanol or ammonia, the container space loss is low in relation to the total TEU capacity of the vessel (Figure 2). Interviewed experts have confirmed that while a loss in cargo-carrying capacity of ships running on methanol is expected, there is enough bunkering space onboard to maintain the trade route or operating range.

Figure 2 - Container space loss for a methanol or ammonia conversion



Source: MMKMC (2022)

Nowadays, bunker capacities on deep-sea ships are usually sufficient for several voyages (DNV 2022b). For example, a large container ship travelling between Asia and Europe is able to conduct one round trip without needing to bunker. This allows shipowners today to be opportunistic and bunker where and when fuel is cheapest. Future bunkering behaviour might change if future fuels cannot cover the same distance. However, it might also be possible that ships simply bunker more often along their trade route without making an extra stop, given that bunker quantities today last for several voyages. The latter can, perhaps, partially explain why the bulk carrier fleet examined by Stolz et al. (2022) can still perform 80 % and more of its transport work without cargo loss or extra refuelling stop (see above). In the final analysis, it will depend on the ship type/size and energy density of the future fuel. It is thus not possible to conclude across all ship types if operational changes even occur, if ships run on future fuels, or if cargo capacity will be lost given the different bunkering patterns. Experts indicated that a cargo space loss of about 6-8 % might be acceptable (thus allowing most of the transport capacity to be maintained, according to Stolz et al. (2022) above). However, interviewed experts and LR; UMAS (2020) concurrently point out that the actual or 'acceptable' loss of cargo capacity will be different for each ship type and size due to their different technological and operational specifications. For example, cargo-carrying capacity is very important for an investment decision within the container segment, but also depends on many factors and cannot be generalized for all container ships. The option to refuel more often also depends on the availability of the specific fuel type in ports. Dual-fuel engines can be useful in this regard (section 1.4). Also, with a common global (or regional) effort to agree on one type of future fuel, the availability could be increased easier and quicker.

While space requirements and certain operating range are important factors, the overall cost of the new fuel systems, the potential revenue loss due to cargo space loss and/or the implication of more frequent bunkering all impact the decision on a future fuel and how much tank capacity is accounted for in the newbuild or retrofit design (section 3). To predict the dominant future fuel(s) in shipping thus depends not only on technical facts, but also on developments of costs, global supply chains and trade routes and the availability of fuels.

While the high efficiency of **fuel cells** (about 55 % according to Korberg et al. (2021)) requires less fuel and hence tank space, the power output per fuel cell module is still rather low (Cames et al. 2023). As a solution, fuel cells can be stacked to increase the power output. However, this would again require more space onboard the ship. Horton et al. (2022) even state that the combined size and weight of the fuel cell system would thus be larger than for an ICE. Also the case study of a large bulk carrier by LR; UMAS (2020) shows that cargo capacity loss is slightly higher if methanol and hydrogen are used in fuel cells instead of in ICE. The use of fuel cells to power the main engine of a large ship might, therefore, still be limited (DNV GL 2019). Mao et al. (2020) examine the use of hydrogen fuel cells in container ships operating between the United States and China crossing the Pacific Ocean. It was found that especially medium-sized ships are capable of serving the corridor with about 80-85 % of the original transport work and that only about 5 % cargo loss would be sufficient to cover 99 % of the cargo operations. Considering the actual 2015 fleet operating in the corridor, Mao et al. (2020, p. 11) state that approx. 43 % of the fleet's voyages "could be completed when powered by hydrogen fuel cells without replacing cargo space with fuel and without additional refueling along the way."

1.2 Internal combustion engines and compatibility

All future fuels can, in principle, be used in an internal combustion engine (ICE) (Table 1). However, not all of them are compatible with ICE that are already in operation. Table 2 provides an overview of the compatibility of each fuel with existing engines, if they can be used blended or neat (in its pure form), and if a pilot fuel or other system modifications are necessary. Pilot fuels are used to facilitate combustion of fuels which are hard to ignite. Typically, fossil diesel is used as a pilot fuel in dual-fuel engines. In future, bio- or e-diesel could be used in the same way. Some of the findings presented in the table need to be considered as preliminary as, for example, ammonia and hydrogen engines are still under development. This paper generally focuses on 2-stroke marine diesel engines because they are the most common engines for deep-sea shipping, with 2-stroke engines also powering 80 % of the global fleet according to the interviewed experts.

Table 2 shows that all diesel-like fuels are compatible with existing engines. Due to their MGO-like characteristics, they also do not require any pilot fuel to start the combustion process. Due to their favourable flammability characteristics, **e- or biodiesel** can be used as a pilot fuel for other future fuels. For example, Maersk plans to use biodiesel for its new fleet of methanol-powered container ships. While e-diesel can be easily used in existing engines in varying blending ratios or neat, the three types of biodiesel slightly differ. FAME biodiesel can only be used in existing ICE if blended (up to 20 %). If FAME were to be used neat, the engine would need to be modified and additives used to inhibit bacterial growth and to address the lower pour point (Zhou et al. 2020). Hydrotreated renewable diesel and Fischer-Tropsch (FT) biodiesel do not require engine modifications and can be used as a blend or neat. Given the availability, diesel-like future fuels can thus already be used in smaller shares or neat on existing ships. Several vessels are already operating on hydrotreated renewable diesel (Zhou et al. 2020).

The use of **bio- or e-methanol** as a marine fuel requires dedicated engines. Methanol engines can be retrofitted with minor modifications or methanol can be used in dedicated engines for a newbuild vessel (EC 2021b). Engine manufacturers Wärtsilä and MAN have developed methanol engines and there are already several ships running on methanol today, with an additional 35 tanker and container ships on order (EC 2021b; DNV 2022b). Methanol engines require about 5 % pilot fuel. For example, Maersk plans to use biodiesel as a pilot fuel for their future methanol-fuelled ships in order to have carbon-neutral vessels. Methanol can be blended with diesel-like fuels but only at very low levels, thus inhibiting the complete switch to methanol (Cames et al. 2023).

Bio- and e-methane benefit from commercially-mature LNG engines and LNG-fuelled ships. There are more than 300 LNG ships operating globally and more than 500 ships on order which are LNG-capable.[4] The majority of new orders running on alternative fuels will be able to run on LNG (EC 2021b; DNV 2022b). LNG is typically used in dual-fuel engines with conventional MGO or HFO as a second fuel. This second fuel or a third diesel-like fuel is also used as a pilot fuel in LNG dual-fuel engines. LNG engines require 1 % to 5 % of pilot fuel, depending on the engine type (Faber et al. 2017). As a first vessel, the "Wes Amelie" was retrofitted with a four-stroke dual-fuel engine and was the first ship to partially run on liquefied e-methane (Fahnestock and Bingham 2021).

Ammonia cannot be used in existing marine engines. Dedicated ammonia engines are currently being developed by big engine manufacturers such as MAN and Wärtsilä. Ammonia is relatively hard to ignite. According to research conducted by Cames et al. (2021) and experts interviewed, future ammonia engines will likely use a pilot fuel for combustion. Besides diesel-like fuels, hydrogen - retrieved by cracking ammonia directly onboard – could help the combustion of ammonia (Cames et al. 2021). It is further relatively certain that future ammonia engines will be dual-fuel engines. The amount of pilot fuel needed is expected to be in a similar range of current dual-fuel engines (e.g. about 5 %). Dual-fuel ammonia engines will allow for flexibility given the expected limitations in ammonia supply globally, i.e. the situation is similar to LNG. Modifications to the whole fuel system will be necessary to account for the corrosiveness and the toxicity of ammonia. Retrofitting a previously LNG-fuelled vessel to an ammonia engine will require fewer modifications than retrofitting a purely HFO- or MGO-fuelled vessel to an ammonia engine (EC 2021b). There are several pilot projects underway to develop ammonia-fuelled vessels such as gas and bulk carriers (Fahnestock and Bingham 2021).

There are no **hydrogen** ICE for marine applications available on a commercial-scale today and the technology readiness level in this regard can be considered the lowest, compared to the other future fuels (EC 2021b). Hydrogen cannot be used in existing engines and if hydrogen ICE were available, retrofitting ships with these engines would require major modifications (EC 2021b). Projects have started to get ships with hydrogen-fuelled ICE on the water with hydrogen stored in pressurized tanks (Fahnestock and Bingham 2021). Whether hydrogen is used in an ICE or a FC depends on the required power output of the ship. If a lower power density is

[4] DNV (2022) – Alternative Fuels Insight Platform: https://www.dnv.com/services/alternative-fuels-insight-128171

sufficient, hydrogen FC could be used (section 1.4). Using hydrogen in ICE is mainly interesting for ships in short-sea shipping and for use in 4-stroke engines (DNV 2022b).

Table 2 - Compatibility of future fuels with existing engine configurations

Future Fuel	Compatible with existing engines/ships	Blending or neat	Blend ratio	Pilot fuel required	Required modifications
Hydrogen	No	-	-	Yes	Fuel tank, piping, engine
Ammonia	No	-	-	Yes, 5-8%	Fuel tank, piping, engine
E- and bio-methane	Yes, dedicated LNG engines	Neat	-	Yes, 1-5%	-
E- and bio-methanol	Yes, dedicated methanol engines	Neat	-	Yes, 3-8%	-
E-diesel	Yes	Blend or neat	-	No	-
FAME biodiesel	Yes, if blended	Blend or neat	Up to 20%	No	Neat usage requires modernizing engines
Hydrotreated renewable diesel	Yes	Blend or neat	Up to 100%	No	-
FT biodiesel	Yes	Blend or neat	Up to 100%	No	-

Notes: Blend = fuel mixed with fossil fuel prior to combustion and directly used in engine, neat = fuel can be used in 100% pure form without mixing (excl. pilot fuel).
Sources: Authors' compilation based on Zhou et al. (2020), Cames et al. (2021), EC (2021b) and interviews with industry stakeholders. Pilot fuel amount also depends on marine engine type (MMKMC 2021a).

1.3 Fuel cells and compatibility

Fuel cells can run on a variety of fuels as there are different fuel cell types and pre-processing steps that can be applied. In principle, all future fuels could be used in a fuel cell. Powering marine vessels with fuel cells has the potential of higher efficiency, less noise, reduced emissions and air pollutants (chapter 2) as well as reduced space requirements compared to ICE (Ash and Scarbrough 2019). Fuel cells types which are deemed suitable for maritime applications are the low and high proton exchange membrane fuel cells (PEMFC) and the solid oxide fuel cell (SOFC) (Cames et al. 2023; van Biert et al. 2016).

Diesel and methane could be used in a fuel cell by reforming them to retrieve hydrogen. However, several processing steps might be needed to use diesel or methane with a fuel cell which lower the efficiency of the fuel cell systems (van Biert et al. 2016). The use of e-diesel or -methane in fuel cells has the additional issue of conversion losses along the upstream production chain of the fuels. These options are not widely discussed in the sector at the moment.

The majority of "fuel cells effectively run on hydrogen" (van Biert et al. 2016, p. 347). Consequently, hydrogen can be used directly in a fuel cell (depending on the purity and hydrogen storage conditions, an additional process step might be needed before hydrogen is used in the fuel cell). Powering vessels with hydrogen fuel cells is a very efficient use of energy as fuel cells have a high energy efficiency and the production of hydrogen has less conversion loss than production pathways of carbon-based future fuels.[5] On the one hand, the latter is limited by additional energy demand required if the hydrogen is transported over long distances and stored before use. On the other hand, other fuels – especially carbon-based future fuels - require more processing steps onboard, reducing the overall efficiency of the fuel cell system (van Biert et al. 2016). There are many projects running which test the use of hydrogen fuel cells on smaller ships (Fahnestock and Bingham 2021).

Ammonia is a hydrogen-carrier which could also be used to power a fuel cell. Ammonia can be cracked into hydrogen and nitrogen onboard. The hydrogen then needs to be purified and can subsequently be used in a PEMFC (Hansson et al. 2020). PEMFC have a higher technology readiness level and provide higher flexibility in terms of engine load than other fuel cells (DNV GL 2019). While using ammonia as a hydrogen carrier saves space compared to the storage of hydrogen, the necessary hydrogen cracking reduces the efficiency of the system and increases the cost and size of the propulsion system (Hall et al. 2018). A second option is to use ammonia directly in a SOFC, thus saving the space and energy needed for hydrogen cracking and purification (KR 2020). There is, however, less experience – especially in marine applications – with SOFC than with PEMFC. When ammonia is used in a fuel cell system, the same conditions regarding materials and tanks apply as in an ICE system onboard a ship (Cames et al. 2021).

Methanol fuel cells have also been tested in the maritime sector in a few projects (EC 2021b). Methanol can act as a hydrogen carrier and needs to be reformed/cracked to receive the hydrogen. For example, the MS Innogy is powered by a PEMFC with previous methanol reformation onboard.[6] There are also fuel cells which can use methanol directly, without the reforming step, but the direct methanol fuel cell itself is still under development and has a low efficiency (DNV GL 2017).

Powering vessels with fuel cells instead of ICE requires a different design of the ship (like the installation of an electric engine). Considering the limits of the power output, a fuel cell system might also require considerable space onboard a ship despite the higher efficiency of fuel cell (section 1.1). Retrofitting ships with fuel cells is possible but, in addition to high capital costs (chapter 3), it is not easy since the fuel system (e.g., crackers) is different and an electric engine is required (DNV GL 2019; Cames et al. 2023). Additionally, new crew trainings will need to be developed as there is very little operational experience with fuel cell powered vessels today

[5] Wissner and Cames (2023) – In-depth analysis 1: Future fuels

[6] https://mfame.guru/first-methanol-fuel-cell-powered-vessel/

(Horton et al. 2022). Fuel cells also currently have a shorter lifetime than ICE or a ship, with approx. 15 years compared to 30 years of an ICE (Horton et al. 2022; Korberg et al. 2021). Considering these technical constraints, fuel cells are rather a propulsion solution for the longer term. However, fuel cells might also play a role in more complex hybrid systems alongside electric motors for propulsion, batteries for energy storage and generator set (engine plus alternator/generator) (DNV 2022b).

1.4 Retrofit versus newbuild

Faced with all these future fuel options and their (dis)advantages regarding storage, safety and compatibility, shipowners will need to make investment decisions soon given the long lifetime of vessels. Is a near-term retrofit a better solution than investing in a newbuild? Can vessels be prepared for a later retrofit when the policy landscape is more certain? The industry has just started to think about these questions (e.g., MMKMC 2022). While there is no universal answer to these questions, there are some aspects to consider besides costs (chapter 3).

The viability of retrofitting a vessel to run on a future fuel or to order a new vessel is critical considering the 2050 climate targets by the IMO or the EU and the long lifetime of vessels. Smith et al. (2021) estimate that almost half of the global fleet in 2050 will be compromised of vessels which are retrofitted to run on future fuels. The investment decision - whether and when a retrofit or a newbuild is worth it - depends on different factors, including:

- remaining lifetime of a ship,
- overall cost of running a ship on a future fuel for a retrofit or newbuild,
- risk assessment,
- certainty of (future) regulation, and
- split incentives of ship owners versus shipping company/charterer.

For example, the cost of retrofitting a vessel has to be weighed against the remaining lifetime of the vessel (return of investment) and the fact that a newbuild is likely more efficient from the start. Generally, the process of retrofitting a marine vessel is not clearly defined: it could entail exchanging small pieces in the engine or a modification on ship-level (such as engine and fuel systems) or energy efficiency measures (like installing air lubrication technologies).

The **age** of a vessel and its remaining lifetime are a key parameter for a retrofitting decision. A vessel closer to the end of its life is less likely to receive investments for a retrofit than a newer vessel. The average demolition age and lifetime of a ship are in the range of 23 and 45 years, depending on the ship type, with an overall average of about 25 years (EC 2021b; Horton et al. 2022). Retrofitting activity will thus vary for different ship types up to 2050. Industry experts indicate that today ships which are up to 5 years old are the strongest candidates for retrofits, whereas older vessels are better suited for less costly retrofits (like methanol) or only drop-in fuels (GtZ 2021).

Each retrofit requires the ship to be out-of-service for one or up to a few months depending on the extent of the retrofit. Further, the interviewed experts highlighted that shipyard capacities are fully booked for the next three years, which impedes planning and decisions on retrofits and newbuilds. In addition to the age, the likelihood of a retrofit is also influenced by the ‘value’ of the shipping segment and the **complexity** of the required retrofit. Higher value segments or those with high demand pressures and margins (such as large cargo vessels and cruise ships) have a higher likelihood for retrofits whereas cheaper vessel types (like small bulk carriers) are more likely to be replaced by newbuilds (GtZ 2021). Also, tankers or gas carriers might start out transporting a future fuel, like ammonia, and later be retrofitted to use that cargo also as a fuel to power the ship because the transition is easier compared to other conversions. While engines can be relatively easily modified, the fuel systems require more effort and investment. Generally, it would be possible to retrofit a ship or engine to be compatible with any future fuel. For example, all electronically-controlled engines of engine manufacturer MAN can be retrofitted to run on any alternative fuel in principle (Aabo 2023). The extent of the retrofit depends not only on the characteristics of the new fuel but also on how the respective vessel has previously been fuelled (e.g. mono-fuel HFO/MGO, LNG-fuelled or diesel-electric propulsion system). For example, it requires more effort to transition a ship running on HFO (mono-fuel engine) to a dual-fuel ammonia engine than retrofitting an LNG ship to run on ammonia (EC 2021b). The main engine is also the smallest cost factor in a retrofit compared to the fuel system or loss of cargo-carrying capacity (see chapter 3). From a lifecycle or rather a systemic perspective, the GHG emissions from building a new vessel (incl. the necessary steel) could be compared against the emissions from retrofitting and continuing the lifetime of an existing (likely less efficient) vessel.

Whether retrofitting a vessel with a new engine or designing a newbuild vessel, **dual-fuel (DF) engines** are thought to provide the most flexibility for the future. The modelling in DNV GL (2020b) shows that DF methanol and ammonia engines are a promising solution up to 2050, partly because the increasing number of DF LNG engines can be retrofitted to become methanol or ammonia engines. DF engines, whether Otto or Diesel cycle, generally provide the flexibility to switch between two fuels. As the supply of RFNBOs will likely be limited in the short to middle term, DF engines provide the opportunity to use fossil or biofuels if RFNBOs are not available. Except for diesel-like fuels, future fuels will require a pilot fuel in modern (DF) engines (section 1.2). Therefore, most current and future DF engines are actually Tri-fuel engines. Nowadays, a DF LNG engines can run, for example, on fossil LNG and HFO, but the combustion of LNG requires small amounts of fossil diesel or HFO as a pilot. Future DF engines might be able to run on one readily available fossil fuel or biodiesel and on one harder-to-ignite future fuel such as methanol or ammonia with e-diesel as a pilot. However, not all combinations (like methanol together with ammonia) will be possible in a DF engine.[7] In 2022, more than half of all 2-stroke new orders at the major marine engine manufacturer MAN are dual-fuel engines (Aabo 2023).

Shipping companies and classification societies are exploring ways in which newbuilds can be designed and retrofits implemented, given the uncertainty about future fuels and corresponding regulations. Considering the long lifetime of ships, all newbuilds today should be ready in some way to immediately run on future fuels or to be easily convertible. DF engines play a key role in allowing for future flexibility in the fuel choice but other considerations in the ship design matter, too. This future-proofing of vessels or engines is sometimes referred to as “**x-ready,**” for example ammonia- or methanol-ready. This term is not, however, clearly defined. For example,

[7] https://www.globalmaritimeforum.org/news/engines-and-onboard-systems

an ammonia-ready vessel could entail that the ship design considers what pumps, pipes and safety measures are suitable for ammonia. An ammonia-ready engine might simply describe that an engine can be easily retrofitted to run on ammonia. Stakeholders have confirmed that the concept of "x-readiness" is not clearly defined and that even a "x-ready" declared ship might still involve a considerable amount of investment to be a zero-emission vessel. Ensuring a retrofit or new-build to be "x-ready" depends again on the ship type, liner or tramp shipping, the fuel strategy chosen and more. The following list is an example of necessary considerations and preparations for a fuel-/x-ready newbuild or retrofitted vessel design based on a LNG-fuelled bulk carrier case study by DNV GL (2021b): capacity requirements of the potential future fuel including weight of tank and fuel, material compatibility, accounting for hazardous and toxic zones, hull strengthening to support tank structure, checking trim and stability calculations with new fuel tanks, modification of main and auxiliary engines and fuel supply system, etc.

Overall, retrofitting will play a crucial role in the transition of the sector up to 2050. The percentage of newbuilds capable running on alternative fuels (incl. LNG) is increasing (DNV 2022b) and simultaneously retrofitting programs[8] have also already started. The extent of retrofits, however, remains difficult to predict as the interviewed experts highlighted that the decision about a retrofit or a newbuild will be individual for each ship. The cost-benefit of a retrofit versus a newbuild also depends on the risk of stranded assets. Based on calculations on stranded assets of LNG ships, Fricaudet et al. (2022, p. 5) argue that "*[e]arly clarification of policy is key for avoiding a build-up of stranded value in the shipping industry*". The (un)certainty about future regulation and choice of fuel will thus influence the share of retrofits up to 2050.

2 Tank-to-wake GHG and air pollutant emissions

Emissions from ICE

Bio- and e-**diesel** emit similar amounts of CO_2 TtW as HFO or MGO. If produced with renewable energy and CO_2 from renewable sources,[9] the net (WtW) emissions of CO_2 should be zero for e-diesel (LR; UMAS 2020). E-diesel burns much more cleanly than conventional marine fuels, thus reducing air pollutant emissions (Schmied et al. 2015). Depending on the assumed carbon sequestration and land-use change emissions from the biodiesel variants considered upstream,[10] only a few biodiesel types discussed in this paper achieve WtW GHG emissions of around zero, e.g. FT biodiesel made from Miscanthus or corn stover (Zhou et al. 2020). FAME biodiesel has a very low sulfur content and thus reduces SO_x and particulate matter emissions drastically compared to HFO or MGO (Zhou et al. 2020). NO_x emissions from FAME biodiesel vary depending on the engine but are lower than in the case of conventional fuels (Zhou et al. 2020). Hydrotreated renewable and FT biodiesel have zero SO_x emissions when used neat and also offer reductions when used in blends (Zhou et al. 2020). Particulate matter emissions are also reduced and NO_x emissions slightly (Zhou et al. 2020).

Generally, **LNG** engines produce lower amounts of CO_2 than HFO- or MGO-powered engines. The combustion emissions of CO_2 are ideally compensated by CO_2 from renewable sources as an

[8] https://www.hapag-lloyd.com/en/company/press/releases/2022/08/investing-in-sustainability--hapag-lloyd-to-make-existing-fleet-.html

[9] Wissner and Cames (2023) – In-depth analysis 1: Future fuels

[10] Wissner and Cames (2023) – In-depth analysis 1: Future fuels

input in the production process.[11] Values for TtW GHG emissions from methane vary across studies and strongly depend on the engine used and the resulting methane slip. New high-pressure LNG engines can reduce methane slip to very low levels (0.15 % of fuel consumed) but unfortunately represent only a minor share compared to popular low-pressure DF LNG engines with a high methane slip (3.53 %)(Horton et al. 2022; Pavlenko et al. 2020; Comer et al. 2022). Depending on the engine used, the combustion of bio- or e-methane can thus result in lower GHG emissions than from MGO or HFO (Pavlenko et al. 2020). There are basically no SO_x emissions from methane combustion and particulate matter emissions are much lower than in the case of HFO (Horton et al. 2022). NO_x emissions are also lower when compared to fossil marine fuels but could additionally be treated with exhaust gas after-treatment systems (DNV GL 2018).

Similar to diesel-like fuels, TtW GHG emissions from bio- or e-**methanol** have the same order of magnitude as from fossil methanol. Again, these emissions are compensated by negative WtT emissions.[12] Methanol combustion will produce NO_x emissions, though in lower amounts than from HFO or MGO (LR; UMAS 2019; Zhou et al. 2020). The amount of NO_x emissions depends on the engine; they will not be below Tier III limits and will thus require exhaust gas after-treatment systems (EGR o SCR) (DNV GL 2018). Bio- or e-methanol combustion results in no (significant) SO_x or particulate matter emissions and will mainly occur due to the pilot fuel (Zhou et al. (2020), expert interviews).

As ICE running on **ammonia** are still being developed, there is a lack of studies and data on the TtW GHG and air pollutant emissions. It is expected, however, that the combustion of ammonia will result in emissions of NO_x which can be sufficiently treated with exhaust gas aftertreatment systems (Ash and Scarbrough 2019; MAN 2019). Ammonia slip might also occur but can be addressed through engine calibrations and controlled combustion conditions or via ammonia slip catalysts, which exist for land-based and road transport (MAN 2019; Ash and Scarbrough 2019). The greatest concern regarding TtW emissions from ammonia are potential emissions of N_2O, which is a very potent GHG. N_2O could be reduced by modifying the combustion process (like increasing the temperature) (Niki et al. 2019a; 2019b). Engine manufacturers are currently working to solve this issue and are testing modifications to the combustion process. The interviewed experts indicated that first tests show the emissions of N_2O will be in the range of 5-10ppm in the flue gas, which is comparable to the Global Warming Potential of 1g/kWh of methane slip (which is similar to the lowest level of methane slip achievable by high-pressure dual-fuel engines as reported in Pavlenko et al. (2020)). Engine manufacturers are further exploring N_2O abatement technologies by removing N_2O from the exhaust gas with ammonia as a reducing agent in case that engine optimizations are not sufficient to handle N_2O (Aabo 2023). There are no particulate matter emissions to be expected from combusting ammonia (LR; UMAS 2019).

The combustion of **hydrogen** will result in no direct TtW GHG emissions, but emissions of water vapour and potential hydrogen slippage can have (an indirect) global warming potential.[13] NO_x

[11] Wissner and Cames (2023) – In-depth analysis 1: Future fuels

[12] Wissner and Cames (2023) – In-depth analysis 1: Future fuels

[13] Wissner et al. (2023) – In-depth analysis 3: Lifecycle emissions of future fuels

emissions can occur (Horton et al. 2022). There are no SO_x or particulate matter emissions from hydrogen combustion (LR; UMAS 2019).

If future fuels require a pilot fuel (Table 2), additional emissions are created through the combustion of the pilot fuel. As this will likely be a diesel-like fuel, the TtW emission factor will be similar to the ones mentioned before of bio- or e-diesel.

If only CO_2 emissions are considered, ammonia, hydrogen and bio- and e-methane offer significant reductions in TtW emissions. There is thus an incentive to use these fuels if maritime climate policies consider only CO_2 emissions upon combustion. The actual climate benefit of future fuels is determined, however, by the complete WtW emissions profile of all relevant GHGs. For example, the EU ETS for maritime transport will be a step in the right direction when including not only CO_2, but also methane and N_2O emissions in the long term. Ammonia and hydrogen offer the largest reduction in GHG emissions when used in ICE from a TtW perspective. Carbon-based future fuels offer no TtW GHG emissions reductions compared to their fossil counterparts. Methane performs better than diesel-like fuels. Concerns about N_2O emissions from ammonia persists as ammonia engines are still being developed. First tests from engine developers indicate, however, that with the optimal engine design, N_2O emissions can be lowered to amounts with a similar climate impact as 1 g/kWh of methane slip. While the advantage of ammonia and hydrogen from a TtW perspective is clear from the above, the real climate impact of all future fuels is determined by the WtW emissions. If policies only consider TtW GHG emissions, climate benefits from carbon-based future fuels are not distinguishable from their fossil counterparts. The complete WtW emissions profile is further addressed in in-depth paper 3.[14]

All future fuels offer a significant reduction or even the avoidance of SO_x and particulate matter emissions. NO_x emissions can be produced by all future fuels to varying degrees. An existing exhaust gas after-treatment system can be applied here. Therefore, future fuels are able to comply with existing emission control areas, e.g. in EU waters, and offer reduced health risks for the population in coastal regions.

Emissions from fuel cells

Fuel cells are expected to provide lower emission and air pollutant levels compared to ICE. If hydrogen is used to power the fuel cell, (TtW) GHG emissions are likely to be zero as the products from the fuel cell reaction are only water, electricity and excess heat (Horton et al. 2022). Also, air pollutants, such as SO_x, particulate matter and NO_x, are not expected for hydrogen fuel cells (Vries 2019; DNV GL 2018).

Ammonia needs to be reformed in order to use the hydrogen in a PEMFC. As above, hydrogen-fuelled PEMFC will not produce emissions of air pollutants and GHGs (Tronstad et al. 2017; Vries 2019). Emissions from ammonia SOFC are still uncertain due to a lack of tests (Hansson et al. 2020). They will, however, be significantly lower compared to ICE (Ash and Scarbrough 2019). According to Vries (2019) and KR (2020), there will be no NO_x emissions from ammonia SOFC.

Methanol fuel cells produce CO_2 emissions, but reduce air pollutants like other fuels used in fuel cells (Horton et al. 2022; Tronstad et al. 2017).

[14] Wissner et al. (2023) – In-depth analysis 3: Lifecycle emissions of future fuels

Fuel cells thus have the potential of TtW GHG (with regard to energy efficiency) and air pollutant emissions, which are significantly lower than emissions from ICE. The amount and kind of emissions depend on the fuel used to power the fuel cell. The advantage of fuel cell regarding emissions is, however, currently still outweighed by other unfavorable aspects of fuel cell (such as lifetime, costs, technological readiness) (section 1.3).

3 Costs and operational changes

From a shipowner perspective, the decision for a future fuel and for an investment in a retrofit or newbuild depends to a large degree on cost. Different costs arise compared to a baseline of using fossil marine fuels: capital costs for new fuel systems including storage, operational costs (fuel cost, crew, port charges) and potential revenue loss (due to loss of transport capacity). Together, these costs are called the total cost of operation or ownership (TCO). Generally, an asset with a lower TCO has a greater value in the long run.

Capital expenditure or capital costs are higher for those future fuels which differ the most from current marine fuels regarding energy density and other characteristics (see Table 1). Toxicity and flammability also impact the investment cost upfront as new safety installations and different fuel storage systems that are more expensive might be necessary, especially in the case of ammonia. Capital costs also include investments in new or retrofitted engines as well as complementary components, such as reformers or exhaust gas after-treatment systems. During operation, costs are determined by fuel cost, port chargers etc. and by potential losses of transport capacity if future fuels require more space onboard compared to the baseline of using HFO/MGO. Operational expenditure might also increase compared to the baseline if additional safety measures need to be integrated in the daily operations.

As ships transport varying amounts of goods or passengers and as the value of the cargo differs, a potential loss of cargo space in favour of storage space for a future fuel is not equally impactful for each shipping segment.

Table 3 shows the cost of cargo space loss for different voyage lengths and ship types. As can be seen, ferries and particularly container ships face higher revenue losses. Given the variety within, for example, ferries, values shown are only an indication of the revenue loss. TCO of vessels running on future fuels which require much more storage space than HFO or MGO (section 1.1) are thus higher for shipping segments where cargo space is more valuable.

Generally, absolute TCO vary depending on the ship type and size. Container ships usually have higher TCO than bulk carriers, tanker or ferries (Korberg et al. 2021; MMKMC 2021b). Considering size, cargo loss is, for example, a more significant part of the TCO for a very small bulk carrier than for a large deep-sea bulk carrier (LR; UMAS 2020). Nevertheless, loss of cargo-carrying capacity plays only a minor role for bulk carriers compared to other cost drivers of TCO (ibid). The overall market situation additionally influences the cost of cargo loss. Given the abrupt reduced demand in the last months, cargo capacity reduction would be less problematic today than a few years ago (UNCTAD 2022).

Table 3 - Cost of cargo space loss

Voyage length	General cargo ship [€/t of space loss per day]	Bulk carrier [€/t of space loss per day]	Ferry [€/m3 of space loss]	Container ship [€/TEU/trip]
Short	0.1	0.1	6	600
Medium			8	900
Long			10	1100

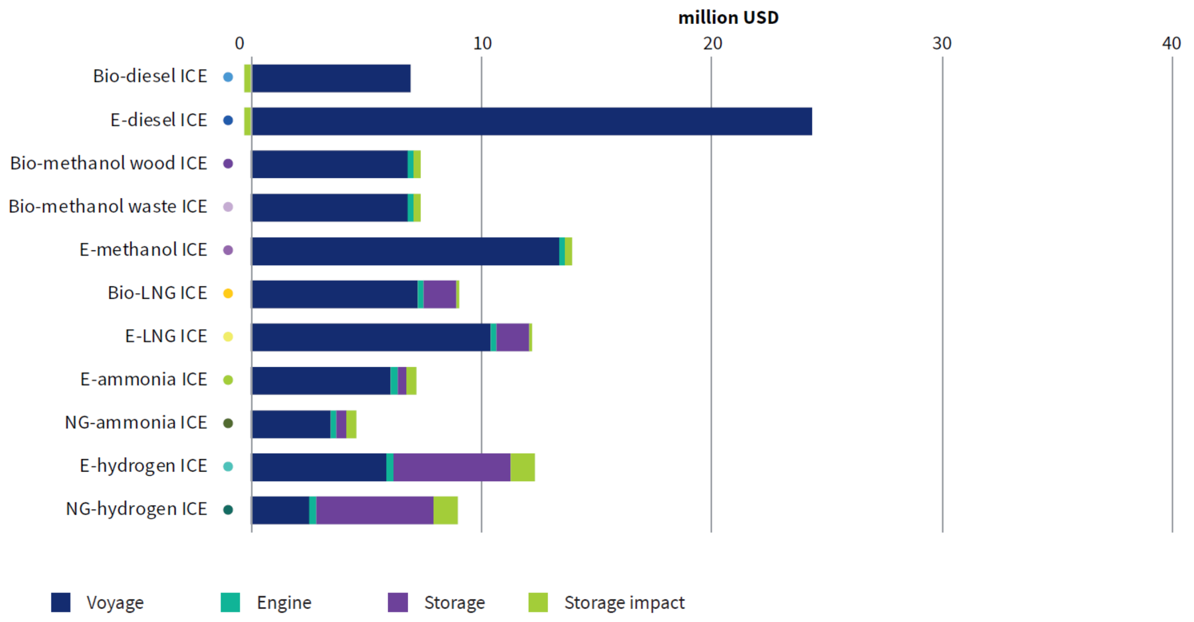
Source: Korberg et al. (2021)

A few studies have been conducted on the TCO of different fuels and ship types (MMKMC 2021b; LR; UMAS 2020; Korberg et al. 2021; Horvath et al. 2018). Typically, these studies include capital costs for fuel storage systems, investments in engines, potential losses of cargo capacity and the fuel costs in the TCO. Nowadays, fuel costs represent about 20-35 % of TCO. Fuel costs have a higher share in TCO of container vessels than of tanker or bulk vessels (MMKMC 2021b). In the future, fuel-related costs will constitute the largest share (>80 % for ICE propulsion) of TCO (LR; UMAS 2020; Korberg et al. 2021).

ICE-propelled vessels

Figure 3 provides an overview of the TCO in 2050 and the different cost shares for the fuels analyzed in LR; UMAS (2020). Depending on the assumed price scenarios, fuels with high fuel cost have a disadvantage over fuels with low fuel costs despite higher capital cost of the latter.

Figure 3 - Cost components of TCO of a bulk carrier in 2050



Source: LR; UMAS (2020), low-price scenario assuming no carbon price. NG = natural gas, ICE = internal combustion engine

- For **diesel**-like future fuels, capital costs for a newbuild are the same as for previous HFO-fuelled vessels as the fuel properties are similar to current fossil fuels. However, operational costs differ compared to a reference HFO ship as fuel costs will be much higher (LR; UMAS 2020), but also different for advanced biofuels versus RFNBOs (see in-depth paper 1 on Future Fuels[15]).
- Also for vessels with a **methanol** ICE, most of the TCO is made up of voyage costs which are mainly fuel costs (LR; UMAS 2020). Only a few percent of the TCO can be attributed to higher capital costs for new engines and revenue loss due the storage impact compared to a fossil reference ship (ibid).
- TCO for bio- or e-**methane** vessels are also dominated by voyage costs but capital costs for the fuel storage and engine make up a larger share compared to a methanol-fuelled vessel (LR; UMAS 2020). The revenue loss due to the storage impact is considered to be comparable or even smaller than for a methanol vessel in LR; UMAS (2020).
- The share of capital costs for engine and fuel storage is smaller for **ammonia**-fuelled than methane-fuelled vessels, with voyage cost again making up the largest share of TCO (LR; UMAS 2020). The storage impact on revenue loss is considered to be higher than for methanol- or methane-fuelled ships (ibid).
- Finally, capital costs for storage are about one third to half of the TCO of **hydrogen**-fuelled vessels with an additional considerable storage impact/revenue loss on TCO (LR; UMAS 2020).

It is difficult to compare absolute TCO between studies as different assumptions and fuels included lead to very different absolute costs (Stolz et al. 2022). For example, very optimistic assumptions of future fuel and electricity costs as well as direct air capture costs result in substantially lower TCO in Horvath et al. (2018) than in LR; UMAS (2020) and Korberg et al. (2021). However, it is still possible to derive conclusions on a relative basis from the available studies (MMKMC 2021b; LR; UMAS 2020; Korberg et al. 2021; Horvath et al. 2018):

- TCO for RFNBOs are thought to decrease across all studies up to 2050;
- Running vessels on biofuels is cheaper than on RNFBOs, but LR; UMAS (2020) assume that increasing biofuel prices and decreasing electricity cost can turn the picture around until 2050 for all RFNBOs (except for e-diesel);
- E-methane and/or e-diesel were always found to be the options with the highest cost depending on the study;

[15] Wissner and Cames (2023) – In-depth analysis 1: Future fuels

- Based on case studies for bulk carriers and container ships, e-ammonia or e-methanol is the RFNBO option with the lowest TCO in 2030;
- Container ships will face higher TCO for future fuels than other ship types such as bulk carriers or tankers;
- Influential factors for the future development of TCO are electricity prices and derived fuel costs and, to a lesser degree, investment costs and the efficiency of propulsion systems.

TCO influence not only the choice of future fuel but also whether or not retrofits are worth it. MMKMC (2022) recommend on the basis of conversion and newbuild costs that if a vessel is planned to run on methanol within the next five years, a dual-fuel newbuild has the lowest costs. If methanol operation is planned in five years or more, retrofitting the existing vessel to varying degrees might be better value.

Overall, costs and investments on land (for fuel infrastructure and production) will outpace the costs onboard or within the maritime sector (DNV 2022b). Future TCO of vessels running on future fuels can, however, be influenced by policies. If regulations decrease the electricity costs and if climate policies, like carbon pricing, incentivize certain production pathways, particularly the share of operational cost of TCO (i.e. the fuel cost) might change. For example, ETC (2018) expand the modelling carried out by LR; UMAS (2020) and find that fuelling a bulk carrier with ammonia would be cheaper than HFO if electricity prices were less than USD 0.06 per kWh with a carbon price of USD 300 per tonne of CO_2.

Fuel cell-powered vessels

Fuel cells (systems) are more costly than ICE (systems) (Vries 2019; Horton et al. 2022). The case study for bulk carriers by LR; UMAS (2020) shows that the fuel cell option is always more expensive than the ICE options for each future fuel because the capital costs are higher. The higher capital costs consist not only of the fuel cell cost but also of costs for reformers – in case of hydrogen-carriers like methanol – or purification appliances (Cames et al. 2023). However, Wu et al. (2022) find that while CAPEX of an ammonia SOFC system is higher, OPEX are comparable and conclude that the overall cumulative costs of an ammonia SOFC propelled vessel is competitive with an LNG or HFO fuelled vessel. Future decreases in investment costs or even higher efficiencies of the fuel cell system than ICE would be needed for fuel cells to outcompete ICE, both of which are rather unlikely up to 2030 given the current costs and technology readiness levels (Korberg et al. 2021).

4 Conclusion

Safety precautions and regulations are important for the large-scale introduction of future fuels in shipping. For methanol, ammonia and hydrogen, international safety regulations are still lacking but are a key parameter for investment decisions on future fuels. There are concerns about the toxicity of methanol and ammonia in particular. Methanol has a head start with preliminary guidelines and first methanol-fuelled ships already in operation whereas ammonia is still lacking pilot projects and experience. With only a few years remaining, the years up to 2030 will likely be decisive for the technological readiness and competition between these two fuels.

It is clear that current voyages or transport work cannot be achieved with all future fuels. The actual impact of the differing energy densities of future fuels (except bio- and e-diesel) will depend on factors such as cargo space loss, current bunkering frequency, trade routes and vessel design. Depending on the future use of the vessel, shipowners might decide to accept a loss in cargo-carrying capacity if operating range and refuelling pattern can be maintained whereas in other use cases, a reduction of cargo-carrying capacity will not be needed as ships can simply refuel more often along their trade route.

Only bio- and e-diesel can be blended with MGO at significant amounts. Except for ammonia and hydrogen, future fuels will be compatible with engines available in the market today. Dual-fuel engines and retrofitting options will be crucial for the transition of the sector to ensure flexibility given the uncertainty about future fuels. While many retrofits are possible in theory, the challenge for shipowners will be to evaluate the cost-benefit of a retrofit versus a newbuild.

Future fuels could also be used in fuel cell systems. However, their application in shipping might be limited to certain distances and ship types and, in addition, limited by even higher investment costs, volume and weight.

Ammonia and hydrogen offer the largest GHG emission reductions from a TtW perspective. All relevant GHG need to be considered when designing policies to incentivize future fuels (as in the EU ETS for maritime transport). The real climate impact of all future fuels is determined by their WtW emissions. If policies only consider TtW GHG emissions, the climate benefits from carbon-based future fuels are not distinguishable from their fossil counterparts and even carbon-free future fuels with high WtT emissions would be compliant (e.g. ammonia produced with natural gas or hydrogen produced with electricity from lignite).

The air pollutant levels of future fuels comply with existing emission control areas, e.g. in EU waters, and future fuels offer reduced health risks for the population in coastal regions. The use of future fuels is thus also beneficial from a health perspective.

Technical challenges onboard are smaller compared to the challenge of sufficient supply of future fuels. A business case exists to trigger investments in future fuels (and future-fuel capable ships) through, for example, climate policies/regulations. Policy makers need to focus, therefore, financial flows on the production of future fuels and reducing the production costs as well as setting the right incentives so that shipowners can make long-term decisions. Industry stakeholders highlight that decisions can be made relatively quickly in the shipping industry if there is certainty. For example, as soon as the global sulphur regulations of the IMO became binding, scrubbers were quickly sold out.

From a TCO perspective, fuel costs will determine the choice of the future fuel. Studies have found that both methanol- and ammonia-fuelled vessels will have the lowest TCO in future, assuming that advanced biofuels will remain limited and expensive in future.

To date, ships have been built for a very specific purpose and bought as cheaply as possible. Policies or regulations for the transition of the shipping industry need to incentivize a transition which also allows for flexibility since a future fuel is not yet known and for rewarding first movers/over-achievers. Interviewees highlighted that if over-compliance is rewarded, ships would be built for the long run and to comply with climate policies. Otherwise, ships would be built to meet only the minimum requirements, making future improvements more difficult.

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