Fuel Shortlist Analysis - Summary

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Approach

The main fuel of the NAUTILUS project is LNG. However, since it is often seen as transitional fuel, we are also interested in the application of other fuels for Solid Oxid Fuel Cells (SOFC) in cruise ships. A shortlist of four other future fuels is established as alternatives of LNG, which will be used in the consortium for a technical-, economical-, emission- and life cycle analysis.

At the first stage a longlist of future fuels was established. The longlist of fuels is provided in Table 1 and includes **hydrogen (LH2), biodiesel (BIO D), Fischer-Tropsch diesel (FT D), methanol (MeOH), ethanol (EtOH), dimethyl ether (DME) and ammonia (NH3).** The analysis includes fuels regardless of their primary feedstock, meaning that they are mainly defined by the technology they require to use on the ship.

Table 1: Longlist of fuels that are of interest to marine sector and can be used with SOFC, including their onboard storage technique.

Longlist	Fuel	Storage Technique
MGO (benchmark)	*Marine gas oil*	Liquid (Amb. T)
LH2	*Hydrogen*	Cryogenic (-253°C)
BIO D	*Biodiesel*	Liquid (Amb. T)
FT D	*Fischer-Tropsch Diesel*	Liquid (Amb. T)
LNG (main fuel of NAUTILUS)	*Liquefied Natural Gas*	Cryogenic (-162°C)
MeOH	*Methanol*	Liquid (Amb. T)
EtOH	*Ethanol*	Liquid (Amb. T)
DME	*Dimethyl ether*	Compressed (5 bar)
NH3	*Ammonia*	Cryogenic (-33°C)

Several criteria were defined (Table 2), on which fuels are evaluated for the current situation. In the end, a shortlist of four fuels (besides LNG) were selected. The criteria included: practical, technical, economic, and environmental considerations. Size of the reforming plan, maintenance costs and bunker speed are also valuable criteria, but were not considered in this analysis.

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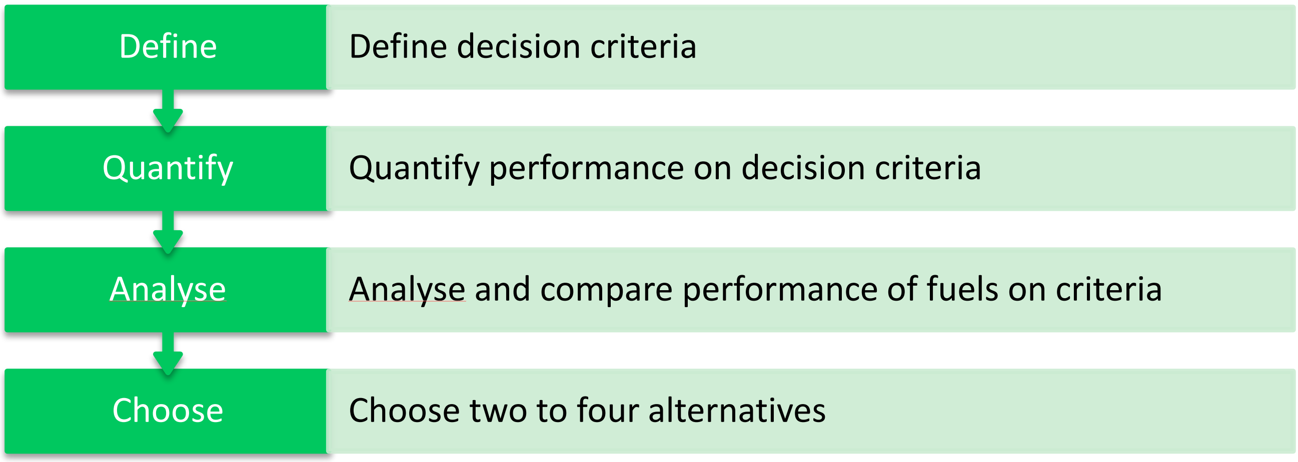

Table 2: Decision criteria

Criteria	Type of criteria	Influenced by
Production capacity	Availability	Supply chain
Volumetric energy density	Ship design	Storage system, efficiency of whole system
Gravimetric energy density	Ship design	Storage system, efficiency of whole system
TRL	Technical feasibility	Fuel storage, fuel processing, interaction with fuel cell
Safety	Technical feasibility	Toxicity, flammability, explosivity, corrosivity
Fuel cost	Economical	Efficiency of powerplant, fuel production, fuel transport, fuel storage, future prognosis
Cost fuel storage system	Economical	Storage system, efficiency of system
Environmental impact	Environmental	Emissions, materials, lifetime

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Analysis

The different fuels are evaluated on the criteria of Table 2. A part of the analysis is shown in the following sections. During the evaluation, it was considered that the future fuels must be applied on long-haul cruise ships and/or expedition cruise ships.

Production capacity

To get a feeling of the required scale up to apply the future fuel, the supply of marine fuels is compared with the production capacity of the future fuels, see Figure 1. Most alternative fuels have comparable or higher global supply as the common marine fuels. However, the supply of DME and liquefied hydrogen is still very low and would require a massive scale-up for wide application in the marine industry. Nevertheless, it must be noted that the capacity of DME and especially LH2 is rapidly growing. The capacity of Fischer-Tropsch Diesel is larger, but would still need significant scale up.

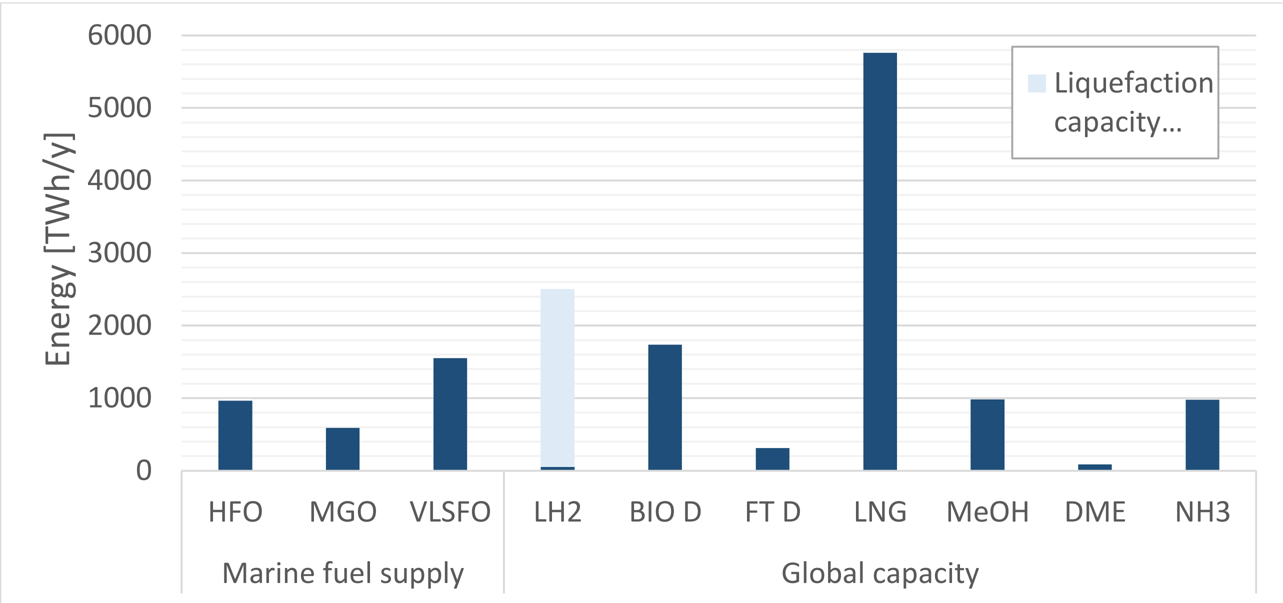

Figure 1: Global supply of marine fuels and global capacity of considered alternative fuels in Tera Watthour per year. The light blue bar does not include liquefication capacity. Data is mainly from 2021, otherwise as close as possible to 2021 (Food and Agriculture Organization of the United Nations, 2019; Fleisch, 2012; IEA, 2019; IEA, 2020; IEA, 2021; Methanol Institute, 2020; Prabowo et al., 2017).

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Energy density

Current marine fuels (e.g., Heavy Fuel Oil - HFO, Marine gasoil - MGO) can be stored very energy densely. Most of the alternative fuels struggle with low energy density. Partly due to the lower energy density of the fuels and partly due to physical conditions of storage (some fuels must be stored in pressurized tanks, which are heavy and require insulation). The volumetric energy densities for onboard fuel storage are compared in Figure 2. It is visible that MGO and biodiesel can be stored quite energy dense. Fischer-Tropsch diesel can be stored at the highest energy density, since the composition of the diesel is very modifiable during the production process. Compared with the other future fuels, cryogenic hydrogen storage has very low energy density. Consequently, much ship volume would be required to fit hydrogen. In cruise ship design, the available space is usually more critical than the weight of the components. Hence, the volumetric energy density is deemed more important that the gravimetric energy density.

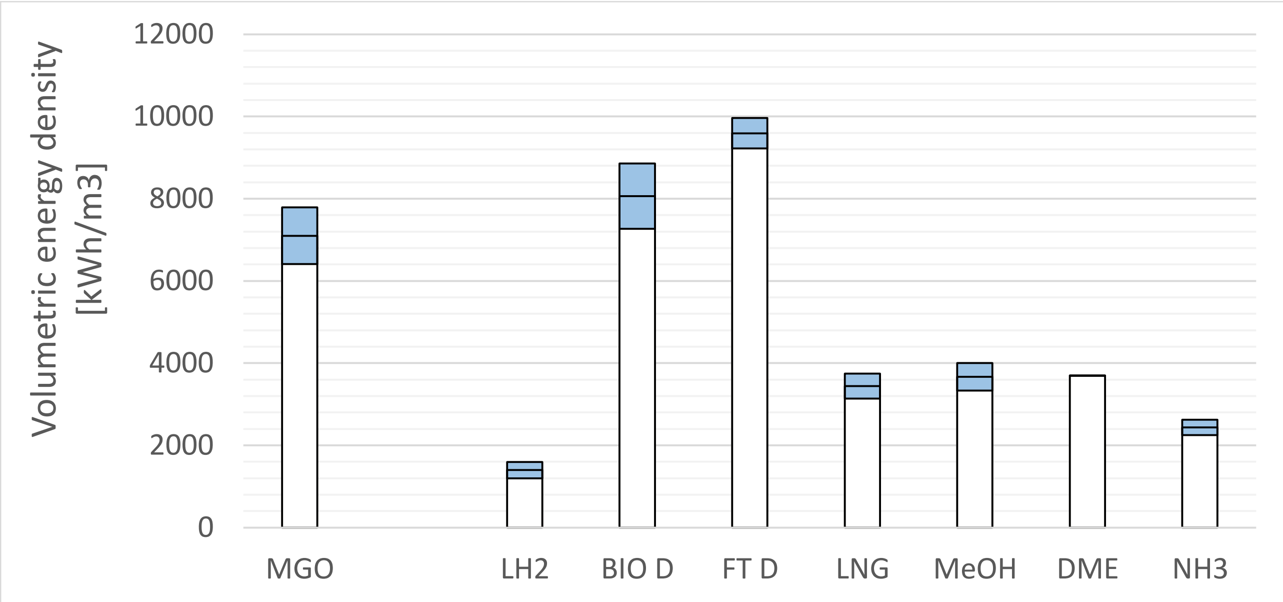

Figure 2: Volumetric energy density of future fuels including the storage system of the concerned fuel. The benchmark (MGO) has been compensated for the efficiency difference between diesel generators (43%) and SOFC (55%). The blue bars show the data ranges found in literature, projects, and supplier specifications. Based on LHV of fuels. (Aceves et al., 2010; Sapra, 2020; van Biert et al., 2016; van Veldhuizen et al., 2020)

Technological readiness level

To evaluate whether a future fuel is applicable in the near future, the fuels are rated based on their technological readiness for marine applications on a scale of one to five (where five means the highest technological readiness). A distinction is made in readiness in fuel infrastructure (production and distribution, bunkering, onboard fuel handling (storage and supply to consumers), and the readiness to be used in combination with SOFC.

Fuel infrastructure

Obviously, diesel infrastructure for marine applications is already in place. It has been stated that diesel infrastructure can be used for methanol after minor adjustment. LNG infrastructure has been increasing last years. Hydrogen, methanol and ammonia infrastructure is already large and can be

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extended when it must be used to fuel ships. DME infrastructure is very small (see also Figure 1) and the knowledge about production storage and distribution is very limited.

Bunkering

The bunkering time is also very dependent on the successful operation of the cruise ship, especially since the energy density of the alternative fuels is lower than that of conventional fuels, it might be needed that the ship is refuelled more regularly, in order to limit cost and size of the fuel storage system. Sufficient bunkering speed is required to guarantee successful operation of the ship. Cryogenic fuels (LNG, LH2) often have a considerably lower fuelling speed. It is expected that the bunker speed of LH2 (which is currently done via trucks) is 10 times lower than diesel. Of course, the technological readiness of diesel bunkering is very high. Since several ships are currently operated on LNG and bunkering can be performed truck to ship or ship to ship, it has moderate bunkering TLR. For methanol bunkering, IGF codes (The International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels) have been established. The other fuels are barely used to bunker ships.

Onboard fuel handling

As was just explained only diesel and LNG have been widely applied to fuel ships. However, LH_2, $MeOH$ and NH_3 are often applied in other industries, meaning there is much knowledge about storage, distribution, system control and safety regarding these fuels. This knowledge would still need to be transferred and converted to the marine industry, hence a moderate TLR for these fuels.

Fuel in combination with SOFC

Most SOFC research has been focused on a LNG-fuelled system. Moreover, all currently commercially available SOFC systems (Solid Power, BlueGen; Mitsubishi, Megamie; Bloom Energy, Energy Server; Hexis, Galileo) are designed for LNG. Most alternative fuels have been theoretically verified or simulated for SOFC systems, however, modifications to the reforming process and the system control are often necessary. Most studies report not difficulties for an ammonia-fuelled SOFC. Most alternative fuels have not been practically tested in a full-scale SOFC system, but methanol has also been physically demonstrated.

Table 3: Technological readiness of fuels on four different areas on a scale of one to five, where five represents the highest technological readiness (Balcombe et al., 2019; DNV GL Maritime, 2016; Geertsma & Krijgsman, 2019; Mohd Noor et al., 2018; van Biert et al., 2016; Wang & Notteboom, 2014; Zhou et al., 2020).

	Fuel infrastructure	Fuel bunkering	On-board fuel handling	Fuel in combination with SOFC
MGO	5	5	5	2
LH2	3	1	2	3
BIO D	3	5	4	1
FT D	3	5	4	2
LNG	4	3	4	5
MeOH	4	3	3	4
DME	1	1	1	1
NH3	4	1	2	3

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Fuel cost

The fuel cost is often a large contributor to the total cost of ownership. SOFC's high efficiency could save fuel cost and gives an opportunity to counteract the high capital cost of SOFC systems. However, some of the alternative fuels are currently very expensive, see **Chyba! Nenalezen zdroj odkazů.**3. Especially blue and green hydrogen have high prices. LNG, MeOH and DME cost similar or even less compared with MGO (after compensating for the efficiency difference between diesel generators and SOFC). Biodiesel and ammonia are more expensive than MGO. Fischer-Tropsch diesel has a large range of fuel cost, since there are many different possibilities in feedstock and production method. It must be noted that over 95% of the currently produced hydrogen (Figure 1) is grey hydrogen, although blue and green hydrogen plants are in number and size.

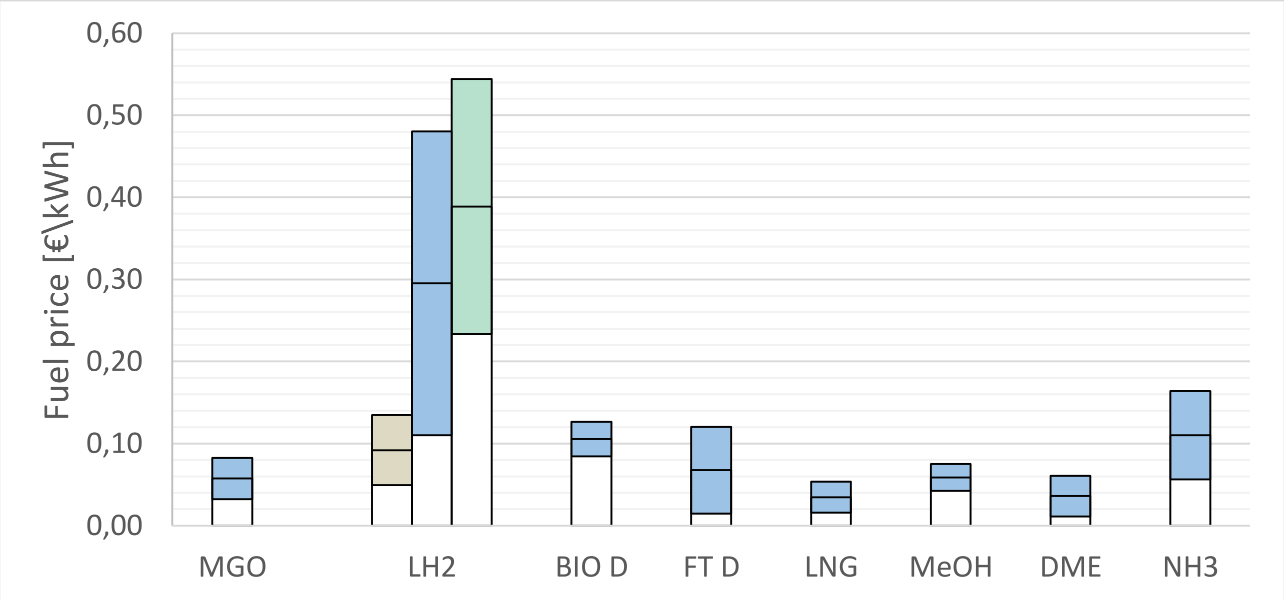

Figure 3 Fuel price of benchmark fuel and longlisted fuels. Due to large discrepancies in fuel price of hydrogen three categories are defined: grey hydrogen (produced from natural gas), blue hydrogen (produced from natural gas with carbon capture) and green hydrogen (produced with sustainable energy). The benchmark (MGO) has been compensated for the efficiency difference between diesel generators (43%) and SOFC (55%). The coloured bars show the data ranges found in literature, projects, and supplier specifications. Data is mainly from 2021, otherwise as close as possible to 2021. Based on LHV of fuels. (Aurora Energy Research, 2020; Baldi et al., 2020; Bloomberg, 2020; Damen, 2020; de Vries, 2019; IEA, 2020; Fleisch, 2012; ING, 2020; Klomp,2015; Rivarolo et al., 2018; S&P Global Platts, 2020; Ship & Bunker, 2021; U.S. Geological Survey, 2021; Volger, 2019; Zhou et al., 2020)

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Shortlist of future fuels

The following fuels are selected for the shortlist:

- ***Methanol***
  Methanol scored very moderately on all criteria. It can be stored at reasonable energy density and relatively low cost of the storage system. Since it is a commodity, scale-up for the marine industry is easier to realise and it is expected that existing infrastructure can be used after small modifications. The price of methanol is comparable to current fuels. All in all, this fuel leads to a solution that can be justified from a technical view as well as from an economical view.
- ***Fischer-Tropsch Diesel***
  Although Fischer-Tropsch cannot be operated without carbon emissions, it can be used carbon neutral relatively easily. The Fischer-Tropsch production has been invented a long time ago and is well-known. Since the substance is so similar to fossil diesels, it can be applied in the fuel infrastructure and in ships, which is a big advantage. It results in high energy density, low fuel storage cost and medium too high fuel price.
- ***Ammonia***
  Although ammonia and its storage system are more expensive than methanol and DME, it is widely available, making it easier to expand its fuel infrastructure. Its energy density is quite low, but still much better than hydrogen stored in cryogenic conditions. Ammonia also results in much lower CO_2-eq emissions compared with the other options.
- ***Hydrogen***
  A long-haul hydrogen-fuelled cruise ship would require such large storage tanks that it would be technically very challenging to design such a vessel. Moreover, the liquefaction capacity of hydrogen is currently very low, accompanied by a low technological readiness. On top of that, the very high fuel- and storage cost would lead to an economically infeasible ship. Finally, although hydrogen is often considered as an ultra-low emission solution, this is only locally and significant emissions are apparent during the production process when produced form natural gas. However, the just described context is merely based on the current situation. Green hydrogen production is increasing rapidly and there exist different technologies that can mitigate the storage disadvantages of hydrogen. Moreover, hydrogen has global political support. Because of its future prospects, hydrogen is still included in the shortlist.

This results in the future fuel shortlist presented in 4:

Table 4: Shortlist of future fuels.

Shortlist	**Fuel**	**Storage Technique**
LNG ***main fuel of NAUTILUS***	Liquefied Natural Gas	Cryogenic -162°C
MeOH	Methanol	Liquid Amb. T
FT D	Fischer-Tropsch Diesel	Liquid Amb. T
NH3	Ammonia	Cryogenic -33°C
LH2	Hydrogen	Cryogenic -253°C

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