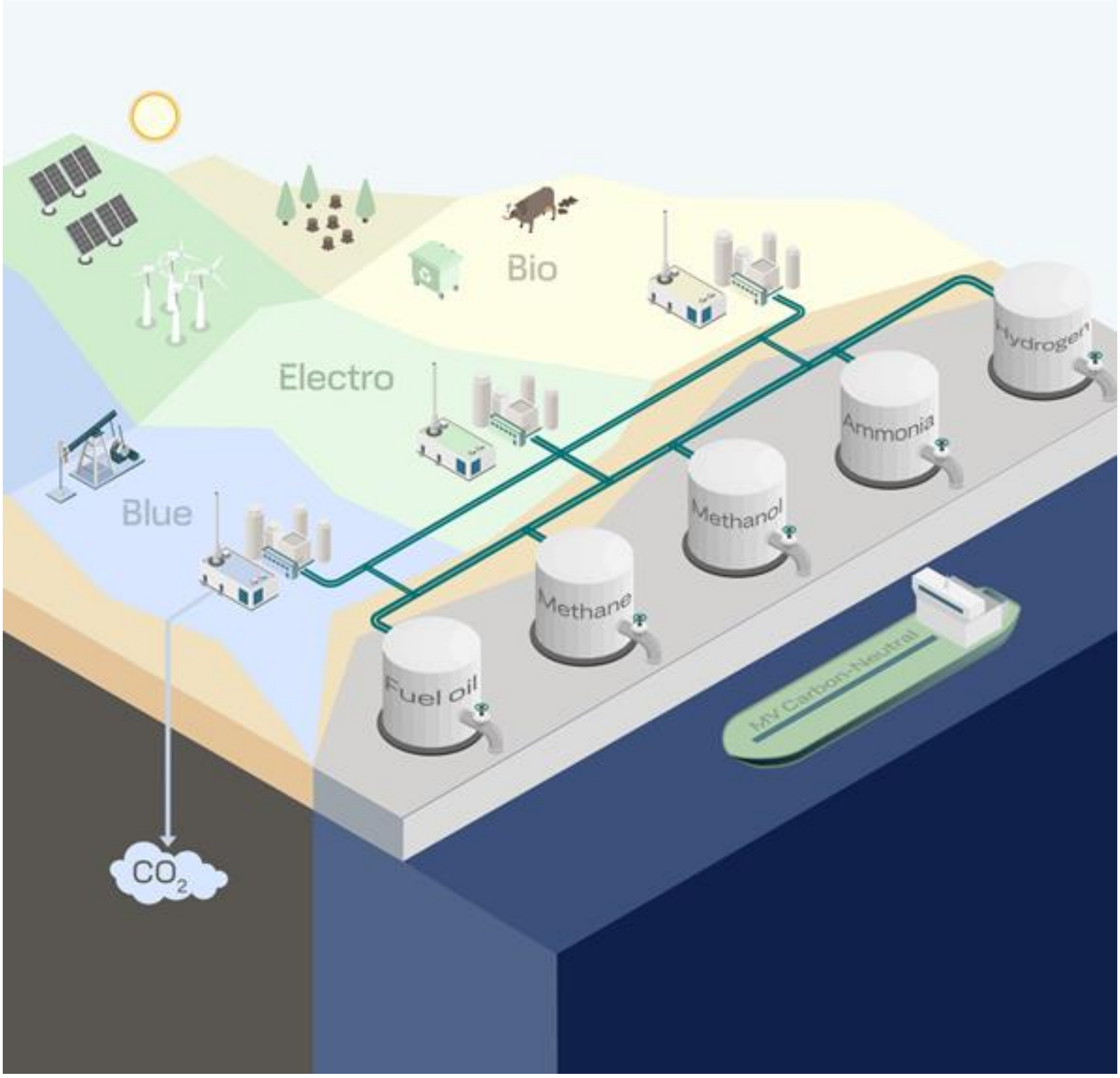
Nordic Roadmap

Future Fuels for Shipping



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Foreword

DNV and partners Chalmers, IVL Swedish Environmental Research Institute, MAN Energy Solutions, Menon and Litehauz have been tasked by the Norwegian Ministry of Climate and Environment on behalf of the Nordic Council of Ministers to develop a Nordic Roadmap for the introduction of sustainable zero-carbon fuels in shipping. The overall aim of the project is “to reduce key barriers to implementation and establish a common roadmap for the whole Nordic region and logistics ecosystem towards zero emission shipping”.

To support this overall aim, Menon Economics is responsible for Task 1-A: Screening of sustainable zero-carbon fuels and has prepared this report. Chalmers, IVL, MAN Energy Solutions, Litehauz and DNV have contributed with valuable input.

5th of October 2022

Even Winje
Partner, Menon Economics

NORDIC ROADMAP FOR THE INTRODUCTION OF SUSTAINABLE ZERO-CARBON FUELS IN SHIPPING

TASK 1A – SCREENING OF SUSTAINABLE ZERO-CARBON FUELS

The Norwegian Ministry of Climate and Environment on behalf of the Nordic Council of Ministers

MENON-PUBLICATION NO. 116/2022

By: Maren Nygård Basso, Serli Abrahamoglu, Henrik Foseid, Piotr Spiewanowski, Even Winje and Erik Jakobsen

Content

Executive summary

The Nordic Roadmap aims to accelerate the transition to zero-carbon fuels by reducing the key barriers to their uptake. The term sustainable zero-carbon fuel is used to indicate fuels with potential zero climate impact throughout their lifecycle. The main objective of this report, Task 1A, is to screen and provide a scorecard for the most promising sustainable zero-carbon fuels in a Nordic perspective, including identifying barriers and development needs. The task report can be used as a standalone knowledge base, but also serve as an initial screening and for the in-depth analyses carried out in the project with regards to Life Cycle Assessments (LCA), regulatory and safety challenges and infrastructure barriers.[1]

Methodology – a three step approach

In Task 1A we have conducted a systematic review of relevant sustainable zero-carbon fuels for maritime transportation in the Nordics. The review is based on an assessment of a broad specter of key performance indicators (KPIs) developed and analyzed through a three-step operational framework which is described below.

Step 1 - Identification of relevant sustainable zero-carbon fuels: Through an expert assessment by the members of the consortium and an initial literature review we identified six sustainable zero-carbon fuels for the analysis: battery-electric propulsion, hydrogen, ammonia, methane, methanol and hydrotreated vegetable oil (HVO). We have also separated between the most relevant production paths for each fuel, e.g., green and blue hydrogen and ammonia, and e- and bio-methane and methanol. For battery propulsion systems, only fully battery electric systems are considered.

Step 2 - Develop a set of key performance indicators (KPIs): After the selection process we developed a broad set of KPIs to facilitate a holistic review of the identified fuels in a Nordic perspective. 14 KPIs in all have been developed through the project to allow for a more specific assessment of barriers facing the different fuels than what is provided by the current literature. The 14 KPIs are divided into four main categories:

i. *Onboard barriers/challenges:* This KPI-category focuses on barriers related to energy density, existing ship compatibility, technical maturity as well as economic barriers such as capex and fuel cost.
ii. *Onshore barriers/challenges:* This KPI-category focuses on barriers related to infrastructure and fuel production technology, fuel scalability, feedstock availability and interaction with other sectors.
iii. *Environmental barriers/challenges:* This KPI-category includes barriers related to greenhouse gas emissions in a lifecycle perspective, local pollution and overall energy efficiency.
iv. *Safety barriers/challenges:* This assessment is related to the maturity of rules and regulations for the different sustainable zero-carbon fuels.

In addition to this, a feasibility screening with regards to the fuels' potential to cover the current Nordic voyages was conducted. The review is based on DNV's AIS-analysis in Task 2A, and serves both as a stand-alone screening to identify the respective fuels relevance in a Nordic context and as a vital input to the assessment of market barriers related to the energy density KPI.

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[1] *The main objective of task 1A was to select which fuels to analyze in the life-cycle (task 1C), infrastructure (task 2B) and safety analysis (task 2A). The selection did not intend to pick three "winners" but is based on the potential impact on the Nordic ship traffic, potential zero-carbon value chain, task specific barriers and lack of knowledge about the task-specific barriers at the current stage of the project.*

Step 3 - Scoring – assessment of each sustainable zero-carbon fuel: To assess the sustainable zero-carbon fuels based on the described KPIs, a scoring methodology was established. We have chosen, based on an internal assessment with the consortium, to base the analysis on a score from 1 to 4. The focus has been on the barriers and challenges. For life-cycle emissions, the potential improvements have also been considered. The analysis is based on a score from 1 to 4, where 1 is the lowest and 4 is the highest. The scoring is formulated to align with barriers/challenges assessed, distinguishing between technical, economic and environmental barriers.

Both the scoring and the KPI-identification are based on an extensive literature review. In all, 241 scientific articles and industry reports were identified. Our assessment combines the findings from the most recognized reports, but also supplements these with multiple original research papers not included in those studies. Furthermore, we have organised 10 workshops with expert groups consisting of representatives of the project consortium (DNV, Chalmers, IVL, Litehauz and MAN ES) to validate our assessment and account for conditions specific to the Nordics.

Main findings – hydrogen, ammonia and methanol stand out but still have barriers that need to be addressed

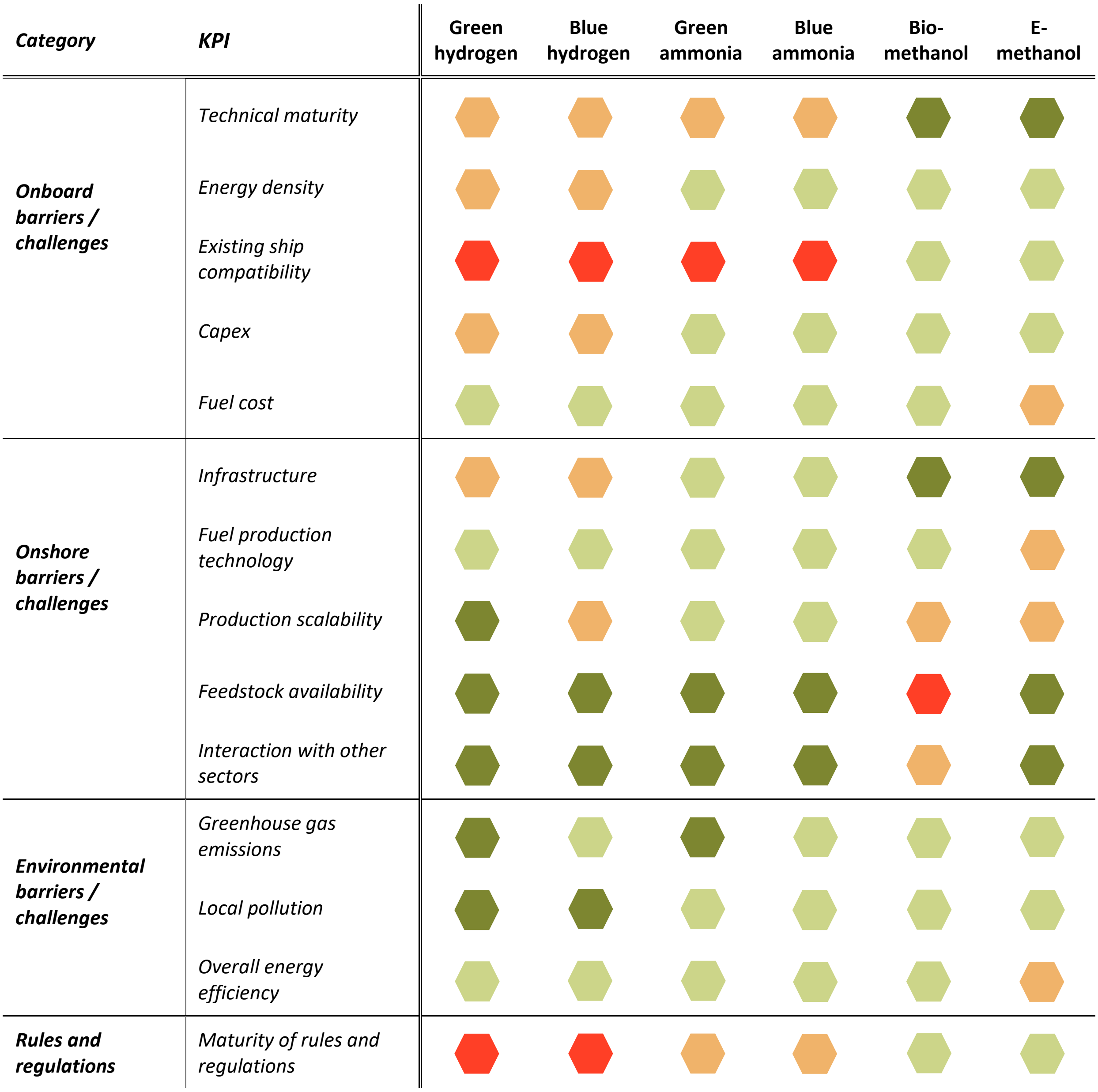
Our analysis shows that a broad range of fuels will be needed on the path to a fully decarbonized Nordic shipping industry. However, three fuels stand out in this context. These are hydrogen, ammonia, and methanol. The table below shows the results of our assessment based on the defined KPIs, for their respective production pathways (e.g., green, blue, bio and E-fuel). The barriers for each of these fuels are further described below. The next chapter fully summarize the assessment of all fuels.

Hydrogen has the potential to become an important zero-carbon fuel for ships sailing shorter and regular distances. Low energy density however limits its relevance for larger vessel. Short-term, green hydrogen offers a highly scalable production technology which makes it possible to increase availability for the shipowners as the demand side matures, even in smaller ports near the end-user. Onshore production technology is also relatively mature, and fuel prices are expected to be favorable compared to other low carbon options. However, low onboard maturity with regards to technical and safety aspects affects both risk assessments and capital costs for shipowners and needs to be addressed. Blue hydrogen also scores lower than green hydrogen on the environmental KPIs due to emission-related barriers which need to be solved.

Ammonia has a higher volumetric energy density compared to hydrogen, meaning that it can cover a larger share of the maritime fuel consumption in the Nordics. However, the main barrier related to ammonia is the low technical maturity of converters, as there are no ammonia engines available today. In addition, compatibility of new ammonia engines is with existing ships is seen to be low, which means that new ships need to be built and/or that comprehensive rebuilds will be necessary. Combined with a low technological maturity onboard, this leads to relatively high capex costs for the shipowners. Ammonia is also a highly flammable gas and has toxic properties for both humans and aquatic life, and the rules and regulations connected to the usage of ammonia as a marine fuel are immature and needs to be further developed. As ammonia is dependent on hydrogen supply, the scaling of fuel production is more complicated than for green hydrogen (alone). Thus, coordination between the two fuels is vital both in the short and the long term.

Methanol is already being used as a marine fuel. Still, most of the vessels that use methanol as fuel are methanol tankers, and the demand for bunkering facilities is limited so far. Like ammonia, methanol can cover a relatively large share of the fuel consumption for the current Nordic fleet traffic. Methanol however has the advantage of a relatively high compatibility with existing ships. The cost to build new and convert existing vessels to run on methanol is therefore significantly lower than for “competing” sustainable zero-carbon fuels. The production technology on the other hand is less mature, and not ready to be scaled on an industrial basis. Production of green e-methanol is a complex process and requires renewable CO_2 which can be sourced through direct air capture or from biogenic sources (which are in limited supply and thus not analysed in detail in this report). Further development and investments to commercially scale up the renewable CO_2 production technology are needed. For bio-methanol, the emission intensity depends on the source of feedstock, which is limited. The latter becomes a major barrier if demand increases, especially as sustainable bio-feedstock is in demand from several sectors and thus a scarce resource.

Figure 1: Assessment of hydrogen, ammonia and methanol for all 14 KPIs



Category	*KPI*	Green hydrogen	Blue hydrogen	Green ammonia	Blue ammonia	Bio-methanol	E-methanol
Onboard barriers / challenges	*Technical maturity*	🟧	🟧	🟧	🟧	🟩	🟩
	Energy density	🟧	🟧	🟨	🟨	🟨	🟨
	Existing ship compatibility	🟥	🟥	🟥	🟥	🟨	🟨
	Capex	🟧	🟧	🟨	🟨	🟨	🟨
	Fuel cost	🟨	🟨	🟨	🟨	🟨	🟧
Onshore barriers / challenges	*Infrastructure*	🟧	🟧	🟨	🟨	🟩	🟩
	Fuel production technology	🟨	🟨	🟨	🟨	🟨	🟧
	Production scalability	🟩	🟧	🟨	🟨	🟧	🟧
	Feedstock availability	🟩	🟩	🟩	🟩	🟥	🟩
	Interaction with other sectors	🟩	🟩	🟩	🟩	🟧	🟩
Environmental barriers / challenges	*Greenhouse gas emissions*	🟩	🟨	🟩	🟨	🟨	🟨
	Local pollution	🟩	🟩	🟨	🟨	🟨	🟨
	Overall energy efficiency	🟨	🟨	🟨	🟨	🟨	🟧
Rules and regulations	*Maturity of rules and regulations*	🟥	🟥	🟧	🟧	🟨	🟨

It is important to notice that while the three fuels are assessed as the *most* promising in our assessment, both **Methane, HVO and battery-electric-propulsion systems** are expected to play an important role in the maritime transition in the Nordics. For certain ship segments, they could be vital, and they all serve as important transitory fuels, already contributing to emission reduction by replacing traditional fossil fuels. This is further examined in the full comparative summary below.

Final remarks – Investments and cooperation are vital for a Nordic maritime transition

Common for all the fuels assessed in this analysis is the expectation that technical and commercial maturity will increase as more ships are developed and bunkering facilities are built, reducing cost and shipowners' risk assessment. Still, to make sustainable shipping competitive with conventional fuels, financial support for R&D and pilots is needed, as well as economic incentives favouring low-emission technologies in the market. Onshore, vast investments in infrastructure and bunkering facilities are necessary, especially for hydrogen, ammonia and methanol. Furthermore, in infant market such as these, demand and supply are mutually dependable. It is vital that actors in the different countries, both government, fuel suppliers, shipowners and other companies, collectively address the key barriers identified in this assessment. To increase the knowledge base for the Nordic roadmap, we recommend that ammonia, hydrogen and methanol are the focus points in the in-depth analysis with regards to Life Cycle Assessments (LCA), regulatory and safety challenges and infrastructure barriers (2B).

Full summary of the KPI assessment and feasibility screening

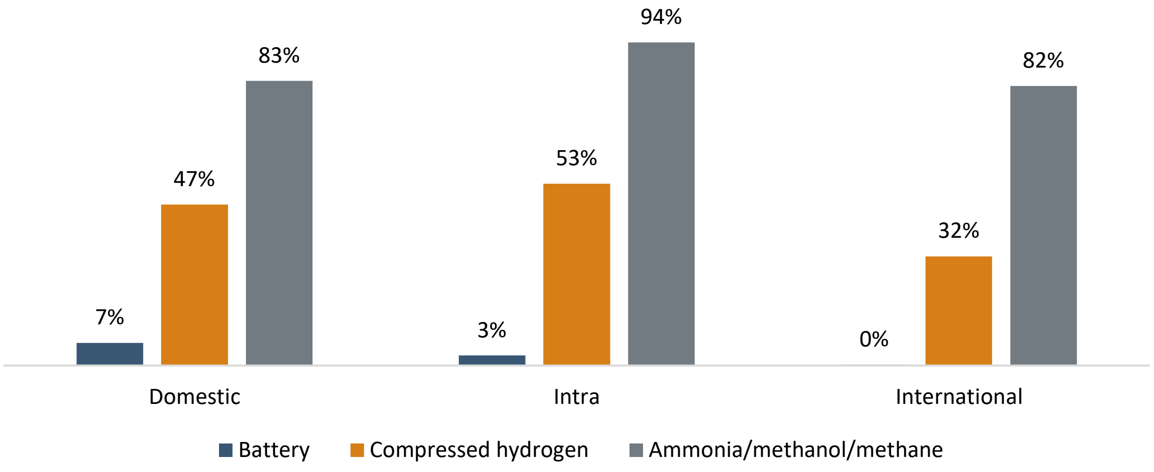
In this chapter we present a complete summary of our analysis in task 1A. The summary starts with the feasibility screening with regards to the fuel's potential to cover the current Nordic maritime fuel consumption, followed by the KPI assessment, based on scoreboards for the four main categories focusing on Environmental, Onboard, Onshore and safety barriers.

Cross-fuel analysis: High energy density fuels are vital for a full-scale Nordic green transition, but hydrogen and battery-electric propulsion are still in the mix

The feasibility screening focuses on the respective fuels' suitability with regards to covering the Nordic ship traffic's fuel consumption both domestically, between the Nordic countries, and for international voyages connected to the Nordics. The aim is to identify the technical market *potential* for the different sustainable zero-carbon fuels, given today's sailing pattern. The screening is based on DNV's AIS-analysis in Task 2A and have two focus areas: "*Nordic feasibility*" looks at the respective fuels' possibility to cover the fuel consumption for the Nordic ship traffic in total, but also the fuels' feasibility for specific ship segments. "D*omestic relevance"* looks at the fuels' relevance in the specific Nordic countries, based on the most relevant vessel segments, to ensure that the geographical variation is sufficiently covered by the respective fuels.

The feasibility screening shows that **ammonia, methanol and methane** could be able to cover between 80 and 90 percent of the Nordic ship traffic's fuel consumption depending on the voyage category. This is shown in the figure below. It is important to note that this screening is on a very general level and based on today's sailing patterns and ship sizes, and that the current traffic patterns might not be representative for sustainable zero-carbon fuels in the future. As such, the residual could be covered by fuels with higher energy density such as **HVO** but also through adjustments ship design and/or sailing patterns. A last option would be to forsake cargo space, to increase fuel storage.

Figure 1: High energy density fuels will be vital for a zero-carbon pathway, but hydrogen's potential is significant



The figure highlights two key aspects with regards to the role of **hydrogen** in the future of Nordic shipping. The market potential of hydrogen, both domestically, intra-Nordic and internationally, is limited by range. Still, the AIS-analyses conducted by DNV show a far greater potential than previously assumed. For smaller ships with an operating profile that allows for frequent refueling, limiting the amount of fuel that needs to be stored onboard, hydrogen could be vital. Compressed hydrogen *can* cover up to 50 percent of the internal fuel consumption of intra-Nordic shipping[2], with a relatively high share for important segments such as passenger ships, cruise ships and ro-pax. Domestically hydrogen is most relevant for internal traffic in Sweden and Norway where it *can* cover up to 62 and 50 percent respectively. In Iceland however, only 20 percent of the fuel consumption is identified as feasible for hydrogen shipping. **Battery-electric propulsion** will also play its part, but its potential impact going forward is more limited as a stand-alone zero-carbon energy carrier, with ferries that sail relatively short distances on a regular basis being the most feasible option. Hybrid systems based on electricity, however, are already important as a transitory option for larger vessels, but not a part of the scope of this project.

Environmental KPIs: Significant differences among the high energy density fuels, due to technological barriers, inherent emissions, and shortage of sustainable energy sources

Table 1: Comparative analysis of the environment KPIs for the different sustainable zero-carbon fuels*

Fuel	***Greenhouse gas emissions***	***Local pollution***	***Overall energy efficiency***
Green hydrogen	🟩	🟩	🟨
Blue hydrogen	🟨	🟩	🟨
Green ammonia	🟩	🟨	🟨
Blue ammonia	🟨	🟨	🟨
Biomethane	🟧	🟨	🟨
E-methane	🟧	🟨	🟧
Biomethanol	🟨	🟨	🟨
E-methanol	🟨	🟨	🟧
HVO	🟧	🟧	🟧
Battery electric propulsion	🟩	🟩	🟩

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

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[2] *Liquified hydrogen has a higher energy density but based on expert assessments it is seen as less relevant due to onboard/onshore barriers.*

The environmental assessment shows that most fuels perform well when focusing on the potential to become zero-carbon in a life-cycle perspective, long-term. Still, there are differences with regards to barriers to scaling the fuels from a sustainability perspective. To assess the fuels' potential in an environmental perspective, we have scored them on the following KPIs: greenhouse gas emissions, local pollution, and overall energy efficiency. The scores are shown in the table above.

Battery-electric propulsion receives the highest score of all alternatives, especially in countries with low emissions from electricity generation. It does however score the highest on overall energy efficiency. In regions with close to zero-emission energy grids, battery-electric propulsion has the lowest emissions compared to the other fuels. **Green hydrogen** and **green ammonia** are the best prospects for near zero-emission shipping for longer sailing routes today with full scale pilots being developed as we speak. The former is produced using only water and electricity while the latter combines green hydrogen with nitrogen from the air. Neither contains any carbon atoms, and thus, neither emits any CO_2. For ammonia however, emissions of other greenhouse gases that occur in combustion (N_2O) need to be eliminated. Furthermore, upstream emissions in electricity generation and fuel production need to be reduced to facilitate zero-emission shipping. In other words, there is a need to scale up renewable production capacity. With a relatively low score on overall energy efficiency, full scale use of green hydrogen and/or ammonia as a zero-emission maritime fuel would require significant investment in primary energy supply such as offshore wind, solar power, and onshore wind. From a Nordic perspective one could argue that the need for regional supply is lower for ammonia since it is easily transported, making import a viable option. The scoring reflects the energy requirements regardless of geographical origin.

Production of **green e-methanol** is based on synthesis of green hydrogen and has the potential of becoming near zero-emission in the future. However, the fuel has a complex production process which includes CO_2 capture either directly from air or from biogenic sources. A relatively lower score than ammonia and hydrogen reflect that there still are major technical barriers that must be addressed to commercially scale up the technology. Direct air capture also increases the energy intensity of the production process. As for ammonia, import could be an option, if production of "green" fuels scales up in other regions. **E-methane** also receives a relatively low score on greenhouse gas emissions due to fugitive leaks in methane transportation and methane slip onboard a ship. Methane is a highly potent climate gas itself and the fugitive leaks are hard to eliminate. Even if advances in technology make it possible to significantly reduce the emissions, complete elimination of these emission sources is unlikely. As such, these fuels seem less suited from a climate perspective. Combustion of methanol, methane and ammonia also causes some local pollution, albeit significantly lower than in the case of traditional maritime fuels.

HVO scores lowest in our assessment, reflecting major barriers for zero-carbon shipping if we assume a significant increase in demand. Emissions from biobased fuels will depend on the feedstock used in fuel production. A limited sustainable feedstock availability makes it hard to scale up production without competing for renewable energy sources with other sectors. The same factors affect **bio-methanol** and **biomethane's** potential to become zero-carbon options.

Onboard barriers: Variation in technical maturity, compatibility and costs could affect short term scaling and long-term relative competitiveness

The onboard assessment shows that the fuels vary both with regard to technical maturity, existing ship compatibility and costs. To assess the fuels' potential in relation to the onboard barriers, we have scored them on the following KPIs: technical maturity, energy density, existing ship compatibility, CAPEX and fuel cost. The scores are shown in the table below.

The main barriers **hydrogen** faces within this KPI category are closely related to its technical maturity. A relatively low technical maturity affects both the short-term scaling potential and the associated investment costs. As shown above, a low energy density will also affect the potential market impact. Fuel prices, however, are favorable compared to other fuels as hydrogen production requires less energy and less capital-intensive infrastructure than other fuels in the assessment. Most of the challenges hydrogen is facing are also apparent when assessing **ammonia**. The exception is the investment cost, which is expected to be lower and the fact that ammonia can cover a much larger share of the Nordic fuel consumption due to higher energy density. Both fuels have a low “existing ship compatibility” highlighting the need for installation of new engines and fuel storage systems, as well as additional safety measures to tackle the risks related to these fuels. The latter is assessed below.

Table 2: Comparative analysis of the onboard KPIs for the different sustainable zero-carbon fuels*

Fuel	*Technical maturity*	*Energy density*	*Existing ship compatibility*	*CAPEX*	*Fuel cost*
Hydrogen (Green and blue)	🟧	🟧	🟥	🟧	🟨
Ammonia (Green and blue)	🟧	🟨	🟥	🟨	🟨
Biomethane	🟩	🟨	🟧	🟧	🟨
E-methane	🟩	🟨	🟧	🟧	🟧
Biomethanol	🟩	🟨	🟨	🟨	🟨
E-methanol	🟩	🟨	🟨	🟨	🟧
HVO	🟩	🟩	🟩	🟩	🟧
Battery electric propulsion	🟩	🟥	🟧	🟨	🟩

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

The other sustainable zero-carbon fuels are assessed to have little to no *technical* barriers with regards to engine technology and have all been taken into use at full scale on merchant vessels. **HVO** is already used as a drop-in fuel and is compatible with existing propulsion systems for diesel, indicating that it could be a vital transitory fuel going forward. The volumetric energy density for all the sustainable zero-carbon fuels is lower than for conventional fuels, highlighting a need for adjustments if shipowners want to attain the same amount of cargo space and/or range as they currently have on fossil-based ships. The exception is HVO which has an energy density closer to conventional diesel. HVO faces lower barriers when it comes to onboard KPIs. **Methanol** scores relatively high on the onboard barriers compared to the other fuels. Methanol is not fully compatible with conventional engine technologies like HVO, but retrofitting is possible. “Furthermore, existing tanks can potentially be retrofitted to store methanol onboard”. Methanol ships are also expected to be less expensive than most of the other sustainable zero-carbon fuels. **Methane’s** main barrier compared to its high energy density rivals lies in higher investment costs and that using methane onboard requires the installation of new engines or modification of existing ones, in addition to installation of cryogenic fuel tanks for onboard storage. However, the technology has been in use for decades and is technologically mature, and there are several vessels already built, and some in the orderbooks that have LNG engines, which will be fully compatible with e-methane or biomethane.

The main barriers for **battery-electric propulsion systems** are already reflected in the screening of the fuels’ feasibility to cover the fuel consumption of the Nordic ship traffic. A low volumetric energy density significantly reduces the reach of such systems within Nordic shipping traffic. As stated above, hybrid solutions that combine batteries with conventional fuel are often a preferred short-term option in the market today, even for large vessels, but this is outside the scope of this project, since our focus is on (near) zero-carbon shipping.

Onshore barriers: Significant differences between fuels, affecting their Nordic relevance

Table 3: Comparative analysis of the onshore KPIs for the different sustainable zero-carbon fuels*

Fuel	*Infrastructure (Storage, bunkering & transportation)*	*Fuel production technology*	*Production scalability*	*Feedstock availability*	*Interaction with other sectors*
Green hydrogen	🟧	🟨	🟩	🟩	🟩
Blue hydrogen	🟧				
Green ammonia	🟨				
Blue ammonia	🟨				
Biomethane	🟨				
E-methane	🟩				
Biomethanol	🟩				
E-methanol	🟩				
HVO	🟩				

	🟧	🟧	🟩	🟩
	🟩	🟧	🟥	🟥
Battery electric propulsion	🟩	🟩	🟩	🟩

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

The onshore assessment shows that the barriers vary significantly between fuels and KPIs. The largest spread is identified within infrastructure, fuel production technology and production scalability. To assess the fuels' potential in relation to the onboard barriers, we have scored them on the following KPIs: Infrastructure, maturity of fuel production technology, production scalability, feedstock availability and interaction with other sectors. The scores are shown in the table below[3].

Hydrogens main barriers in related to the onshore KPIs are the current infrastructure and challenges with regards to transportation. A low score does not mean that these barriers will limit the fuels' potential, but rather that further investment and/or technical progress are needed. Short-term, green hydrogen offers a highly scalable production technology which makes it possible to increase availability for the shipowners as the demand side matures, even in smaller ports near the end-user. Local production also compensates for some of the issues related to for example transportation. However, facilities for bunkering must also be addressed to fit the properties of hydrogen, as the risk of leaks is high, implying a need for specially made bunkering facilities. Hydrogen's onshore barriers are also expected to be eased by increased usage in the industrial sector. The same goes for other hydrogen-based fuels such as green ammonia and e-methanol and e-methane. The renewable electricity potential is vast in the Nordics, implying little to no restrictions on feedstock availability.

Ammonia has been produced and stored as a liquid for many years and can be considered to have reached high maturity. However, ammonia is not capable of utilizing existing infrastructure for storage onshore, which implies that large investments will be needed to facilitate an increased uptake in the maritime sector. As with hydrogen, facilities for bunkering must also be addressed to fit the properties of ammonia, as the risk of leaks is high, implying a need for specially made bunkering facilities.

Methanol is already available at several ports, but bunkering options are not sufficient for scaling Nordic zero-carbon shipping. However, expanding the storage capacity for methanol features many of the same characteristics of regular fossil-based fuels, and the infrastructure barriers are more economic than technical. For e-methanol, the main barriers lie in the technical and commercial readiness of the fuel production technology, which relies on renewable CO_2 extracted through direct air capture or from biogenic sources. This technology is far from ready to be scaled up both technically and commercially. Hence there is a need for increased investments in both infrastructure, bunkering and the development of the production technology itself. The main challenge of bio-methanol production is the reliance on specific organic matter feedstocks due to gasifiers not being able to cope with a wide variety of feedstocks. The latter are also a barrier for biomethane production.

One of the main advantages of **methane** is that it can use existing LNG-infrastructure for bunkering. Liquified natural gas (LNG) has a well-established fuel supply and logistics for both storage and bunkering. On the production side, the barriers are like those for e-methanol. The size of e-methane plants is currently restricted by the technologies used to capture CO_2, diminishing economies of scale and increasing costs.

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[3] *This is an initial screening. Task 2B performs a more detailed assessment of the onshore barriers.*

For bio, rich sources of woody biomass in countries like Finland, Sweden and Norway raise the potential for substantial scaling of regional production. The challenge for biobased fuels such as **HVO**, bio-methanol and biomethane is highlighted when we assume increasing demand, both within shipping and other sectors. Producing fuels from bio-based feedstock has the potential to cause food shortages in some areas, and supply challenges in other sectors reliant on waste-based feedstock. Sustainable feedstock is scarce and this significantly reduces these fuels' market potential. For HVO, the positives lie in the fact that transportation and bunkering can be done using existing onshore infrastructure, which is deemed very mature both commercially and technically. Low barriers with regards to production, transportation, bunkering and onboard challenges are reflected in the fact that HVO already plays a significant role as a transitory low-carbon fuel. However, long-term major barriers exist with regards to environmental or onshore barriers. Finally, infrastructure for **battery-electric propulsion** requires case-by-case analysis of the local electric grid, which is beyond the scope of this analysis. Even though there exists infrastructure in some ports, the infrastructure is not established in a Nordic perspective. The main barrier for expanding the bunkering possibilities is sufficient investment in the electricity grid.

Maturity of maritime rules and regulations is an important short-term challenge for ammonia and hydrogen

The assessment shows that the maturity of maritime rules and regulations differs for the individual fuel types. Some of the sustainable zero-carbon fuels assessed in this report have come a long way in terms of maturity of rules and regulations, as they have already been taken into use or there is accumulated experience in terms of transportation of the fuel. To assess the potential with regards to maturity of rules and regulations, we have looked at the sustainable zero-carbon fuels' attached safety risks, such as toxicity and flammability, as well as the rules and regulations that handle these aspects. There needs to be enough testing and experience with transportation, bunkering and onboard usage of these fuels so that all safety risks are understood in order to prepare rules and regulations. The relevant scores are shown in the table below.

Table 4 Comparative analysis of the rules and regulations KPIs for the different sustainable zero-carbon fuels*

Fuel	*Maturity of maritime rules and regulations*
Hydrogen (green and blue)	🟥
Ammonia (green and blue)	🟧
Methane (biomethane and e-methane)	🟩
Methanol (biomethanol and e-methanol)	🟨
HVO	🟩
Battery electric propulsion	🟩

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Hydrogen is the fuel scoring the lowest among sustainable zero-carbon fuels in the safety screening. Hydrogen is explosive and highly flammable, which requires safety precautions both onboard and onshore. Use of hydrogen is regulated mainly by IGF code. However, IGF code does not include specific design requirements for hydrogen as fuel. In addition, there are class rules that govern the use of fuel cells on board, which is the main choice of converters for hydrogen, although these do not cover storage and distribution of hydrogen as fuel. There is a need to build more experience with bunkering and onboard usage to prepare specific rules and regulations. Therefore, the rules and regulations for this fuel are assessed to be the least mature.

Hydrogen is followed by **ammonia**. There is extensive experience and knowledge accumulated over the years as ammonia is a commodity shipped around the world. As ammonia is a flammable gas and has toxic properties for both humans and aquatic life, measures to mitigate the risk associated with handling and storage and implementing effective safety measures is highly important. Although the regulatory framework for carrying ammonia as commodity is quite mature, the framework for using ammonia as fuel is mainly governed by IGF framework that is applicable to all low flashpoint fuels. However, the code does not include specific design requirements for ammonia. However, similar to hydrogen, there are class rules developed for ammonia.

Methanol has been newly adopted as a marine fuel. The main rules and regulations that govern the use of methanol as marine fuel are adopted by IMO’s “Interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel”. In addition, class societies have adopted class rules related to methanol used as a marine fuel. However, experience with using methanol as marine fuel is limited, which is also reflected in the maturity of maritime rules and regulations.

Methane has been used as marine fuel since the early 2000s, and the rules and regulations regarding storage and bunkering/handling of methane are assessed to be mature. These are governed by IGF code. In addition, there are class rules existing that govern onboard use of methane. Similarly, **HVO** and **battery electric propulsion** systems are already used today, and the rules and regulations are well documented in the literature.

1. Introduction and methodology

The shipping sector is responsible for 2.8 percent of the annual global emissions. Decarbonization of the shipping sector is inevitable and can be made by transitioning into low- or zero-carbon marine fuels. As of today, around 95 percent of the bunker fuels used to power ships are made of marine diesel oil (MDO), heavy fuel oil (HFO) or marine oil gas (MGO). Thus, nearly the entire world fleet needs to be decarbonized within the next 28 years (Menon Economics, 2022).

In 2018, IMO announced a long-term goal to reduce GHG emissions from the shipping industry by 50 percent by 2050 compared to emissions in 2008.[4] To reach the IMO's 2050-target, sustainable zero-carbon fuels are being discussed, such as hydrogen, ammonia, methanol and methane, as well as battery electric propulsion. However, there is a dilemma. Investments made today are for the long term, as vessels and infrastructure are built with long lifespans. In addition, there is a lack of infrastructure needed to support the bunkering of sustainable zero-carbon fuels. This infrastructure will however not be profitable unless the market and demand for the different fuels are more mature. Further on, it is not clear from either a demand perspective or a supply perspective which fuels dominate in this process. There is therefore a need to investigate the strengths and weaknesses of each of the sustainable zero-carbon fuel options to prepare shipowners, stakeholders, and policy makers for the ongoing and upcoming fuel transition.

The focus of the project is on "sustainable zero-carbon fuels" from a Well-to-Wake perspective in the Nordic countries. The term sustainable zero-carbon fuels is used to indicate fuels with potential zero climate impact throughout their lifecycle. The objective of this report, Task 1A, is to screen and provide a scorecard for the most promising potential sustainable zero-carbon fuels in a Nordic perspective, including identifying barriers and development needs. The delivery is a screening and a scorecard, identifying barriers and development needs for relevant potential zero-carbon fuels. The task report can be used as a stand-alone knowledge base for zero-carbon fuels in the Nordics, but also serve as an initial screening for the more in-depth analyses carried out in the project with regards to Life Cycle Assessments (LCA), regulatory and safety challenges and infrastructure barriers.

1.1 Operational framework

In this task we have conducted a systematic review of relevant sustainable zero-carbon fuels for maritime transportation in the Nordics. The review will be based on a broad specter of KPIs and serve as an initial screening for the project. The screening process will be carried out for each identified alternative (e.g., hydrogen, ammonia, biofuels and others). The operational framework is a three-step approach, as illustrated in the figure below.

Figure 2 Operational framework – method for scoring of sustainable zero-carbon fuel

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[4] *In addition, from January 2020, the Sulphur content of marine fuels was limited to 0.5 percent or 0.1 percent in IMO-enforced Emissions Control Areas (ECAs). Most ships use very low-Sulphur fuel oil (VLSFO) to comply with the new limit. LNG and biofuels are also being used as low- or zero-Sulphur fuels.*

Step 1: Identification of relevant sustainable zero-carbon fuels

The aim of the first step was to identify the most relevant sustainable zero-carbon fuels for maritime transportation in the Nordics for further assessment. This selection is based on a joint assessment in our Nordic collaboration group at start-up, with DNV's work on zero-carbon fuels as a basis for the assessment, e.g., the Maritime Energy Transition Outlook (DNV, 2020b). An important aspect in this selection is to include a sufficiently broad specter of alternatives to capture regional and fleet specific barriers and potentials. We have only looked at fuels that have the *potential* to become (fully) zero-carbon alternatives for the maritime industry. This means that e.g. LNG is excluded from the analysis.

Fuels

A range of sustainable zero-carbon fuels and technologies are available for ships to reduce emissions. The emission reduction potentials for these fuels vary significantly, depending on the primary energy source, the fuel processing, the engine type/converter, and the supply chain. The various sustainable zero-carbon fuels and their diverse characteristics make it difficult to find the optimal and most cost-efficient zero-carbon fuels for the various ship types and operation patterns. In this task, we are assessing different fuels that are considered in previous research to have a potential to become zero-carbon fuels. The fuels included in the analysis are shown in the list below. The list does not include conventional maritime fuels, LNG or LPG, since they do not have the potential to become zero-carbon fuels. The term zero-carbon fuel is used to indicate fuels with potential zero climate impact throughout their lifecycle.

- Hydrogen (green and blue)
- Ammonia (green and blue)
- Methanol (bio- and e-methanol)
- Methane (bio- and e-methane)
- Biofuel (HVO)
- Battery electric propulsion

When assessing the sustainable zero-carbon fuels, we have included both the well-to-tank perspective and the tank-to-wake perspective. The well-to-tank perspective includes production, processing, and delivery of a fuel, while the tank-to-wake perspective focuses on issues related to fuel use onboard of a ship. This means that the scope of the assessment is quite comprehensive.

The fuels included in the list above can be produced through various methods, using electrolysis of water (green, and e-), steam reforming of natural gas with carbon capture and storage (blue) or processing of organic matter (bio) to produce the required feedstock. Thus, for each fuel the entire fuel family needs to be assessed in a well-to-tank analysis. This part is to some degree overlapping with the LCA-analysis, and we have therefore not included too many details on the production method. When assessing the tank-to-wake perspective, properties of the fuel are to a large degree independent of how it is produced. However, for each fuel there are several different propulsion systems that affect its competitiveness and emission intensity.

Propulsion systems

Fuels analysed in the task can be used in either internal combustion engines (ICE) or in fuel cells (FC). The two propulsion systems differ in technological maturity, efficiency, environmental impact and costs; thus, the choice of propulsion technology affects nearly all dimensions of the analysis.

In assessing various aspects of fuels, we attempt to separately discuss the two technologies; however, such a distinction is not always possible within the scope of this task. Fuel cells are still under development and there is lack of sufficient evidence that would allow for comprehensive analysis across all dimensions. **Thus, to limit the complexity of the task, we assign only a single score regardless of the technology used.** This was decided together with the consortium.

FCs are more efficient than ICEs. Fuel cells convert the chemical energy of a fuel and oxygen directly into electricity which is converted to mechanical energy at little energy loss. Combustion engines must first convert their fuel into heat, then into mechanical energy at a relatively high energy loss. The efficiency of gas-fuelled internal combustion engines is around 42-45 percent for small units and up to 48-50 percent for large engines. Efficiency is a couple of percentage points lower when fuelled with liquid fuel oils. In comparison, the efficiency of fuel cells is in the 50-60 percent range (Pawelec, 2020), depending on the technology used. FC is still an emerging technology, thus some further increase in energy efficiency can be expected in the future. Furthermore, FC in contrast to ICE is an emission-free technology.

There exist multiple fuel cell technologies differing with regard to the electro-chemical reactions that take place in the cell and the kind of catalysts required. Most fuel cells are powered by hydrogen, which can be fed to the fuel cell system directly or can be generated within the fuel cell system by reforming hydrogen-rich fuels such as ammonia, methanol, ethanol, and hydrocarbon fuels. Direct methanol or ammonia fuel cells are also under development; however, the technology is not yet ready for commercialisation in the maritime setting (Jeehr, Zhang, & Tao, 2021).

Step 2: Develop a set of key performance indicators (KPIs)

The aim of the second step was to develop a broad set of key performance indicators covering the most relevant aspects of technical and economic barriers for assessing the potential of zero-carbon fuels for marine use in the Nordics. The KPIs are developed in cooperation with the consortium, where we have had several discussions on which KPIs to include. Since this is a comparative analysis, only KPIs that differentiate between the fuels are included in the assessment.

The selection of the KPIs is based on the following[5]:

1. **Relevance:** The indicator needs to mirror one or more dimensions with regards to quality or efficiency in association with the specific goal set out in the project. In this case, facilitating a transition to zero carbon fuels in maritime transportation in the Nordics.
2. **Measurable**: The indicator needs to be measurable or at least be assessable with available statistics and data.
3. **Consistent:** The indicator needs to be consistent, e.g., it is vital that it measures the same aspects across all alternatives and that data can be collected in the same manner and quality over time.
4. **Impressionable**: The indicator needs to have sufficient "resolution", so that it can be influenced over time by targeted actions from stakeholders and the industry.
5. **Accepted:** The indicator needs to build on established knowledge with a broad consensus among technical and economics professionals. E.g., it should be based on current guidelines/regulations, documented experience, official statistics, and transparent data/knowledge. This is to ensure that the indicator is verifiable.

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[5] *https://www.socialstyrelsen.se/globalassets/sharepoint-dokument/artikelkatalog/ovrigt/2020-8-6877.pdf*

The chosen KPIs will be the indicators that fulfill the criteria explained above in the best and most comprehensive way for each category. DNV has already established a broad specter of KPIs for their assessment of emerging fuels in the Maritime Energy Transition Outlook (DNV, 2019c; DNV, 2020b). A majority of these are also part of this task as well.

The transition to zero-carbon fuels faces barriers and challenges on multiple fronts, from fuel production to ship design to economic performance. To allow more systematic and easier comparison between the fuels we have split indicators into the following four categories:[6]:

1. **Onboard barriers/challenges:** This is characterized by capital-intensive installations, with different grades of technical maturity that increase the investment and performance risk.
2. **Onshore barriers/challenges:** This is made up of lack of production capacity and infrastructure for zero-carbon fuels, and it is also linked to the availability of the feedstock and the overall energy market locally or regionally.
3. **Environmental barriers/challenges:** Related to greenhouse emissions and other forms of pollution associated with fuel production and fuel use (a well-to-wake perspective) and the possibility to eliminate those emissions in the future. Those challenges also address the overall resource use determined by the overall energy efficiency of fuel production and fuel use.
4. **Maritime rules and regulations:** The maturity of maritime rules and regulations to mitigate the risks associated with handling of fuels in transportation, bunkering and on board and ensuring safety for crew and operations.

Step 3: Scoring – assessment of each sustainable zero-carbon fuel

Once the KPIs were established, the next step was to assess them for each fuel identified in step 1. The KPIs are assessed based on their current "score" and expected improvement, given the current trends and developments. For some categories, such as emissions, the potential improvements have also been considered. The timeframe is important as a long-term Nordic transition could be best facilitated by fuels that are less mature today, but with barriers that are easily to overcome.

1.2 Literature review and expert assessment

The results in this task, Task 1A, are based on an extensive literature review, expert opinion, input from the partners in the consortium and DNV's AIS-analysis from Task 2A.

We have identified 241 scientific articles and industry reports throughout the project period. This is on average 15 articles per KPI. Furthermore, we have organised around a dozen workshops with expert groups consisting of representatives of the project consortium (DNV, Chalmers, IVL, Litehauz and MAN ES) to validate our assessment.

This is not the first assessment of the barriers faced by the near zero emission maritime fuels. The challenges faced by the industry and the knowledge gap that needs to be bridged have made this a prolific research topic. Similar assessments of maritime fuels have been performed earlier, with DNV (2019b) and Mærsk McKinney Møller Center for Zero Carbon Shipping (2021) being notable examples. Those reports are natural reference points for our analysis. However, we have also identified multiple original research papers not included in those

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[6] *More information about these can be found in the chapter about the KPIs.*

studies and performed independent analysis of maritime traffic data to identify key barriers to the uptake of zero emission fuels in the Nordics.

The analysis performed in this task goes beyond what can be found in the literature. First, we have focused on the Nordic market, while the other studies take the global perspective. We thus emphasize the suitability of near zero-emission fuels for use in the Nordics, as well as make a preliminary assessment of the compatibility with existing infrastructure and natural resources in the region. Those aspects will also be analysed in more detail in the subsequent parts of the project. Secondly, we have included only the potentially zero emission fuels in the analysis. Not including the traditional fuels as an alternative allows for a more nuanced comparative analysis of the feasible zero-emission options. Finally, we present a more granulated list of KPIs that allows for a more specific assessment of barriers facing the individual fuels.

2. Key Performance Indicators and scoring methodology

This chapter provides a description of the different key performance indicators that are used to assess the onboard and onshore challenges and the environmental and safety barriers related to the different fuels. In addition, it gives a description of the scoring methodology used in the analysis.

2.1 Onboard

The onboard challenges include technical and economic barriers related to the adaptation of sustainable zero-carbon fuels onboard the ship, and they will have a direct impact on the shipowner's investment decision. Energy density is an important barrier that will have implications for vessel types and sailing patterns that sustainable zero-carbon fuels are compatible with. Similarly, existing ship compatibility will be a factor considered by shipowners while making investment decisions for sustainable zero-carbon fuels. The economic aspects and availability of the fuels will also be important for shipowners when rebuilding or building new ships. Economic aspects include both the capital costs of propulsion systems suitable for those fuels as well as fuel prices. As of 2022, zero-emission fuels are significantly more expensive than traditional maritime fuels. This gap is likely to close once technology becomes more mature and fuel production scales up. The pace of the development in fuel cost reduction remains however highly uncertain. Fuel prices can also vary locally between ports, depending on the availability of transportation and bunkering infrastructure.

Pilot projects, technology qualifications, joint industry projects and collaboration with relevant approval bodies and authorities are some of the steps needed to overcome these barriers.

Table 5 Definition of the KPIs related to onboard barriers

CATEGORY	KPI	DESCRIPTION
Technical	Technical maturity	Maturity level of technology
	Energy density	Volumetric energy density and how much space different fuels need for storage on board
	Existing ship compatibility	How compatible is today's engine technology with sustainable zero-carbon fuels
Economical	CAPEX	Cost of converter and fuel storage tanks
	Fuel cost	Assessment of fuel costs as of now and the predicted price path in the future determined by technology and resource availability

Technical maturity:

This KPI assesses the technical maturity of the technology energy carriers. While some sustainable zero-carbon energy carriers can use existing propulsion systems and storage onboard, most of them require installation of technologies such as new engines or fuel storage systems. Some of these technologies are fully mature and some are in different phases of development. The investment into and adoption of sustainable zero-carbon fuels will depend on the maturity of the technologies.

Energy density:

Energy density of marine fuels is a decisive factor when assessing the applicability of sustainable zero-carbon fuels. This KPI assesses how each sustainable zero-carbon fuel performs in terms of volumetric energy density. Fuels with lower volumetric energy density will require more space for the same amount of propulsion compared to higher density fuels. This comes with extra costs, such as liquification or compression of fuels that are in gas state and storage costs related to these, as well as increased space dedicated to onboard fuel storage. Gravimetric energy density is less relevant in most cases, since the space required becomes a restricting factor before the weight does.

Existing ship compatibility:

This KPI assesses to what degree the sustainable zero-carbon fuel can be used in existing engine and storage systems. Some sustainable zero-carbon fuels will be compatible with the existing fleet's engine and storage systems, some will require adjustments and some installation of completely new systems. Compatibility between existing fleet and sustainable zero-carbon fuels will be an important factor for shipowners, as it will have a significant impact on investments into new technology and retrofitting.

CAPEX:

CAPEX constitutes around 50 percent of the lifetime ownership cost of a vessel, although a significant part of that cost is not fuel-specific. This KPI is based on the installation of new engines and propulsion systems where needed, and costs related to handling and storage of the fuel onboard. Ship designs for sustainable zero-carbon fuel are still in the research and development phase, thus the estimates are subject to a significant degree of uncertainty. This KPI does not differentiate between different production methods of fuels, as this will not have any impact on CAPEX related to the vessel.

Fuel price/cost:

Fuel cost is another large part of lifetime ownership cost of a vessel. Fuel cost is closely related to the feedstock cost, process complexity and maturity of fuel production. In other words, there are some overlaps with the onshore barriers. If sustainable zero-carbon fuel can be produced with more mature technology and at lower prices, fuel transition would appear to be more economic.[7] Fuel price in 2030 is very uncertain yet heavily influences the results. The uncertainty, however, affects both the sustainable zero-carbon fuel as well as the traditional fuels for which the total cost is also affected by climate policies.[8] The evaluation criteria for this KPI are scarcity of key inputs, demand from other sectors, potential for increase in energy efficiency and current prices.

2.2 Onshore

The onshore barriers include both technical barriers and barriers related to fuel scalability and interaction with other sectors. Developing the necessary infrastructure and production capacity will take time, be costly, and involve many stakeholders in the supply chain. Co-operation with major energy and fuel providers will be

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[7] *A Comparison of Sustainable zero-carbon fuel for Shipping in Terms of Lifecycle Energy and Cost.*

[8] *The fuel price of fossil fuels can be increased by a carbon tax, and shipping stakeholders have indicated a willingness to pay 50 \$/t of CO_2 emissions in a survey by Lloyds Register. However, a significant change in the fuel ranking in this study requires a carbon tax above 300 \$/t of CO_2-equiv. (Hansson et al., 2019).*

important to provide supply of zero-carbon fuels. Joint investments in infrastructure might also alleviate some of the availability concerns in the short term. The work on developing alternative fuel infrastructure also involves establishing harbors as energy hubs and harmonization with the EU alternative fuel strategies.

Table 6: Definition of the KPIs related to onshore barriers

CATEGORY	KPI	DESCRIPTION
Technical	Infrastructure (Storage, bunkering & transportation)	Availability of infrastructure, replacement of current infrastructure
	Fuel production technology	Technology readiness for fuel production
Fuel scalability & interaction	Production scalability	Ease of production scaling / distributed small scale production close to end user.
	Feedstock availability	Access to the feedstock needed to produce the fuel, such as biomaterials, electricity, natural gas etc.
	Interaction with other sectors	Demand from other sectors that contribute to competition and technological innovation

Infrastructure (storage and bunkering):

The variation in chemical characteristics of different fuels yields both challenges and opportunities when considering necessary storage, bunkering and transportation infrastructure. While some sustainable zero-carbon fuels can exploit existing infrastructure, others might need improved or new infrastructure to be a viable solution. Our assessment includes the fuels' substitutability with current storage and bunkering infrastructure, key challenges when building new infrastructure, and lastly, whether storage and bunkering infrastructure can be built in small or large ports, or both. Additionally, the KPI assesses the main transportation infrastructure needed for each fuel, where factors such as distance from production facilities and transportation methods, e.g., trucks, trains, ship etc., are included and evaluated.

Fuel production technology:

This KPI assesses the production technologies used to produce different sustainable zero-carbon fuels and the potential these technologies carry for future expansion. We assess the maturity level of the currently most used production techniques. Some fuels utilize several production technologies for different parts of production, in which each part will be evaluated. In cases where production is restricted by challenges related to specific parts of production, the overall scoring will be based on the implications this has for the total production output. For the cases where the production technology (or parts of the production technologies) has only reached a low level of maturity, we will assess whether these are expected to become mature in the foreseeable future and what must be accomplished to enable production.

Production scalability:

This KPI assesses the ability to scale fuel production and whether there are implications with scaling of different technologies. Increasing production is important to meet increasing market demand. However, factors such as the above-mentioned technological maturity and characteristics of each production technology/technique increase the risk of investing in large scale production facilities. Incremental production capacity expansions/ investments are thus positive for risk management as the markets mature. Furthermore, small scale production could be vital for fuels that are “harder” to transport. This KPI focuses on whether the fuels can facilitate such incremental increases in production, or heavily rely on large-scale production facilities.

Feedstock availability:

This KPI assesses the current and future availability of resources used in production of different fuels. The potential resources analyzed include both feedstock such as natural gas for blue hydrogen production and biomass for biofuels, but also other potentially scarce resources such as geological potential for carbon storage. Fuels with lower energy density can put pressure on volume of feedstock needed in production and call for larger investments.

Interaction with other sectors:

This KPI assesses demand for fuel from other industries and its potential impact on fuel availability and prices in the future. How demand from other sectors affects prices depends on the technology maturity and scarcity of resources. New technologies typically have significant scope for an increase in efficiency and a decrease in production costs. Experiences from other industries, such as for example solar panels, show that learning by doing is the main driver of cost reduction and it is best approximated by cumulative production. Such a decrease in production costs is not expected for mature technologies. At the same time, demand from other sectors may drive prices up when resources are scarce. The size of this demand from other sectors will depend on the size of those sectors and alternative sources of energy (or feedstock) available to them.

2.3 Environment

Environmental challenges are related to greenhouse gas emissions when using various fuels, as well as local pollution, such as air pollution, noise or impact on marine habitat related to fuel use. In the analysis, we also take the energy systems perspective and assess the overall energy efficiency of various fuels and applicable propulsion systems. Overall energy efficiency determines the total primary energy use and thus the stress of the fuel choice on the available energy resources. Those resources at least in the transition phase to a net zero economy are limited. A brief description of those KPIs is presented in Table 7.

The assessment is based predominantly on a literature review. However, the studies reviewed for this analysis use a variety of assumptions and system boundaries, which restricts the comparability of the results between sources (Grahn, et al., 2022). Therefore, the score combines quantitative data from the reviewed articles with expert opinions from the consortium.

Table 7: Definition of the KPIs related to environmental barriers

CATEGORY	KPI	DESCRIPTION
Environment	Greenhouse gas emissions	Greenhouse gas emissions well-to-tank and tank-to-wake
	Local pollution	NOx emissions, noise pollution, marine pollution
	Overall energy efficiency	Total primary energy required per unit of propulsion

Greenhouse gas emissions:

Greenhouse gas emissions are analyzed in two stages: a well-to-tank analysis (fuel production and transportation) and a tank-to-wake analysis (fuel use). However, in the scorecard, only one integrated score is given. This is important given that some fuels (such as biofuels, e-methanol, and e-methane) inherently generate GHG emissions in the tank-to-wake stage due to carbon content of the chemical compounds. However, those fuels can still be zero-emission if carbon used in fuel production comes from sustainable sources, such as direct air capture, or biomass.

The well-to-tank analysis focuses on the upstream emissions related mainly to fuel production and transportation. Our analysis includes the following:

- Emissions related to development of production infrastructure, including upstream infrastructure (such as electricity production or natural gas production infrastructure).
- Process emissions, such as emissions related to electrolysis of water or steam reforming of natural gas required to produce hydrogen. Our assessment also includes upstream process emissions, such as fugitive leaks associated with natural gas extraction.
- Emissions related to transportation of fuels from their production site to bunkering facilities and further on board of the ship.

The tank-to-wake analysis assesses downstream emissions, meaning the use of the fuel that is already in the tank. In this stage, emissions depend on the fuel type (e.g., hydrogen or ammonia) but not on the fuel source (green, i.e., from water electrolysis or blue, i.e., from fossil fuels with carbon capture and sequestration). For each of the fuels, emissions vary depending on the engine technology (e.g., internal combustion engine or a fuel cell). When multiple technologies exist, we assign score to the best alternative but discuss the differences in emission levels between the technologies.

The analysis is based on literature review only. For selected fuels the scope of the analysis will be extended in a comprehensive life cycle assessment in the subsequent stages of the project.

Local pollution:

When assessing local pollution, we analyze the levels of Sulphur dioxide (SO_2), nitrogen dioxide (NOx), particulate matter (PM 2.5) and Black Carbon pollution associated with fuel use. We also consider the impact on maritime/marine life through noise and water pollution.

Overall energy efficiency:

The overall energy efficiency is assessed by looking at the total primary energy required to provide one unit of propulsion. The analysis includes the energy required in the fuel production and distribution phase (well-to-tank) as well as use of fuel on board (tank-to-wake). This KPI determines the total energy requirements for the maritime sector. This in turn translates to requirements for land and other scarce resources used in renewable energy production. The more energy that is required per unit of propulsion, the harder it is to scale the technology.

2.4 Maritime rules and regulations

Maturity of rules and regulations related to sustainable zero-carbon fuels will play an important role in the adoption of these as well as safety of crew and environment. The onboard technologies for zero-carbon fuels are novel to the maritime industry and are not covered by prescriptive rules, creating a comprehensive and expensive design and approval process with a high degree of uncertainty for each unique installation.

Table 8: Definition of the KPIs related to rules and regulations

CATEGORY	KPI	DESCRIPTION
Rules and regulations	Maturity of maritime rules and regulations	How mature rules and regulations are to handle the risks related to fuels

Maturity of maritime rules and regulations:

Like conventional marine fuels, sustainable zero-carbon fuels come with safety risks attached, such as toxicity and flammability. There needs to be enough testing and experience with onboard usage and bunkering of these fuels so that all safety risks are understood to prepare rules and regulations. Some of the sustainable zero-carbon fuels in this report have come a long way in terms of maturity of rules and regulations, since they have already been taken into use or there is accumulated experience in terms of transportation of the fuel. However, some sustainable zero-carbon fuels are completely new to shipping and extensive testing and learning are required to take these into use safely. This KPI evaluates the maturity of maritime rules and regulations regarding each alternative fuel.

2.5 Scoring methodology

To assess the sustainable zero-carbon fuels based on the described KPIs, a scoring methodology was established. In previous papers, this has varied from a score from 1-3 to a score all the way up to 10. We have chosen, based on an internal assessment with the consortium, to base the analysis on a score from 1 to 4. The five areas mentioned in step 2[9] constitute different challenges. The scoring is therefore formulated to align with the barriers/challenges that are assessed, as described in the following, ordered by each main KPI category. To illustrate the scoring, we have made tables with color codes. Red=1, orange=2, light green=3 and dark green=4.

2.5.1 Onboard KPIs

Scoring for the following Onboard KPIs: **(X) Technical Maturity, (Y) Existing ship compatibility**

Score	Description
1	**Severe technical and/or economic barriers.** Onboard fuel technology only tested at an experimental stage / No compatibility with existing propulsion
2	**Major technical and/or economic barriers.** Pilots identified, but technology not demonstrated at a large scale / Compatible with certain fuel systems, but lacking commercial maturity

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[9] *Market driven challenges, onboard challenges, onshore challenges, environmental challenges and rules and regulations*

3	**Moderate technical and/or economic barriers**. Onboard fuel technology demonstrated, but still not fully mature / Compatible with a wide range of fuel systems, but still lacking commercial maturity
4	**Little to no technical and/or economic barriers**. On board technological maturity not a barrier for commercial usage / Already compatible with most fuel systems

Scoring for the following Onboard KPIs**: (X) CAPEX, (Y) Fuel Cost**

Score	Description
1	**Severe economic barriers.** Cost levels much higher than competing technologies. Low commercial potential.
2	**Major economic barriers.** Cost levels higher than competing technologies. Limited commercial potential without significant relative reductions
3	**Moderate economic barriers**. Cost levels competitive with most zero-carbon fuels, but still far off traditional options.
4	**Little to no economic barriers**. Cost levels competitive with most fuel options.

Scoring for the following onboard KPIs**: (X) Energy density**

Score	Description
1	**Severe technical and/or economic barriers.** Energy density *significantly* limits the fuel's possible impact in a Nordic shipping context.
2	**Major technical and/or economic barriers.** Energy density limits the fuel's possible impact in a Nordic shipping context, but still a viable option for several ship segments.
3	**Moderate technical and/or economic barriers**. Energy density is not limiting the fuel's technical potential, but still affecting cargo space negatively compared to existing fuels.
4	**Little to no economic barriers**. Energy density is not limiting the fuel's technical or economical potential with regards to sailing patterns and cargo space.

2.5.2 Onshore KPIs

*Scoring for the following Onboard KPIs**: (X) Production technology, (Y) Infrastructure***

Score	Description
1	**Severe technical and/or economic barriers.** Little to no availability/experience and severe technological barriers to scale.
2	**Major technical and/or economic barriers.** Limited availability/experience and still major technological barriers that need to be solved.
3	**Moderate technical and/or economic barriers**. Moderate availability/experience. Still some barriers that need to be addressed
4	**Little to no economic barriers**. High degree of availability/experience. Investments might be needed, but no vital technical barriers to scaling.

*Scoring for the following Onboard KPIs**: (X) Production scalability***

Score	Description
1	**Severe technical and/or economic barriers.** Little to no possibility of small-scale production
2	**Major technical and/or economic barriers.** Small-scale production possibility very limited by technical aspects as well as economic ones
3	**Moderate technical and/or economic barriers**. Small-scale production technically viable, but economic barriers limit the commercial application.

4	**Little to no economic barriers**. Small-scale production is both technically and economically viable as markets mature and/or if transportation is difficult/costly

*Scoring for the following Onboard KPIs****: (X) Feedstock availability, (Y) interaction with other sectors***

Score	Description
1	**Severe economic barriers.** Little to no availability / large degree of competition for feedstock from other sectors and/or limited technological spillover effects.
2	**Major economic barriers.** Limited availability / some competition for feedstock from other sectors and/or some technological spillover effects.
3	**Moderate economic barriers**. Feedstock not a major barrier/ limited competition and/or positive technological spillover effects from other sectors
4	**Little to no economic barriers**. Feedstock availability not affecting zero-carbon potential / large technological spillover effects from other sectors.

2.5.3 Environmental KPIs

*Scoring for the following KPIs****: (X) Greenhouse gas emissions; (X) local pollution***

Score	Description
1	**Severe technical and/or economic barriers**. Low potential to become zero emission in the Nordics.
2	**Major tech technical and/or economic or economic nical barriers**. Breakthrough innovation required to reach (near) zero-emission in Nordic shipping.
3	**Moderate technical and/or economic barriers**. High potential to become (near) zero emission in Nordic shipping, but several barriers must be addressed to commercially scale up technology.
4	**High potential/relevance** Existing best available techniques for low emission shipping in Nordic. Innovation still needed to reach (near) zero carbon in a life-cycle perspective.

*Scoring for the following KPI: **(X) Overall energy efficiency***

Score	Description
1	**Severe environmental and/or economic barriers**. Low potential to become zero emission due to vast primary energy required.
2	**Major environmental and/or economic barriers**. Zero-carbon fuel production will require major increase in the supply of primary energy.
3	**Moderate environmental and/or economic barriers**. Zero-carbon fuel production will require a large investment in primary energy supply, but to a lesser extent than the less energy efficient fuel options
4	**High potential/relevance.** The most energy efficient zero-carbon fuels with regards to primary energy requirements.

2.5.4 Rules and regulations

*Scoring for the following KPI: **(X) Maturity of maritime rules and regulations***

Score	Description
1	**Severe barriers for commercial usage.** Research and development phase
2	**Major barriers for commercial usage.** Prescriptive requirements under development
3	**Moderate barriers for commercial usage.** Prescriptive requirements available
4	**Little to no barriers for commercial usage.** Uniformly accepted prescriptive requirements available.

3. Cross-fuel analysis

Shipowners have conventionally gravitated towards solutions that are cheaper, more reliable, more efficient and demand less space onboard. This will not change going forward. The challenge is however that the solutions to reduce global maritime GHG emissions are typically more expensive, less mature, less efficient and require more space onboard. These barriers are assessed in the fuel-by-fuel analysis. This chapter gives a brief description of the sustainable zero-carbon fuels' feasibility in covering the Nordic ship traffic's fuel consumption. The feasibility screening focuses on the respective fuels' suitability with regards to covering the Nordic ship traffic's fuel consumption both domestically, between the Nordic countries, and for international voyages connected to the Nordics. The aim is to identify the technical market *potential* for the different sustainable zero-carbon fuels, given today's sailing pattern. The screening is based on DNV's AIS-analysis in Task 2A. The aim of the feasibility analysis is to assess the feasibility of battery electric propulsion systems, hydrogen, and ammonia/methanol/methane. Except for battery electric, all these fuels have hydrogen as a basis and most of the energy required in the production of these fuels is spent on producing hydrogen (Hoecke et al., 2021). They do however vary significantly in energy density, which affects their possibility to cover the current voyages taking place in Nordic waters. The analysis is divided into two focus areas which are described below:

- *Nordic feasibility:* The assessment of the Nordic feasibility looks at the respective fuels' possibility to cover the fuel consumption of the Nordic ship traffic in total, but also the fuels' feasibility for specific ship segments. The broader the scope of each fuel, the lesser the technological risk of the portfolio will be. Thus, a high cross-type-feasibility is positive going forward. However, the fuels' ability to cover the consumption of the most important ship types must also be reviewed. This latter aspect is important if fuels that have less cross-type-feasibility could potentially be more commercially viable for "main-types-segments" in a Nordic perspective.
- *Domestic relevance:* Some fuels could be valuable due to their ability to facilitate a transition to zero-carbon fuels for *specific* Nordic countries and/or less important if they are not. It is therefore important to check the domestic relevance in each Nordic country, based on the most relevant vessel segments, to ensure that the geographical variation is sufficiently covered by the respective fuels.

It is important to notice that the feasibility task is done on a high level. DNV's analysis is based on energy needed per voyage for each ship, to determine if the different fuel options are feasible for this ship.[10] The energy consumption of each voyage will, amongst other internal and external factors, mainly depend on the ship's operational profile, weather conditions, given by sailing distance, engine power curve and sailing speed.[11] The analysis does not take into account safety aspects, availability of the fuel, costs, onboard design, fuel costs etc. As such, even though a fuel may be assessed as feasible for a ship type, it does not mean that the shipowner would actually prefer this fuel when faced with an investment decision. This chapter is therefore a preliminary chapter to the fuel-by-fuel analysis, where the demand side and supply side of the market are analyzed in more detail on the different KPIs. It is also worth noticing that adjustments in ship design, sailing patterns and/or shipowners' valuation of cargo space could affect the respective fuels' feasibility going forward.

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[10] *By* this ship, *we mean a ship with the same characteristics in terms of type, size and sailing pattern as the existing ship identified through the MASTER and GSCM model. It is not necessarily feasible to retrofit all existing ships to new technologies and fuels.*

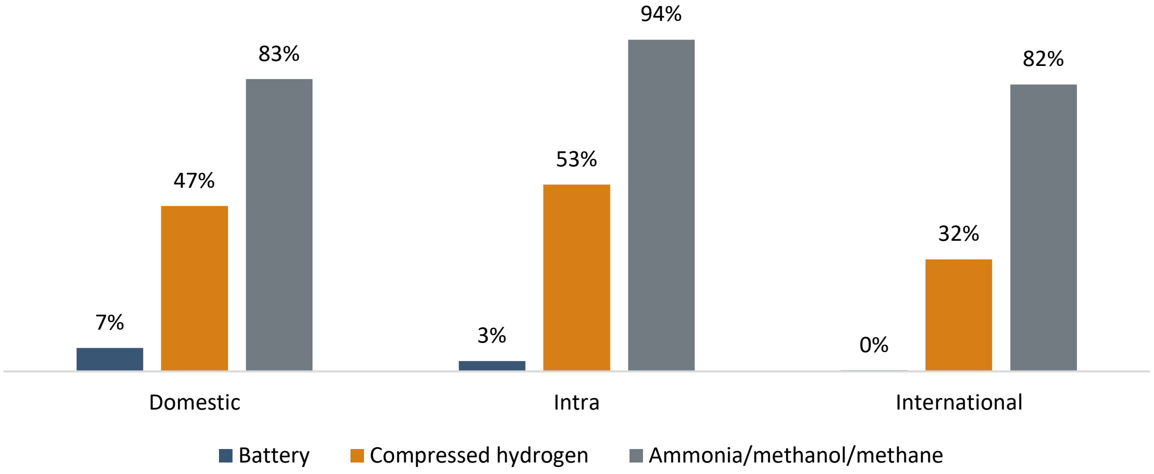
[11] *For more information about the methodology, see Appendix C.*

3.1 Nordic feasibility

The assessed sustainable zero-carbon fuels, battery electrification, compressed hydrogen and ammonia, methanol and methane[12] represent three feasibility "levels", ordered by increasing energy density. Higher energy density leads to a higher feasibility with regards to covering the maritime fuel consumption in the Nordics. HVO is not included in the feasibility analysis due to its similarities with conventional diesel fuel, e.g., energy density, engine compatibility, as well as storage and bunkering. Given the sailing pattern and ship size, HVO can cover the fuel consumption of the Nordic traffic in line with conventional fuel. However, the main challenge with HVO as a fuel is related to production scalability and feedstock availability. This is something we analyze further in the fuel-by-fuel analysis.

The figure below shows the high-level results from DNV's feasibility screening. As seen in the figure, battery electric propulsion has the lowest feasibility to cover the Nordic ship traffic's fuel consumption, followed by compressed hydrogen. Battery-electric ships are already commercialized and there exist several ships, especially within the ferry segment, which are already sailing on battery-electric propulsion. Hydrogen is assessed to be feasible to cover up to 30 percent of the Nordic ship traffic, while the high energy density fuels can cover between 80 and 90 percent. The residual needs to be covered by fuels with even higher energy density such as HVO or through adjustments in sailing pattern, ship size or ship design. A last option is to forsake some cargo space, to increase fuel storage.

Figure 3: Feasibility screening: Share of total fuel consumption for the Nordic ship traffic that can be covered by battery-electric propulsion, compressed hydrogen and ammonia/methanol/methane. Source: DNV



3.1.1 Battery electric propulsion most feasible for the passenger segment

Although battery technology is under constant development, the technology is currently suitable only for a narrow sample of vessel types. These are usually vessels that sail relatively short distances on a regular basis, due to low volumetric density compared to many other energy carriers. Even though battery electric technology

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[12] *In Task 2A, DNV has divided between battery electrification, compressed hydrogen and methanol. Due to the fact that ammonia, methanol and methane have relatively equal energy density, ammonia and methane are included in our analysis in this task.*

can only cover a small share of the Nordic ship traffic's total fuel consumption, it can potentially cover a higher share of the fuel consumption within the passenger vessel segment. This is shown in the table below.

Figure 4: Battery-electric propulsion feasibility, percentage of energy consumption. Source: DNV

	Domestic Nordic	Intra Nordic	Nordic International
Cargo	0 %	0 %	0 %
Cruise ship	0 %	0 %	0 %
Fishing	0 %	0 %	0 %
Passenger	**24 %**	**8 %**	**1 %**
Wet and dry bulk	0 %	0 %	0 %
Work/service	1 %	1 %	1 %

The relevance of battery electric propulsion systems for passenger ships is already visible in Norway, where a large part of the ferry segment has been electrified already. In addition, it is also to some degree feasible for intra-Nordic passenger routes. The feasibility within other ship categories is very limited. It should be noted that this refers to fully battery electric propulsion, not hybrid solutions. The latter are feasible and relevant as a short-term emission reduction measure for most ship types and could be vital as a transitory solution.

3.1.2 Compressed hydrogen is feasible to cover several ship types

Compressed hydrogen has a higher feasibility in covering the Nordic ship traffic's fuel consumption compared to battery electrification. It is especially relevant for smaller ships with an operating profile that allows for frequent refueling, limiting the required amount of fuel that needs to be stored onboard. It can also be relevant for larger ships, but only the ones which can more easily accommodate the extra volume of fuel needed. This can for example be inland passenger ships, which normally are smaller ships navigating on fixed routes with the possibility of relying on fixed bunkering points along their routes (Pawelec, 2020). The table below shows hydrogen's feasibility across ship types.

Figure 5: Compressed hydrogen's feasibility, percentage of energy consumption. Source: DNV

	Domestic Nordic	Intra Nordic	Nordic International
Cargo	**46 %**	25 %	34 %
Cruise ship	**53 %**	**61 %**	**50 %**
Fishing	9 %	3 %	3 %
Passenger	**85 %**	**98 %**	**99 %**
Wet and dry bulk	19 %	12 %	7 %
Work/service	42 %	30 %	19 %

The feasibility of compressed hydrogen is quite substantial for several ship categories, in particular passenger vessels and cruise ships. Feasibility *is the least limited* for wet and dry bulk and fishing. Although the energy density of hydrogen is low compared to ammonia and methanol, there is potential also for using compressed hydrogen for short sea routes to Northern Europe and intra Nordic routes. An example of an ongoing project is the world's first hydrogen-powered cargo ship operated by Heidelberg Cement and Felleskjøpet.[13]

The table above shows the potential for compressed hydrogen, but liquified hydrogen is also an option. One example is MF Hydra, the world's first vessel to be powered by liquid hydrogen[14]. Hydrogen also has the potential to cover the fuel consumption within the cargo segment, especially for the domestic fleet.

3.1.3 High density fuels essential for the Nordic green transition

Ammonia, methanol and methane can cover between 80 and 90 percent of the Nordic fleet's fuel consumption. This is also reflected in the table below, showing a high cross-type relevance. The limitation of feasibility is for fishing vessels sailing on international routes. These are typically smaller ships, with limited carrying capacity and long sailing distances. In this segment, there are few vessels with alternative fuel technology. A few LNG trawlers have been built, and the storage space problem has been solved by building the ships larger than if they were conventional, due to the fuel's lower energy density.

Figure 6: High energy density fuels' feasibility, percentage of energy consumption. Source: DNV

	Domestic Nordic	Intra Nordic	Nordic International
Cargo	94 %	94 %	83 %
Cruise ship	90 %	96 %	97 %
Fishing	65 %	54 %	36 %
Passenger	99 %	100 %	100 %
Wet and dry bulk	95 %	97 %	79 %
Work/service	70 %	73 %	52 %

There already exist around 200 gas tankers that can take ammonia as cargo tankers and around 40 of them are deployed with ammonia cargo at any point of time. These ships will be ideal first users of ammonia as a marine fuel as they already have the fuel as cargo and crews with experience in handling ammonia.[15] DNV expects the first ammonia-fueled vessel to sail in the second half of this decade. A large-scale uptake of the technology is not expected until the early 2030s. While the supply of ammonia will take time, the development of engine technology is progressing fast.

The use of methanol has been around for some time, but its application to shipping started in 2015 with the conversion of the Stena Germanica RoPax Ferry to test the viability of using methanol as a marine fuel.[16] Since then, methanol as a marine fuel has attracted interest within the shipping community from several shipowners, shipyards and fuel suppliers.[17] Maersk announced in June 2021 the world's first methanol-powered shipping vessel. This is a steppingstone towards the industry's goals to reduce environmental impact and the company

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[13] *https://www.statkraft.com/newsroom/news-and-stories/archive/2021/hydrogen-deliveries/, retrieved 17.08.2022*

[14] *https://fuelcellsworks.com/news/worlds-first-liquid-hydrogen-powered-vessel-wins-ship-of-the-year-award/, retrieved 17.08.2022*

[15] *https://www.dnv.com/expert-story/maritime-impact/Harnessing-ammonia-as-ship-fuel.html*

[16] *https://www.ship-technology.com/projects/stena-germanica-ropax-ferry/, retrieved 23.08.2022*

[17] *https://www.dnv.com/maritime/advisory/afi-update/Methanol-as-a-potential-alternative-fuel-for-shipping-A-brief-talk-with-Chris-Chatterton.html, retrieved 23.08.2022*

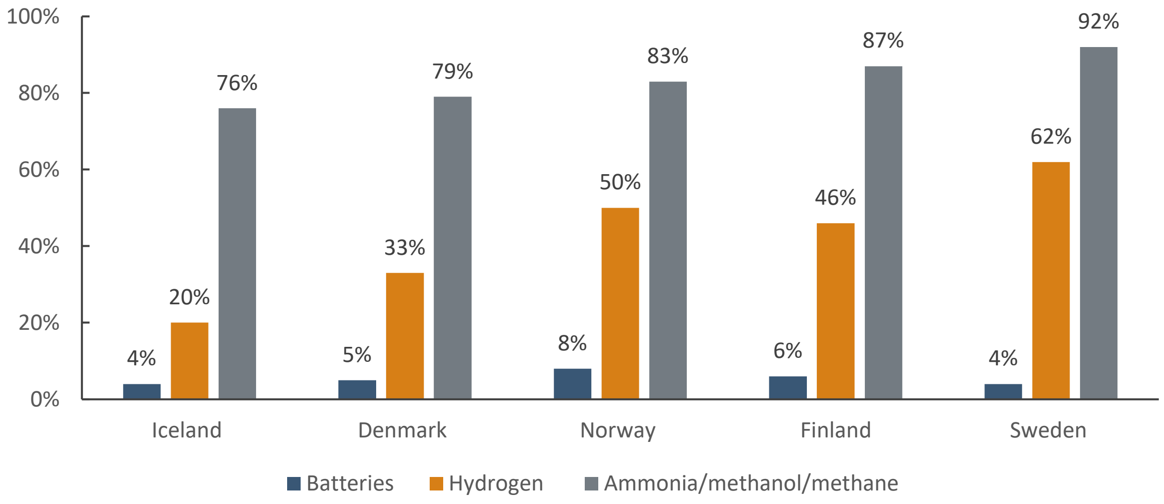
believes that green methanol is the fuel for the future.[18] Since methanol is either available at or within easy proximity of many ports, it will become more attractive for shipowners due to the fact that they know that the supply and availability of methanol is present. However, to be able to supply large fleets, there is a need to scale production. This is not necessarily a problem, since it has never been an issue historically for the sector to meet demand requirements, but the increase in capacity would require significant capital expenditure, and zero-carbon shipping would require access to green alternatives.[19]

Like ammonia, vessels carrying methane (today LNG) are the ones that have started using methane as fuel (Clarksons Research, 2022). Even though methane tankers had an advantage in fuel uptake, LNG is being adopted by many vessel types and as fuel availability around the world increases, it will be relevant for all types of vessels.

3.2 Domestic relevance

This chapter gives a description of the sustainable zero-carbon fuels' potential to cover the consumption in each Nordic country. Some fuels could be valuable due to their ability to facilitate a transition to zero-carbon fuels for specific Nordic countries and others less relevant if the sailing patterns do not "fit" with the attributes of the respective fuel. The latter is especially important when assessing the domestic relevance of fuels with limited energy density. The figure below shows the main findings of the country-specific feasibility analysis.

Figure 7: Share of total fuel consumption, Nordic domestic, that can be covered by high energy density fuels, hydrogen and battery-electric in the Nordic countries. Source: DNV/Menon Economics



The Nordic countries' fleets differ in terms of type of ships, both in terms of operation (fishing vessels, offshore supply and passenger vessels) and in terms of size (short-sea and deepsea). This means that the sustainable zero-carbon fuels' potential to cover the fuel consumption of the domestic ship traffic in the Nordic countries also differs. In addition, although smaller ships typically travel shorter distances than large ones, there is considerable

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[18] *https://www.ship-technology.com/analysis/is-methanol-the-best-fuel-to-meet-shippings-green-goals-icct-qa/, retrieved 23.08.2022*

[19] *https://www.dnv.com/maritime/advisory/afi-update/Methanol-as-a-potential-alternative-fuel-for-shipping-A-brief-talk-with-Chris-Chatterton.html, retrieved 23.08.2022*

variation in the fleet and relatively small vessels can also sail long distances, especially for ship types such as offshore and fishing.

As seen in the figure above, battery-electric propulsion has the lowest potential in covering the fuel consumption of the ship traffic in all the Nordic countries. Even though the market for batteries is quite mature, the technology is still under development, and it is believed that batteries suitable for larger vessels/longer voyages will be developed going forward. Battery-electric propulsion is most relevant in Norway, mainly due to the large fleet of ferries and passenger vessels with shorter voyages and more frequent bunkering opportunities. Compressed hydrogen can cover a larger share of the fuel consumption, but this differs significantly between countries. Hydrogen is most relevant in Sweden, followed by Norway and Finland. In Iceland however, hydrogen has a significantly lower feasibility. This is mainly because a large share of the fleet in Iceland consists of fishing vessels, and this could affect the profitability of infrastructure investments and bunkering services. The high energy density fuels can in theory cover between 70 and 90 percent of the fuel consumption in the Nordic countries, but there is a need for modifications with regard to ship size, design, sailing patterns and/or shipowners' valuation of cargo space in order for the sustainable zero-carbon fuels to cover the whole Nordic ship traffic.

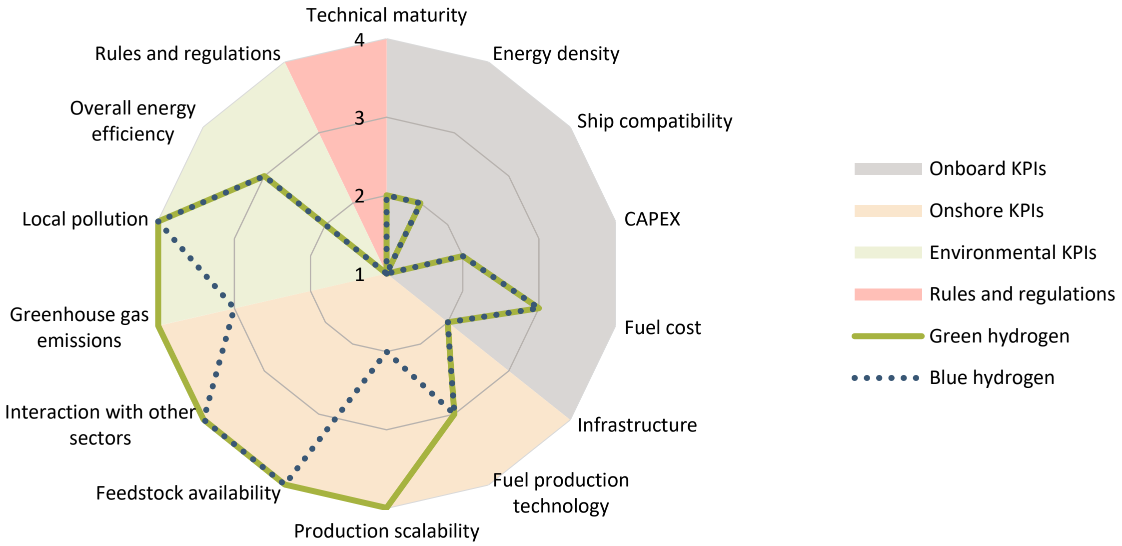
4. Fuel-by-fuel analysis

In this chapter, we conduct a fuel-by-fuel analysis based on the included KPIs. KPIs are split into onboard, onshore, environmental, and implementation of rules and regulatory frameworks KPIs for each fuel.

4.1 Hydrogen

Hydrogen can play an important role in the Nordic shipping industry's journey towards decarbonization. The feasibility analysis conducted in task 2A shows that hydrogen could potentially cover up to 50 percent of the intra Nordic fuel consumption. Green hydrogen has a potential to become a zero emissions fuel. This requires efforts to reduce upstream emissions (scale up renewable production capacity), especially related to renewable electricity generation. Blue hydrogen, however, scores lower than green on the environmental KPIs due to emission-related barriers in a life-cycle perspective that need to be resolved. Hydrogen has an advantage of high production scalability. This means that hydrogen can facilitate bunkering in smaller ports near the end-user, increasing the short-term availability for shipowners as the market matures. Even though several actors in the industry recognize hydrogen's potential, there are still important barriers that need to be addressed to make hydrogen shipping a commercially mature alternative. A low compatibility with existing ship types means that new ships need to be built and/or that comprehensive rebuilds will be necessary. Currently, a relatively low onboard maturity with regards to technical and safety aspects affects both risk assessments and capital costs for shipowners. Fuel costs are expected to be favorable, but bunkering hubs need to be developed to ensure sufficient availability. The main barriers identified signal a need for significant investments both onshore and onboard with regards to R&D and infrastructure development. Furthermore, coordination between shipowners, fuel suppliers, bunkering service and authorities will be vital to ensure that hydrogen reaches its commercial potential as a zero-carbon fuel in the Nordics.

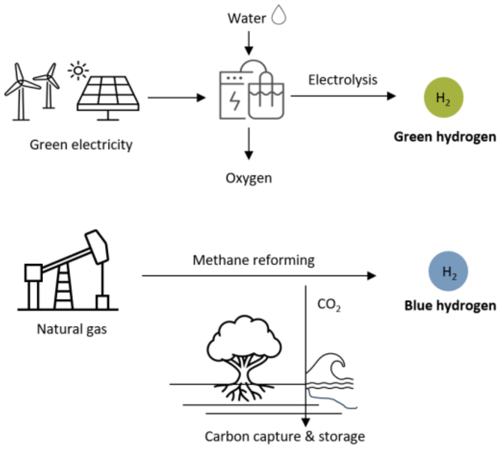
Figure 8: Scoring of onboard, onshore, environmental and safety-related KPIs for both green and blue hydrogen. Source: Menon Economics



In this report our focus will be solely on green and blue hydrogen. Hydrogen that is produced via natural gas reforming or of other fossil fuels *without CCS* is outside the scope of this report, since the production process will cause greenhouse gas emissions and hydrogen produced in this way cannot be considered a zero carbon fuel.

The figure below illustrates two potentially emission-free ways of hydrogen production. The first path is through electrolysis of water which consists of hydrogen and oxygen. If the electricity powering the electrolysis process is generated through renewable sources such as wind power, solar power etc., the hydrogen produced is referred to as green hydrogen. Another path is through addition of CCS to the existing production technology based on reforming of fossil fuels. Hydrogen produced this way will be referred to as blue hydrogen.

Figure 9: Illustration of green and blue hydrogen production



In this chapter, we assess hydrogen's potential to become a near zero-carbon fuel in the maritime sector. It gives a description of the KPIs related to the barriers and challenges of using hydrogen as a marine fuel, from a market perspective, and an onboard, onshore, environmental and safety perspective.

4.1.1 Onboard

This section provides a description of the onboard KPIs for hydrogen. We do not differentiate between blue and green hydrogen for technical KPIs, since this does not make a difference, but we do differentiate between compressed and liquified hydrogen where we see necessary. Economic KPIs differentiate between blue and green hydrogen where it is necessary. The table below shows the score for each onboard-KPI for the use of hydrogen as a marine fuel.

Table 9: Onboard KPIs for blue and green hydrogen

CATEGORY	KPI	GREEN HYDROGEN	BLUE HYDROGEN
Technical	*Technical maturity*	🟧	🟧
	Energy density	🟧	🟧
	Existing ship compatibility	🟥	🟥
Economical	*CAPEX*	🟧	🟧
	Fuel cost	🟩	🟩

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Technical maturity: Hydrogen as a marine fuel can be used both in internal combustion engines and fuel cells.

In the internal combustion engine, hydrogen is used as the combustor and mechanical energy is generated through burning hydrogen. Internal combustion technology has been widely used with a variety of fuel types; therefore, the technology is known to producers and users in principle. On the other hand, using internal combustion engines with hydrogen requires certain modifications to the engines and extensive testing. The technology is currently under development; however, it is not ready to be taken into use yet.[20]

Fuel cells generate electricity without combustion. There are hydrogen fuel cells available on the market today, even though there needs to be innovation in technology to make these suitable for marine use (Frelle-Petersen, Howard, Poulsen, & Hansen, 2021). There have been pilot projects and demonstrations of this technology on small boats[21]. Fuel cell technology at a bigger scale is expected to be taken into use in the MF Hydra ferry in Norway[22] in addition to Penguin Tenacity in Singapore[23]. However, there are no commercial vessels that operate on hydrogen currently.

In addition to engine systems, hydrogen faces challenges with onboard storage technology. Due to the physical properties of hydrogen, onboard storage systems should be suitable for storing liquified hydrogen under cryogenic conditions. This requires installation of cryogenic tanks on board.

Even though there are pilot projects and demonstrations, both fuel cell and internal combustion technologies have low technical maturity and are therefore scored as one of the lowest among all the sustainable zero-carbon fuels.

Energy Density: Hydrogen is the lightest atom and has a very low volumetric density in its gas state. Thus, from a commercial perspective, only compressed and liquified hydrogen are considered viable for the shipping sector. Volumetric density of hydrogen is between 5-10 MJ/l depending on whether it is compressed or liquified (DNV, 2019a). A very low volumetric density leads to challenges in terms of onboard storage, in that it will have a higher opportunity cost since there will be limited capacity to carry cargo. In addition, limited onboard fuel storage capacity will affect the range a vessel can operate in, so that ships using hydrogen will need to bunker more often than those using fuels with higher volumetric energy density. This is a serious barrier in terms of using hydrogen as a marine fuel and limits the types of vessels hydrogen can be used for. Onboard storage of liquified hydrogen requires installation of cryogenic tanks, or vacuum insulated tanks to limit boil-off[24] (Rivard, Trudeau, & Zaghib, 2019). The technology is known, and it is mature, but has some price implications, as discussed under economical KPIs. Compressed hydrogen on the other hand can be stored in high pressure hydrogen tanks at 350 bar or 700 bar, which is a less energy intensive way of storing hydrogen. However, as compressed hydrogen has a lower energy density, the loss of cargo space will be bigger.

Although hydrogen has the lowest volumetric energy density across the fuels that are discussed in this report, it has the potential to cover a big share of Nordic ship traffic. Still, lower energy density creates a major barrier for adoption of hydrogen, which leads to a score of 2.

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[20] *https://www.man-es.com/discover/designing-the-engines-of-the-future, retrieved 17.08.2022*
[21] *https://www.reuters.com/article/uk-dutch-fuelcell-idINLNE69E05220101015, retrieved 17.08.2022*
[22] *https://www.tu.no/artikler/mf-hydra-fyller-hydrogen-pa-tanken/521174?key=W9e0WdyR, retrieved 17.08.2022*
[23] *https://maritime-executive.com/article/shell-sembmarine-penguin-plan-hydrogen-fuel-cell-test-in-sngapore, retrieved 17.08.2022*
[24] *Boil off: Boiling of a small share of cryogenic fluid due to ambient temperature outside the tank.*

Existing ship compatibility: None of the internal combustion engines that are in use today can be used with hydrogen without extensive modifications (Foretich, Zaimes, Hawkins, & Newes, 2021). However, hydrogen is compatible with diesel electric and battery electric propulsion systems, although it requires major modifications onboard. When it comes to fuel storage tanks onboard there is a need for modification to tolerate cryogenic temperatures in case of liquified hydrogen, or high-pressure tanks in case of compressed hydrogen, and fuel storage capacity will need to be increased to compensate for lower volumetric energy density of hydrogen.

For this reason, hydrogen performs lower among sustainable zero-carbon fuels in terms of existing ship compatibility as it faces major technical barriers, and is hence scored 2.

CAPEX: Hydrogen is ranked low in several studies due to its expected high investment costs (Hansson, Månsson, Brynolf, & Grahn, 2019). Hydrogen scores relatively low due to its low compatibility with existing engines[25]. In addition, when assessing converter costs, it is evident that fuel cells are currently many times more expensive than internal combustion engines. Moreover, the big spread in cost estimates for fuels cells indicates a large degree of uncertainty. Fuel cells also have a significantly shorter life expectancy than internal combustion engines, and fuel cell stack replacement is expected several times during a vessel's lifetime, leading to additional capital costs. For hydrogen, DNV has found tanks for liquefied hydrogen to be significantly more expensive due to lower storage temperatures, higher insulation quality and fewer maritime applications (DNV, 2019b). Compressed hydrogen comes with similar costs as liquified hydrogen with regard to the installation of appropriate propulsion systems on board, but storage related to this will be cheaper as high pressure tanks are less complex than cryogenic tanks.

CAPEX scoring is the same for both blue and green hydrogen, as there is no difference between different production methods in terms of CAPEX. Due to the expected high investment and converter costs, hydrogen gets a score of 2, among the lowest scores for the sustainable zero-carbon fuels.

Fuel cost: Green and blue hydrogen are in several studies ranked low compared to other zero-carbon fuels due to the expected high fuel cost (Hansson, Månsson, Brynolf, & Grahn, 2019). Furthermore, due to high transportation costs the hydrogen price will be to a certain degree affected by distance to production facilities and local production costs, as mentioned in the onshore chapter where the transportation to harbor KPI is described. However, since returns to scale are relatively low in green hydrogen production, high transportation costs could be avoided with local small-scale production.

Cost of green hydrogen: green hydrogen is not yet produced at a large scale. The development of electrolyzers for green hydrogen production is moving fast, and the electrolyzer CAPEX is expected to decrease rapidly while electrolyzer efficiency is set to increase in the coming years. Both wind and solar energy technology is increasing its efficiency, thus the costs are expected to fall. According to Wood Mackenzie, the levelized cost of hydrogen is expected to go below $2 per kilogram ($14/GJ) in many countries by 2030, and in some countries, it could even fall to under $1 per kilogram ($7/GJ).[26] In order to achieve that cost level, the cost of the clean electricity would need to be under $10/MWh and electrolyzers would have to have a capacity factor of 50 percent (van Dorsten & Sultonn, 2021).

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[25] *According to an article in E24, 02.08.2022, a diesel ship that costs NOK 100 million to build today would have a price of NOK 170 million if it were to sail on hydrogen. (https://e24.no/det-groenne-skiftet/i/34rrzX/det-groenne-skiftet-gaar-i-sakte-fart-paa-sjoeen-vi-er-paa-etterskudd, retrieved 23.08.2022)*

[26] *This price level on per unit of energy basis corresponds to price of crude oil slightly under 50$ per barrel.*

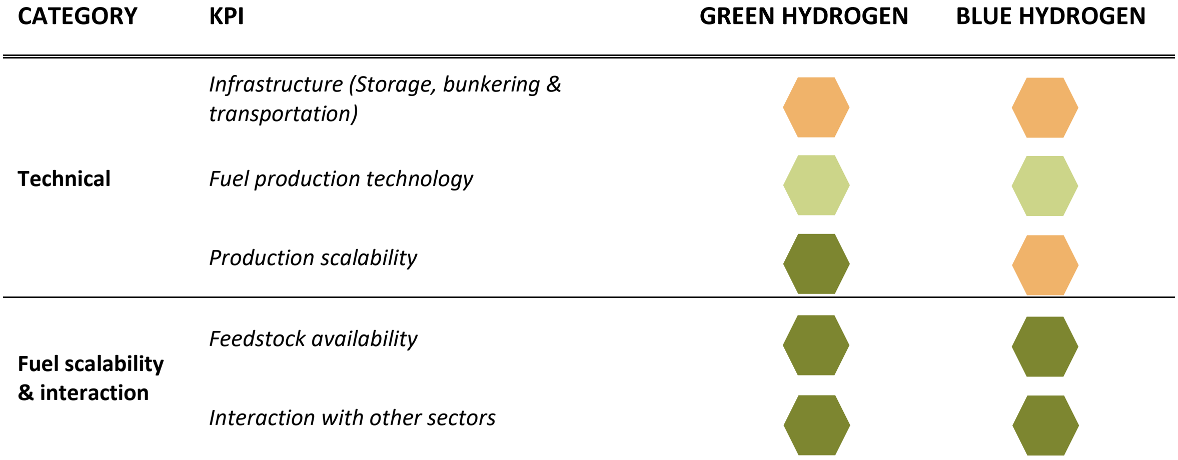
Cost of blue hydrogen: The production cost of blue hydrogen is closely connected to the price of natural gas, which has recently increased significantly. Under extraordinary high natural gas prices in 2022, the costs of blue hydrogen were higher than for green hydrogen in some locations. But even under "normal", i.e., pre-war natural gas prices, green hydrogen was expected to reach lower production cost in some regions by 2030 (van Dorsten & Sultonn, 2021). Another factor is the cost of carbon capture and storage. Based on European gas price forecasts from October 2021, blue hydrogen production cost was expected to be around $2.50-2.70/kg ($17-$19/GJ). The carbon capture technology has for years been optimized to minimize the CO_2 production costs rather than maximizing the carbon capture rate required to produce near zero-emission fuels. Thus, some cost reduction in the technology can be expected in the future.

Both hydrogen types receive a score of 3, which is higher than in the case of carbon-based e-fuels and at the same level as biofuels. Even though currently costs of green hydrogen are significantly higher than that of biofuels, price projections suggest that hydrogen will be the cheaper fuel in the future.

4.1.2 Onshore

In this part we look at the onshore KPIs. This includes the production path, and we therefore distinguish between green and blue hydrogen where relevant, in addition to the difference between compressed and liquified hydrogen.

Table 10: Onshore KPIs for green and blue hydrogen



CATEGORY	KPI	GREEN HYDROGEN	BLUE HYDROGEN
Technical	*Infrastructure (Storage, bunkering & transportation)*	🟧	🟧
	Fuel production technology	🟨	🟨
	Production scalability	🟩	🟧
Fuel scalability & interaction	*Feedstock availability*	🟩	🟩
	Interaction with other sectors	🟩	🟩

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Infrastructure (storage, bunkering & transport): Compressed hydrogen will require high-pressure tanks which can withstand pressures between 350 and 700 bars. Liquification of hydrogen reduces the volumetric space needed for storage and is therefore the most effective way of storing large amounts of hydrogen. However, liquification of hydrogen is an energy intensive process and it must be stored at a constant temperature, as mentioned above. Additionally, there are currently few storage facilities in the Nordic countries. However, SSAB, LKAB and Vattenfall are inaugurating HYBRIT's (initiative aiming to create fossil-free value chain from mine to finished steel) pilot facility for fossil-free hydrogen storage at Svartöberget in Luleå, Sweden. The pilot will have a life span of two years, ending in 2024 (Smart Energy International, 2022).

The technology used for storing hydrogen in cryogenic containers dates back to the Second World War. During this time, stainless steel materials were primarily used for storage. While storage systems for hydrogen, both in pressurized and liquid state, can be considered to have reached high maturity since this time, the methods suffer from far higher complexity when compared to traditional fossil fuels. Additionally, as few ports support hydrogen storage and bunkering today, large infrastructural investments must be made.

There are currently four main ways of transporting hydrogen: (i) through pipelines, (ii) by ship, (iii) by truck or (iv) by train. Existing natural gas pipelines can potentially be used to transport hydrogen, but only once they cease to be used for their original purpose. Hydrogen can be transported by ship in liquid state, as ammonia or as liquid organic hydrogen carrier. Currently, transportation by ships is technically possible only for larger distances where pipelines are not an option[27]. Due to the challenges associated with liquid transportation, hydrogen is mostly transported in smaller volumes. In this case, hydrogen transportation is viable via trucks or trains.

Transportation of hydrogen is dependent on whether blue or green hydrogen is produced, because there are challenges related to maintaining hydrogen purity, and minimizing the leakage.[28] Since green hydrogen can be produced in closer proximity to the harbors and minimizing hydrogen losses in transportation, the related transportation challenges can be avoided by producing hydrogen locally (DNV, 2022). This will be further investigated under the scalability of hydrogen production.

Due to hydrogen's low density at atmospheric pressure, the most viable alternative for large scale transportation is in liquid state in cryogenic tanks. The cooling of hydrogen to a liquid at ambient pressure implies large and expensive tanks that can withstand the extreme temperatures. Liquid hydrogen transportation by vessels must be established and scaled significantly to meet bunkering demand.[29]

The storage and bunkering of both liquified and compressed hydrogen imposes significant infrastructural challenges on the maritime industry. However, the technologies and systems needed to execute such infrastructural change is in existence. While ammonia also needs specialized tanks during liquid state transportation, the challenges associated with liquid hydrogen transportation are considerably more extensive, hence the infrastructure KPI of hydrogen is scored to 2.

Fuel production technology: Hydrogen is most often produced by steam reforming of natural gas, partial oxidation of heavier hydrocarbons, and coal gasification. Blue hydrogen uses natural gas or coal as feedstock and the production technology exploits methane reforming with CCS or gasification with CCS. Current CCS technologies have proven challenging for large scale production, with uncertainties both regarding performance and operation. Additionally, the current market situation for CCS is not at a competitive level, implying low knowledge sharing effects.

There are several electrolysis techniques for producing green hydrogen, with Alkaline currently the most developed. While electrolyzer technologies date to the late 18th century, it is only in the last 10 years that there has been a significant global interest for water electrolysis, with several climate programs to ensure close to net-zero by 2050 (Smolinka, Bergmann, Garche, & Kusnezoff, 2022). However, today's electrolyzers consume large amounts of electricity, making them ineffective (Tao, Azzolini, Stechel, Ayers, & Valdez, 2022). For electrolyzer

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[27] *https://www.rechargenews.com/energy-transition/special-report-why-shipping-pure-hydrogen-around-the-world-might-already-be-dead-in-the-water/2-1-1155434, retrieved 17.08.2022*

[28] *https://www.energy.gov/eere/fuelcells/hydrogen-delivery, retrieved 17.08.2022*

[29] *https://www.rechargenews.com/energy-transition/special-report-why-shipping-pure-hydrogen-around-the-world-might-already-be-dead-in-the-water/2-1-1155434, retrieved 17.08.2022*

technology to be viable, challenges regarding increasing the power density of stacks, enlarging the partial load range and reducing both the size of the system and its complexity must be addressed (Mergel & Stolten, 2012) for large-scale production to be viable (DNV, 2022).

Since the fuel production technology for both blue and green hydrogen exists and is quite mature, they both get a score of 3. There is however a need for further development in both the CCS and the electrolysis technology for reduced cost and increased commercial application, and we only consider the production technology of batteries to be more mature.

Production scalability: Blue hydrogen can be produced with several techniques – predominantly steam reforming of natural gas, although gasification of coal is also a possibility, while green hydrogen is produced through electrolysis of water.

Green hydrogen is not yet produced at scale. However, scaling of green hydrogen production is possible in small increments. Scaling of green hydrogen requires increased grid capacity. Additionally, an increase in the production of electrolyzers is necessary (Mergel & Stolten, 2012). Although there may appear to be competition between green and blue hydrogen production, the opportunities in practice are conditioned by geographical and resource-related constraints, enabling green hydrogen production in more remote areas (Bedani & Mortimer, u.d.). As such, the ability to produce green hydrogen closer to the end users, in smaller incremental steps, to some extent makes up for the low transportation score.

We consider the scalability of green hydrogen to be high, and only matched by that of batteries in this assessment, hence we score green hydrogen to 4. While there are significant opportunities to incrementally scale green hydrogen, blue hydrogen is more reliant on larger facilities. This implies scoring blue hydrogen to 2.

Feedstock availability: The feedstock used in green hydrogen consists of only renewable electricity and water, while blue hydrogen is dependent on natural gas or coal as its feedstock, with carbon capture and storage.

The supply of green hydrogen hinges on whether current power generation systems can support hydrogen production from renewables. Renewable energy resources (wind, solar etc.) are currently available at a large scale in the Nordics. As such, the feedstock *availability* is not considered a barrier for green hydrogen. It is however important to note that large investments in renewable electricity production will be vital. Green hydrogen production will be conditioned on each nation's strategic path towards the transition of utilizing renewable energy.

Although the technology for capturing and storing carbon dioxide is immature, and the efficiency of current electrolyzers used in green hydrogen production is at a low level, we consider the feedstock availability of both green and blue hydrogen to be high and expect it to remain high in years to come. The energy potential and technology for storage exists, there is however a need to increase investments in production facilities.

The feedstocks needed for both green and blue hydrogen production are found in abundant amounts, and we only consider the feedstock availability of batteries to be on the same level. The feedstock availability of both green and blue hydrogen is scored to 4 in our assessment.

Interaction with other sectors: The supply of hydrogen to industrial users is a major business around the world. Demand for hydrogen has grown more than threefold since 1975. The demand for hydrogen is relatively high within the oil refining industry, ammonia production, methanol production and steel production. Over half of all hydrogen produced is used to produce ammonia, whereof most is used to produce fertilizer. About 10 percent of all hydrogen is used in methanol production. Hydrogen can also be used as a reduction agent in steel production via DRI -process (direct reduced iron). Other applications include production of synthetic resin, metal alloys, glass, and electronics, to name a few (DNV, 2019e).

While there are a wide variety of hydrogen applications today, the value chains related to today's use of hydrogen as input in industrial processes are closely related with the value chains of petroleum. The situation will change in the transition to a low emission society with production from renewable energy sources, putting hydrogen in high demand in other energy intensive sectors. This can contribute to technological development and to building the required infrastructure. There may be some competition in the demand and use of hydrogen, but the scaling potential of hydrogen will ease this.

Hydrogen is one of the fuels included in this assessment which do not entail a shortage of feedstock and other disadvantages for other sectors, hence, scoring 4.

4.1.3 Environment

In this part we look at the KPIs related to the environmental challenges. This includes greenhouse gas emissions, both from a well-to-tank and tank-to-wake perspective, local pollution and overall energy efficiency. Since we are assessing the well-to-wake path, we distinguish between green and blue hydrogen within the different KPIs. The results are presented in Table 11.

Table 11: Environmental KPIs for green and blue hydrogen

CATEGORY	KPI	GREEN HYDROGEN	BLUE HYDROGEN
Environment	*Greenhouse gas emissions*	⬢	⬡
	Local pollution	⬢	⬢
	Overall energy efficiency	⬡	⬡

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Greenhouse gas emissions: The two paths for hydrogen production differ significantly in production processes and the associated emissions. Emissions are also affected by the engine technology used – fuel cell or internal combustion engine.[30]

Well-to-tank: Well-to-tank emissions related to the production of green hydrogen are driven by the emissions intensity of the electricity used in the electrolysis process as well as life-cycle emissions of renewable energy infrastructure, electrolysis plants, transportation to harbors and on-board infrastructure. Existing life cycle estimates suggest emissions below 1 kg CO_2e/kg H_2[31]. Further decrease is possible. This would, however, require reduced emissions in the production of steel, cement and other material used in development of infrastructure.

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[30] *For more information on how green and blue hydrogen is produced, see annex A.*

[31] *According to the Hydrogen Council (2021), "solar power achieves 1.0 kg CO_2eq/kg H_2 and wind 0.5 kg CO_2eq/kg H_2 in 2030, the difference resulting from the higher embedded capex emissions for solar panels (due to global grid mix*

Well-to-tank emissions related to blue hydrogen start with extraction of natural gas, which is inherently associated with methane emissions from so-called fugitive leaks, which are difficult to fully eliminate. Subsequently, after methane is broken down to hydrogen and CO_2, emissions occur also in the carbon capture process. The existing technology does not offer a 100 percent capture rate.[32]

Emissions associated with production of blue hydrogen are estimated to be higher compared to green hydrogen and vary significantly depending on the assumptions made. Hydrogen Council (2021) estimates the lifecycle emissions of blue hydrogen at 1.2–1.5 kg CO_2e/kg H_2, assuming 90-98 percent CCS efficiency. Howarth and Jacobson (2021) show that upstream natural gas emissions alone account to 1.34 CO_2e per kg H_2, while total emissions in a Canadian setting are nearly 4 kg CO_2e/kg H_2.

Tank-to-wake: Hydrogen tank-to-wake emissions depend on the engine technology. Hydrogen used in a fuel cell has zero tank-to-wake emissions regardless of the source of hydrogen that is used. Hydrogen combustion in atmospheric air is associated with formation of nitrous oxide (N_2O), a greenhouse gas, even if the fuel itself does not contain nitrogen.[33]

Finally, due to low energy density, space requirements for on board fuel storage are higher for hydrogen than for other fuels. This means there is less allowed cargo for a ship of a given size, resulting in more upstream emissions per ton km (or passenger km) of cargo. The complete impact of the fuel choice on emissions driven by ship design can however be addressed only in a life cycle assessment.

Green hydrogen has a potential to become a zero emissions fuel, but this requires efforts to reduce upstream emissions (scale up renewable production capacity), especially related to renewable electricity generation. Near-zero emission maritime transport in the Nordics is possible with green hydrogen using the existing technology. Thus score 4 is awarded, although scaling up the technology is required.

Blue hydrogen has a potential to significantly reduce emissions compared to the currently used fuels. Strict monitoring of emissions across all sources may allow for further emissions reduction, but improvements in technology are required for the fuel to be assessed as a zero-emission fuel. Therefore, score 3 is awarded, i.e. lower than green hydrogen.

Local pollution: The source of hydrogen does not affect the local pollution; thus the score is identical for both green and blue hydrogen. However, the level of pollution is affected by the type of propulsion. The FCs are emission free, while the ICE engines operating at high temperatures produce high quantities of nitrogen oxides (NOx).[34]

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assumed for the panel manufacture). Electrolysis with run-of-river hydropower can achieve even lower emissions of 0.3 kg CO_2eq/kg H_2. Nuclear power comes in at 0.6 kg CO_2eq/kg H_2, but it is also important to note in this context that it leads to 0.115 g of radioactive waste per kg of hydrogen".

[32] *The efficiency of carbon capture in steam reforming units currently being used to produce commercial hydrogen ranges from 65 percent to 75 percent. These are, however, not optimized for maximum efficiency but for lowest cost. Higher carbon capture rates can be achieved with auto-thermal reforming (ATR) with a capture rate of above 90 percent (Romano, et al., 2022).*

[33] *The emissions intensity depends on combustion temperature, pressure and fuel to oxygen ratio (Colorado, McDonell, & Samuelsen, 2017), and thus can be to large degree controlled through engine operation. In addition, the propulsion technologies differ in their life cycle emissions.*

[34] *Minimising NOx as a by-product from hydrogen boilers and engines is possible through control of combustion conditions, but this can lead to reduced power output and performance. After-treatment and removal of NOx is possible, but this increases cost and complexity in appliances (Lewis, 2021).*

Since fuel cells which do not cause local emissions are the solution preferred by the industry, we award the highest possible score 4 to both green and blue hydrogen.

Overall energy efficiency: Green hydrogen fuel requires between 3.5 and 5 units of primary energy (green electricity) per one unit of propulsion depending on the propulsion system (fuel cell or internal combustion) and physical state of the fuel used (liquid or compressed gaseous) and data source (Pawelec, 2020; Lindstad, Lagemann, Rialland, Gamlem, & Valland, 2021). Electrolysis is the most energy intensive stage, with current electrolyzer efficiency of around 65 percent (IRENA, 2020a). Hydrogen compression is less energy intensive than gasification and fuel cells offer higher energy efficiency than internal combustion engines (Pawelec, 2020).

Energy costs of natural gas reforming and carbon capture are slightly lower than that of electrolysis. The difference in efficiency rate is approximately 10 percentage points[35]. It has to be noted that while in the case of green hydrogen the main source of energy is green electricity, in the case of blue hydrogen the bulk of energy comes from fossil fuels.

Hydrogen regardless of its source requires substantially more primary energy than electric propulsion. Full scale use of hydrogen as a maritime fuel would require significant investment in primary energy supply, thus we award the fuel score 3.

4.1.4 Maritime rules and regulations

Table 12: Rules and regulations KPIs for green and blue hydrogen

CATEGORY	KPI	GREEN HYDROGEN	BLUE HYDROGEN
Rules and regulations	*Maturity of maritime rules and regulations*	🟥	🟥

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Hydrogen, in vast quantities, has been used safely for many years in chemical and metallurgical applications, the food industry, and for space travel applications. As hydrogen and fuel cells begin to play a greater role in meeting the energy needs of our nation and the world, minimizing the safety hazards related to the use of hydrogen as a fuel is essential.

One of the biggest concerns when using hydrogen is its high flammability. The current experience with applying hydrogen for maritime fuel purposes is very limited, and experience with hydrogen storage onboard vessels is very limited as well. While hydrogen has been applied in several industries for decades, large scale transportation and storage for maritime fuel purposes calls for extensive research on its behavior in cryogenic tanks and how to handle potential leakages. The current research activity on hydrogen behavior in different extreme scenario settings is quite extensive, and DNV is engaged in large-scale experimental research in the UK (DNV, 2022).

When it comes to maritime application, there are documentations and requirements with regards to hydrogen fuel cell technology. IGF code is applicable for ships using hydrogen as fuel, as this code applies to vessels using

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[35] *Energy efficiency of electrolysis is approximately 65 percent, while energy efficiency of carbon capture using ATR technology is above 75 percent (Antonini, et al., 2020), although some energy is required also for carbon transportation and storage.*

low flashpoint fuels (International Maritime Organization, 2015). However, the code does not include specific design requirements for hydrogen. In addition, rules and regulations related to use of fuel cells on ships are increasing in number as the technology matures, although it is important to note that the class rules do not cover storage and distribution of hydrogen as fuel. (DNV, 2021)

DNV's handbook for hydrogen-fueled vessels (2021) provides a roadmap to safe hydrogen handling and to increase the effectiveness and speed of the shift towards green shipping, without compromising on safety related aspects. The handbook also describes how to navigate requirements for the design and construction of hydrogen-fueled vessels, so that safety and risk mitigation can be achieved. Similar to DNV, the US Department of Energy (US DOE) is currently working to develop and implement practices and procedures that will enable safety in operation, handling, and usage of hydrogen and hydrogen systems. Not only is this work an indication of the extensive effort being made to ensure that hydrogen can become a feasible solution for maritime use, but it also has the potential to become important for the Nordic countries in the phases regarding implementation.

The current regulations regarding bunkering of hydrogen are not yet finished and can affect applicability in the maritime sector. Regulations for bunkering of liquid and pressurized hydrogen must be developed in parallel with technical solutions. Bunkering will most likely happen under supervision of trained personnel[36].

To sum up, although there is extensive research going on in terms of hydrogen and its maritime applications, technology around hydrogen is not mature enough, which translates into a lack of experience with hydrogen as marine fuel and lower maturity of rules and regulations. For this reason, hydrogen is scored 1, the lowest among sustainable zero-carbon fuels evaluated in this report.

4.2 Ammonia

Ammonia can play an important role in decarbonizing the Nordic shipping industry. Ammonia does not contain carbon, only hydrogen and nitrogen, and thus no CO_2 will be emitted from a ship when fueled by ammonia. If there are no carbon emissions in the production process, ammonia can be a suitable alternative for zero-carbon shipping. Ammonia has a relatively high energy density. The feasibility analysis conducted in this project shows that ammonia could potentially cover over 80 percent of the current Nordic fuel consumption. However, several barriers must be addressed. A low compatibility to existing ship types means that new ships need to be built and/or that comprehensive rebuilds will be necessary. Combined with a low technological maturity onboard, this leads to relatively high capex costs for the shipowners. Ammonia is also a highly flammable gas and has toxic properties for both humans and aquatic life, and the rules and regulations connected to the usage of ammonia as a marine fuel are not yet in place. Further on, there is a need for large investments to scale up bunkering facilities for ammonia, in addition to sufficient production facilities. The investments need to be coordinated, especially since the production scalability of green ammonia depends on green hydrogen supply, making the scaling of fuel production more complicated than for green hydrogen. As more ships are developed and bunkering facilities are built, the technical and commercial maturity will increase both onboard and onshore, reducing fuel and Capex costs as well as shipowners' risk assessment. Commercial scaling and technical development are thus vital for ammonia to be competitive in the long term.

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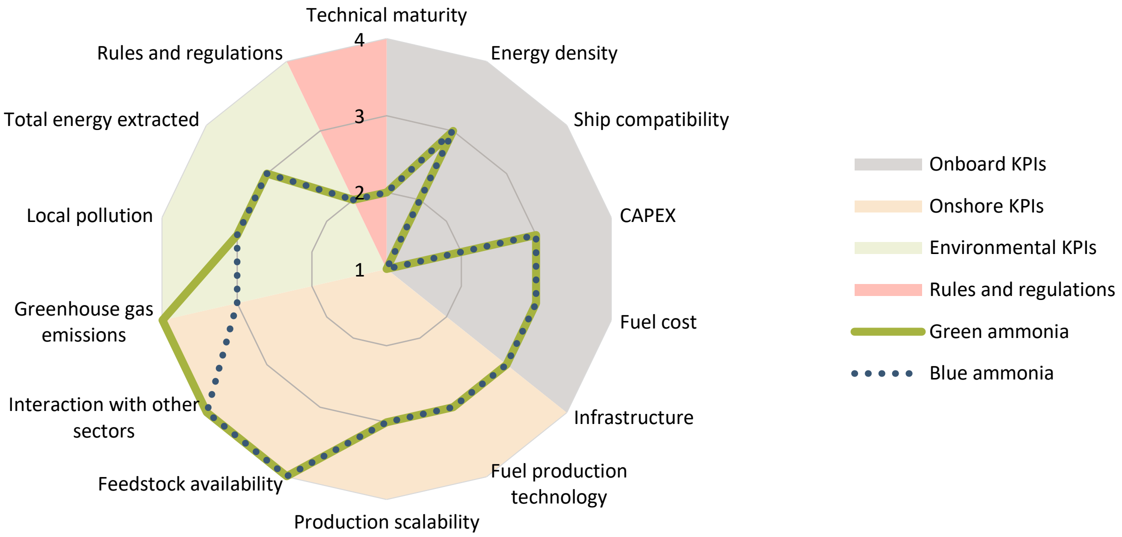
[36] *https://www.energy.gov/eere/fuelcells/safety-codes-and-standards, retrieved 17.08.2022*

Figure 10: Scoring of onboard, onshore, environmental and safety related KPIs for both green and blue ammonia



There are several ways of producing ammonia, including grey[37], blue[38], green[39] (renewable/sustainable ammonia) and hybrid[40] green ammonia. Shipowners or operators can use any of these types of ammonia, they are physically equal but differ in manufacturing origin and hence in their CO_2 footprint (Alfa Laval, 2020). In this assessment we differentiate between green and blue production paths. Hydrogen and by extension ammonia that is produced via natural gas reforming or of other fossil fuels without CCS is outside the scope of this report, since the production process will create greenhouse gas emissions and hence, they cannot be considered as zero carbon fuels.

Current ammonia production is primarily based on reforming of natural gas into hydrogen, which is then combined with nitrogen from air via Haber-Bosch process. CO_2 emissions related to this process are mainly due to methane reforming to produce hydrogen, as covered before. If CO_2 emissions from the production of hydrogen are captured and stored via CCS technologies, ammonia produced this way is considered blue ammonia. This is shown in the figure below. Green ammonia on the other hand refers to hydrogen produced via renewable electricity and electrolysis, combined with nitrogen. This process does not create any CO_2 emissions, and hence is considered zero carbon.

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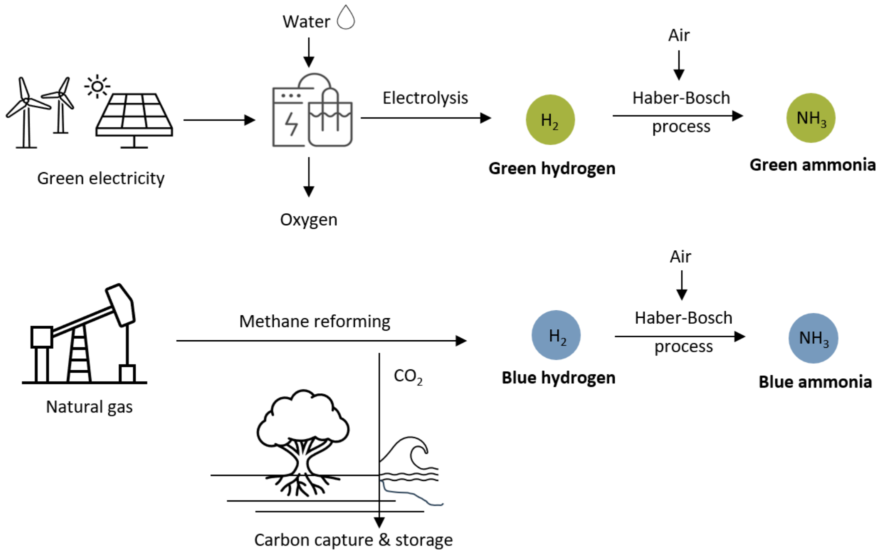
[37] *Conventionally produced from fossil feedstock, most often from natural gas, but it can also be from coal. The CO_2 footprint depends on plant efficiency and feedstock.*

[38] *Basically produced the same way as grey ammonia, except that the CO_2 from production is captured, liquified and transported to permanent storage (CCS).*

[39] *Produced without fossil feedstock but entirely from renewable electricity, air and water. The CO_2 footprint of green ammonia is assumed to be zero (disregarding full lifecycle analysis which should include plant construction and transport to bunkering site).*

[40] *Ammonia produced in hybrid plants which are partially fueled by fossil fuels and partially by renewable electricity. Such a plant can potentially be a new-built hybrid plant or a revamp of an existing conventional plant. The latter represents an economically feasible transition to green ammonia production.*

Figure 11: Illustration of green and blue ammonia production



The next chapters provide a description of the KPIs related to the barriers and challenges of using ammonia as a marine fuel, from a market perspective and an onboard, onshore, environmental and safety perspective.

4.2.1 Onboard

In this part we give a description of the KPIs related to the onboard challenges related to the use of ammonia as a marine fuel. As with hydrogen, we do not distinguish between green and blue ammonia for technical KPIs, since there is no difference between the two when using ammonia as a fuel onboard the ship. For economic KPIs the differentiation is made where it is necessary.

Table 13: Onboard KPIs and score for green and blue ammonia

CATEGORY	KPI	GREEN AMMONIA	BLUE AMMONIA
Technical	*Technical maturity*	🟧	🟧
	Energy density	🟩	🟩
	Existing ship compatibility	🟥	🟥
Economic	*CAPEX*	🟩	🟩
	Fuel cost	🟩	🟩

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Technical maturity: Ammonia can be used both in internal combustion engines and fuel cells. Internal combustion engines are considered a more suitable option for ammonia as a fuel according to DNV (2019). As ammonia has low flammability, there needs to be an additional fuel onboard for ignition. This can be achieved either by mixing hydrogen into ammonia or by starting ignition through another fuel. There are both two-stroke and four-stroke internal combustion engines for ammonia under development, and these are expected to be ready for use within 2023[41,42]. Similarly, retrofitting options are expected to be available in 2025. However, none of these technologies are currently on the market. There is also ongoing research about using ammonia in fuel cells, which is mentioned under pilot projects and initiatives under market KPIs. However, the technology is not ready for use yet. On the other hand, ammonia is a frequently traded commodity, and hence there is existing experience in terms of handling and onboard storage of this fuel (Frelle-Petersen, Howard, Poulsen, & Hansen, 2021).

While experience with handling of fuel onboard increases the technical readiness score of ammonia as marine fuel, the lack of ammonia engines available today brings ammonia's technical readiness score down. Hence, ammonia is scored 2, the same as hydrogen. This is the lowest level of technical maturity among sustainable zero-carbon fuels.

Energy Density: Ammonia has a volumetric energy density of 11 MJ/l. Although this is higher than the volumetric energy density of hydrogen, it is significantly lower than conventional fossil fuels. Lower volumetric energy density will bring about a higher need for storage space on board or bunkering will need to happen more often.

*Ammonia has received the same score as methanol, a score of 3, although the energy density of ammonia is somewhat lower than for methanol. However, for both fuels energy density does not create a major barrier other than loss of cargo space, and both fuels are suited to longer voyages as mentioned under "***Feil! Fant ikke referansekilden.***".*

Existing ship compatibility: Ammonia as a marine fuel is not compatible with the engine technology that exists today. Both the use of ammonia fuel cells and ammonia internal combustion engines need major modifications in the existing engine or installation of completely new engines.

Therefore, ammonia is scored 1, as one of the least compatible fuels for existing engines, after hydrogen.

CAPEX: Ammonia as a fuel is new for the shipping industry, hence new systems will need to be used onboard, each with their own specific requirements. It is expected that capital expenditure for an ammonia two-stroke internal combustion engine and fuel supply system will be at the same level as the corresponding LPG engine. The tanks for ammonia are twice the size as for LPG and correspondingly more expensive (DNV, 2020a). For a new built vessel, the initial CAPEX of an ammonia-powered first-of-a-kind-project has been calculated to be around 25-30 per cent higher than for a standard vessel. Higher CAPEX is a result of both additional fuel tanks that are compatible with ammonia, fuel systems, and safeguards for toxicity (Nordic Innovation, 2021).

Given these, CAPEX for using ammonia as fuel with internal combustion engines is scored at 3, one score higher than hydrogen. CAPEX for both blue and green ammonia is the same, as the production method for ammonia does not play a role for CAPEX.

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[41] *https://www.wartsila.com/media/news/14-07-2021-wartsila-launches-major-test-programme-towards-carbon-free-solutions-with-hydrogen-and-ammonia-2953362?utm_source=organic&utm_medium=press-release&utm_term=marine-power&utm_content=press-release&utm_campaign=ammonia-project-targets-two-and-four-stroke-marine-engine-demonstrators-by-2025, retrieved 17.08.2022*

[42] *https://www.man-es.com/discover/two-stroke-ammonia-engine, retrieved 17.08.2022*

Fuel cost/price: Ammonia prices are closely linked to hydrogen prices, since hydrogen is by far the largest cost component in production process. Thus, costs of green ammonia will be linked closely to costs of green hydrogen, while costs of blue ammonia will be closely linked to costs of blue hydrogen. The Haber-Bosch process to produce ammonia from hydrogen and air is energy consuming, but the costs of the process are compensated by an increased energy density and higher boiling point (higher storage temperature) as a result from hydrogen synthesis, which results in lower transportation costs than in the case of hydrogen.

As a consequence, as ammonia prices are closely linked to hydrogen prices, we have given the score 3, in line with the score for hydrogen.

4.2.2 Onshore

This section describes the onshore KPIs for ammonia. We differentiate between green and blue ammonia pathways, as there are differences to be highlighted. The table below illustrates the scores given to each of the onshore KPIs for the use of ammonia as a marine fuel.

Table 14: Onshore KPIs and score for green and blue ammonia

CATEGORY	KPI	GREEN AMMONIA	BLUE AMMONIA
Technical	*Infrastructure (Storage, bunkering & transportation)*	⬡	⬡
	Fuel production technology	⬡	⬡
	Production scalability	⬡	⬡
Fuel scalability & interaction	*Feedstock availability*	⬢	⬢
	Interaction with other sectors	⬢	⬢

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Infrastructure (storage, bunkering & transport): The production method for ammonia has been known for 100 years, and it has been stored as a liquid ever since. Today, storage of ammonia under atmospheric pressure in tanks is used to store up to 50 000 kilotons of ammonia at plant sites and distribution terminals[43]. Refrigerated ammonia tanks are a common and efficient way to store the compound. In its liquid form, ammonia is stored at -33 degrees Celsius under atmospheric pressure. It can also be stored at ambient temperature under high pressure or in a semi-refrigerated state, at intermediate temperatures and pressure[44].

Ammonia is not capable of utilizing existing bunkering infrastructure in marine applications. The bunkering operation of ammonia including the handling, connection and disconnection of heavy bunkering hoses subjects the personnel involved to the risk of being directly exposed to ammonia, and hence the infrastructure needs to be made especially for ammonia. The development of bunkering infrastructure remains a barrier for marine

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[43] *https://ammoniaknowhow.com/ammonia-storage-tanks/, retrieved 17.08.2022*
[44] *https://cryospain.com/things-to-keep-in-mind-when-working-with-refrigerated-ammonia-tanks, retrieved 17.08.2022*

applications due to safety-related challenges[45]. Additionally, there are only a few geographical locations worldwide that allow green ammonia bunkering today.[46] However, ammonia has been safely stored and used for decades by farmers in the US, where over 200,000 ammonia storage tanks are in operation (Russel, 2011). The successful application of ammonia in that sector bodes well for the prospects of ammonia in the maritime sector.

Ammonia transportation occurs in liquid state, hence it must be compressed or refrigerated or a combination of both. Due to its corrosiveness, there are special requirements for materials used in ammonia storage tanks and associated systems. However, this is not to be considered a transportation barrier, as there is an established global production of ammonia and routes for transportation at sea. In addition, the tanks used for ammonia transportation are insulated but inexpensive and widely adopted. Ammonia can also be transported at atmospheric pressure, reducing the need for pressure tanks.

While there is knowledge on how ammonia bunkering can be carried out, the implied complexity increases the associated investment costs. However, the implied complexity is not as extensive as the infrastructure needed for hydrogen bunkering and storage. While the transportation barriers are few for ammonia, other fuels such as biofuels utilize far simpler solutions for transportation, hence, the infrastructure barrier for both blue and green ammonia is scored to 3.

Fuel production technology: Today's ammonia production is highly energy- and emissions-intensive. In 2020 global ammonia production accounted for around 2 percent of total final energy consumption and 1.3 percent of CO_2-emissions from the energy system.

<u>Blue ammonia:</u> Ammonia synthesis is a mature technology using fossil feedstock. However, to make it carbon neutral the CO_2 from the natural gas must be captured and stored.

<u>Green ammonia</u> is more energy intensive and therefore not as widely available as blue ammonia (Ghavam, Vahdati, Wilson, & Styring, 2021). Green ammonia is created by producing green hydrogen and separating nitrogen from air. There are numerous large-scale ammonia production plants in the world, producing around 235 million metric tons in 2019 in total. There are additional plans to rebuild the ammonia plant in Porsgrunn to produce green hydrogen in order to make green ammonia at this plant. However, this project is a pilot and will not be operational before 2026 given public co-funding and regulatory framework IEA (IEA, 2021a).

Today's most common methods for producing blue and green ammonia are considered mature technologies. However, commercial electrolyzers for green ammonia are still expensive and inefficient and will require large scaling and increased research. For blue ammonia, the technology for CO_2 storage is key to enabling carbon neutral production and currently not available at scale. As technical development progresses, it is necessary to facilitate commercial use in competitive markets.

We consider the fuel production technology of ammonia to be highly mature, only restricted by the efficiency of hydrogen production. Only HVO and batteries score better on production technology, hence we score both blue and green ammonia at 3.

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[45] *https://www.offshore-energy.biz/sintef-commits-to-solving-challenges-related-to-ammonia-as-marine-fuel/, retrieved 17.08.2022*

[46] *A review of the latest trends in the use of green ammonia as an energy carrier in the maritime industry.*

Production scalability: Ammonia is already a highly demanded product and produced in large quantities, especially for the agricultural sector. Due to the Haber-Bosch process being a reversible reaction, the yield of ammonia can be changed by changing the pressure or temperature of the reaction. Increasing the pressure of the reaction will increase the yield of ammonia. Increasing the temperature will decrease the yield.[47]

Ammonia production is dependent on the supply of hydrogen. Hydrogen accounts for nearly 90 percent of input in ammonia production. The hydrogen used is typically produced on-site at ammonia plants from a fossil fuel feedstock. To be able to scale renewable ammonia, the production plants must focus on the hydrogen side of production. Currently, only a small portion of hydrogen used in ammonia production is from renewable sources, which is due to the higher costs of renewable energy.

Production of green and blue ammonia in small-scale facilities is technologically feasible, but usually entails higher production and investment costs compared to large-scale plants. However, the avoidance of storage and transportation costs can make up for the increased investment and production costs. In all, this will be highly reliant on the geographical location and source of energy, whether it is natural gas and/or hydrogen.

Green ammonia has the potential to be produced at a smaller scale just like green hydrogen. However, due to the reliance on a green hydrogen supply, the scaling of fuel production is more complicated than for green hydrogen. Hence we score the scalability of green ammonia to 3. Blue ammonia's dependence on CCS also reduces scalability to some extent, making the scalability of blue ammonia similar to blue hydrogen, hence we score blue ammonia to 3.

Feedstock availability: Ammonia is conventionally produced from natural gas but can also be produced from renewable electricity. Renewable energy, water, and air (nitrogen) are in principle the only requirements to produce green ammonia. Green ammonia production has the theoretical potential to be scaled up to supply the entire marine sector fuel. The investments in renewable electricity capacity are therefore significantly higher than the investments in ammonia plants at today's prices, and the prices for electrolyzers will likely also decrease further if many plants are constructed (DNV, 2020a).

Blue ammonia's use of natural gas as the primary feedstock for production and the fact that it is produced at large scale in almost all regions of the world makes the fuel highly scalable. As with blue ammonia, the feedstock used in green ammonia is readily available, like all non-bio-based fuels in this assessment, hence, scoring both green and blue ammonia to 4.

Interaction with other sectors: Ammonia can be used as fuel in energy production, as a key chemical in feedstock and in chemicals production. Ammonia can be used as a main ingredient in cleaning materials, fuel for engines, and as a refrigerant for cooling systems. The wide range of applications makes ammonia an important, carbon-free alternative (Erdemir & Dincer, 2020).

Ammonia is the basic building block for ammonium nitrate fertilizer, which releases nitrogen, an essential nutrient for growing plants including farm crops and lawns. About 90 percent of ammonia produced worldwide is used in fertilizer, to help sustain food production. Fertilizers can also help increase levels of essential nutrients like zinc, selenium, and boron in food crops[48].

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[47] *https://www.bbc.co.uk/bitesize/guides/z7r7xfr/revision/4, retrieved 17.08.2022*

[48] *https://www.chemicalsafetyfacts.org/ammonia/, retrieved 17.08.2022*

Ammonia is also widely used in household cleaning products, commonly known as household ammonia. It is an effective chemical at breaking down household grime or stains from animal fats or vegetable oils, such as cooking grease and wine stains. Because ammonia evaporates quickly, it is commonly used in glass cleaning solutions to help avoid streaking[49]. Ammonia can be used to purify water supplies and as a building block in the manufacture of many products including plastics, fabrics, pesticides, and dyes. Ammonia can even be used as a refrigerant gas and in air-conditioning equipment to absorb amounts of heat from surroundings[50].

As with hydrogen, the extensive use of ammonia in different sectors makes ammonia particularly attractive for marine applications. Enabling ammonia as a marine fuel has the potential to increase demand and thus reduce prices for other applications as well, hence we score ammonia's interaction with other sectors to 4.

4.2.3 Environment

In this part we look at the KPIs related to the environmental challenges. This includes greenhouse gas emissions, both from a well-to-tank and tank-to-wake perspective, local pollution and overall energy efficiency. Due to the fact that we are assessing the well-to-wake path, we distinguish between green and blue ammonia within the different KPIs.

Table 15: Environmental KPIs and score for green and blue ammonia

CATEGORY	KPI	GREEN AMMONIA	BLUE AMMONIA
Environment	*Greenhouse gas emissions*	⬢	⬡
	Local pollution	⬡	⬡
	Overall energy efficiency	⬡	⬡

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Greenhouse gas emissions: The two paths of ammonia production, green and blue, differ only through the source of hydrogen. Emissions are also affected by the engine technology used – fuel cell or internal combustion engine.

<u>Well-to-tank:</u> Green ammonia production is based on green hydrogen as feedstock while blue ammonia is based on blue hydrogen. The emissions related to the respective production processes are discussed in the section on environmental aspects of hydrogen. Ammonia synthesis in an electrically driven Haber-Bosch process to produce sustainable ammonia requires less than 10 percent of the energy required to produce hydrogen through electrolysis (Smith, Hill, & Torrente-Murciano, 2020). Ammonia synthesis does not generate process emissions, although life-cycle emissions related to infrastructure must be accounted for.

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[49] *https://www.chemicalsafetyfacts.org/ammonia/, retrieved 17.08.2022*
[50] *https://www.chemicalsafetyfacts.org/ammonia/, retrieved 17.08.2022*

Tank-to-wake: Ammonia can be used in combustion engines, or, after cracking into hydrogen, in fuel cells.[51] Ammonia cracking does not create greenhouse gas emissions and the energy costs are approximately 5 percent of the ammonia energy content (Giddey, Badwal, Munnings, & Dolan, 2017).

Ammonia is a carbon free fuel which implies that combustion does not cause CO_2 emissions, but at the same time combustion is associated with N_2O emissions, a highly potent greenhouse gas. The CO_2 equivalent of N_2O emissions is approximately 1/30 of the emissions caused by combustion of traditional maritime fuels and can be further reduced through engine optimisation.[52] For the successful application of ammonia as a fuel in a combustion engine, flame enhancement is required due to low burning velocity of NH3/air flames. Thus, an ammonia cracking installation which produces hydrogen, albeit at a much smaller scale, is necessary even in an ammonia combustion engine (Kobayashi, Hayakawa, Somarathne, & Okafor, 2019).

The scores on this indicator follow the scores awarded to the feedstocks on which the fuel is based, which reflects the significance of the feedstock in ammonia total emissions. Although ammonia combustion is associated with N_2O *emissions, the levels are relatively low and there is scope for improvement through after-treatment. Ammonia, if used in a fuel cell, can avoid this source of emissions. As a consequence, we award score 4 to green ammonia and score 3 to blue ammonia, similar to hydrogen.*

Local pollution: Ammonia used in a fuel cell does not cause local emissions. However, ammonia applied in a combustion engine may lead to significant levels of NOx emissions. These however can by reduced by fitting post-combustion devices, such as catalytic converters.[53] Ammonia is sulphur and carbon free, thus it does not cause SO_2, black carbon or particulate matter pollution.

Local emissions do not depend on the source of ammonia. Local NOx emissions associated with combustion of ammonia can be avoided with the use of after treatment technology or fuel cells, both of which, however, require further innovation before they can be utilized at scale in Nordic shipping. Thus, both green and blue ammonia receive score 3, which is lower than for hydrogen or electric propulsion but on par with methane and methanol.

Overall energy efficiency: Green ammonia in combustion engines requires approximately 5 units of primary energy (green electricity) per one unit of propulsion (Pawelec, 2020). The factor can increase to 4 if ammonia is applied in fuel cells, but the technology is not yet commercially mature. Although ammonia production requires hydrogen and nitrogen synthesis, and subsequent reforming if used in fuel cells, the energy costs of the process are comparable to the energy costs of hydrogen liquefication (Pawelec, 2020).[54] Energy costs of blue ammonia are slightly lower due to lower energy costs of hydrogen produced through methane reforming than through electrolysis. However, since ammonia has not yet been applied on a commercial scale as a maritime fuel, there exists a certain degree of uncertainty about the energy efficiency of that fuel.

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[51] *Direct ammonia fuel cells are being actively investigated but there are several challenges which must be addressed before such technology can be fully appreciated (Jeehr, Zhang, & Tao, 2021).*

[52] N_2O *slip from an ammonia engine is approximately 20g* CO_2e/kWh (Ricardo Energy & Environment, 2021, p. 84)*, but can be reduced through adjusting the engine operation conditions. This compares to around 600g* CO_2e/kWh *for standard fuels* (Lindstad, Lagemann, Rialland, Gamlem, & Valland, 2021).

[53] *A common issue with this NOx treatment process is an 'ammonia slip' where certain levels of ammonia can pass through the system directly. This causes the release of both NOx and* N_2O*, with the latter considered to have high greenhouse gas potential (McKinlay, Turnock, & Hudson, 2021).*

[54] *Ammonia is also stored as liquid but at much higher temperatures.*

Due to the relatively small difference in overall energy efficiency between hydrogen and ammonia the same score 3 is awarded both to green and blue ammonia – significant investment in primary energy is required for both. The fuels receive higher score than carbon-based e-fuels.

4.2.4 Maritime rules and regulations

Table 16: Safety KPIs and score for green and blue ammonia

CATEGORY	KPI	GREEN AMMONIA	BLUE AMMONIA
Rules and regulations	*Maturity of maritime rules and regulations*	⬢	⬢

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Maturity of rules and regulations: Due to ammonia being a flammable gas and having toxic properties for both humans and aquatic life, measures to mitigate the risk associated with handling and storage and inducing effective safety measures is highly important. While ammonia is a highly traded commodity worldwide and has well-established transportation methods, its usage as a fuel for the marine industry is relatively new.

When it comes to rules and regulations regarding ammonia, the current regulatory framework that applies to ammonia is the IGF code for low-flashpoint fuels. However, IGF does not include specific design requirements for ammonia. IMO has just declared that "Development of non-mandatory guidelines for safety of ships using ammonia as fuel" will be added to their work program and these will be included in the regulatory framework over time[55]. Class societies have developed class rules for using ammonia as fuel, but the rules and regulations are considered immature as there are no ammonia ships as of today and there is an extensive need for testing and experience with the fuel to develop safety guidelines.

While the use of ammonia as a marine fuel is still at an early stage, the use and transport of ammonia have been widely adopted and several safety and health guides are in existence[56]*. However, as the class societies are developing class rules and safety handbooks for ammonia in marine applications, there is still work that needs to be done to build experience. Hence we score safety and regulations of ammonia to 2. This is above hydrogen, but below the other sustainable zero-carbon fuels.*

4.3 Methane

Methane is a commodity that has been widely transported via tankers since the late 1950s. As with ammonia, the feasibility analysis conducted in this project shows that it could potentially cover over 80 percent of the Nordic fuel consumption. Methane is already an important alternative fuel for the maritime industry, especially since it is the main component of LNG, a fuel that is already in use. For this reason, methane is compatible with existing LNG ships. For other vessels the compatibility is low, leading to high investment costs. Investment cost is further increased as the storing of methane requires special tanks and low temperatures. Using methane as a marine fuel is known to result in lower emissions. However, methane is a potent

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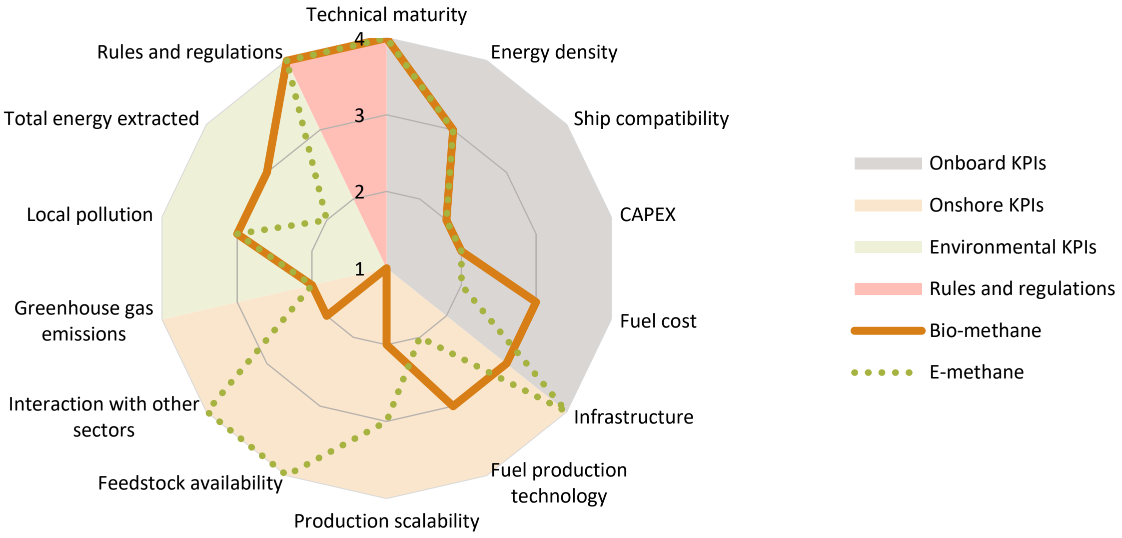
[55] *https://ibia.net/2022/05/04/imo-to-develop-guidelines-for-safe-use-of-ammonia/, retrieved 28.09.2022*

[56] *https://wedocs.unep.org/bitstream/handle/20.500.11822/29582/HSG37Amonia.pdf?sequence=1&isAllowed=y, retrieved 23.08.2022*

greenhouse gas in itself and is prone to slips and fugitive leaks. From an environmental perspective, methane is therefore assessed to be less suitable as a "main fuel" in the Nordic maritime transition. The price of methane is also relatively high at the moment, as the supply of biomethane is restricted by biomass being available near existing gas grids. In addition, competition with other sectors is relatively high, driving the prices even more. E-methane does not suffer from the same feedstock challenges, but the production technology is still relatively immature. The issue with fugitive leaks and methane slips will have to be solved regardless of production technology.

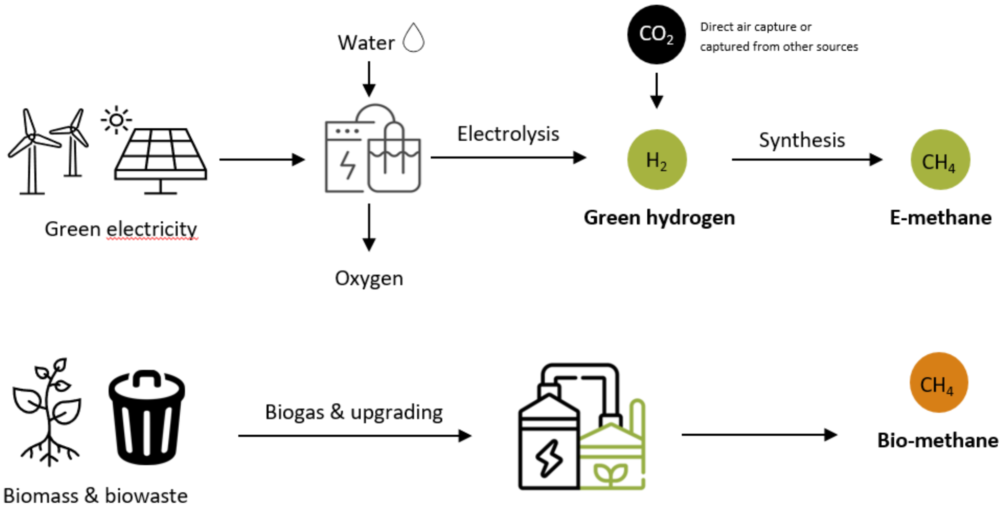
Figure 12: Scoring of onboard, onshore, environmental and safety-related KPIs for both bio- and e-methane



The focus in this report is exclusively on e-methane produced via green hydrogen and biomethane. LNG is outside the scope of this report as it is a fossil fuel. In addition, blue methane is also left out of this analysis. Blue methane is produced through synthesis of blue hydrogen and CO_2. This production pathway differs from the e-methane pathway only with regard to the source of hydrogen used in the production process. In the assessment, we consider only CO_2 sourced from direct air capture or organic sources, excluding a pathway in which CO_2 is sourced from industrial processes.

In addition to fossil resources, methane can be produced from renewable sources. As illustrated in Figure 15, methane can be produced via synthesis of green hydrogen and carbon sourced from direct CO_2 capture. The resulting methane is called e-methane. In addition, methane can be produced via anaerobic digestion and upgrading of organic matter. Methane produced in this way is called biomethane. Both production methods are renewable.

Figure 13: Illustration of e-methane and biomethane production



The next chapters give a description of the KPIs related to the barriers and challenges of using methane as a marine fuel, from a market perspective, onboard, onshore, environmental and safety perspective.

4.3.1 Onboard

This section provides an overview of barriers in using methane as a marine fuel. We do not distinguish between biomethane or e-methane for technical KPIs, since there will be no difference between these two when it comes to using and storing them onboard. We do however distinguish between the two for economic KPIs where it is seen necessary.

Table 17: Onboard KPIs and score for methane

CATEGORY	KPI	BIOMETHANE	E-METHANE
Technical	*Technical maturity*	🟩	🟩
	Energy density	🟨	🟨
	Existing ship compatibility	🟧	🟧
Economic	*CAPEX*	🟨	🟧
	Fuel cost	🟧	🟧

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Technical maturity: LNG consists mainly of methane and has been used as a marine fuel at an increasing rate, especially in the last two decades. Therefore, both engine technology and storage onboard have come a long way. Methane can be used with 4-stroke, 2-stroke high pressure, and 2-stroke low pressure engines, as well as fuel cells (DNV, 2019a). Internal combustion engines have been operational for some time and are commercially available, while fuel cells are currently not available. Methane is gaseous under ambient conditions. For this reason, insulated tanks with cryogenic applications make it possible for methane to be stored as a liquid onboard. The technology has been available for decades and is fully functional.

In total, methane marine fuel scores the highest among alternative zero carbon fuels for shipping in terms of technical maturity, a score of 4, since both propulsion and onboard storage technologies have come a long way and have been used at scale the last several years.

Energy Density: Methane is gaseous under ambient conditions. When liquified it has a volumetric energy density of 20 MJ/l. This means that although liquified methane would require almost 2 times more space for storage than conventional diesel onboard, it will require significantly less space compared to hydrogen, ammonia and methanol.

Even though methane has a higher energy density than methanol and ammonia, this does not create a major technical or economical barrier for using methane as a fuel. For this reason, liquified methane is scored 3 in terms of volumetric energy density, the same as methanol and ammonia.

Existing ship compatibility: Using methane as marine fuel onboard requires installation of new engines or modification of existing engines, in addition to installation of cryogenic fuel tanks for onboard storage. However, there are a number of vessels already built and some in the orderbooks that have LNG engines, which will be fully compatible with e-methane or biomethane. *This pushes methane's score slightly higher to 2, while there are still major barriers related to compatibility of methane for the majority of today's fleet.*

CAPEX: Capital costs related to using methane as marine fuel include installation of new engines, storage tanks and fuel systems**.** Methane is the alternative fuel that has come the furthest for maritime use, but its storage requires low temperatures and is therefore costly. According to DNV, while an LNG-ICE is slightly more expensive than that of conventional marine engines, the main portion of the CAPEX for LNG lies with the storage system (DNV, 2019c). Methane is usually stored in cryogenic tanks where it is liquified. This requires special tanks, which are known to be more costly (Serra & Fancello, 2020).

Given the above-mentioned factors, methane is scored 2, the same level as CAPEX for hydrogen fuel cells, but lower than other sustainable zero carbon fuels that can be stored easily, like ammonia and methanol. CAPEX is still a major economic barrier to adopting methane on board. There is no difference between CAPEX for e-methane and biomethane as CAPEX does not include costs related to the production of fuel.

Fuel cost:

<u>Biomethane:</u> The cost of biomethane is driven by the costs of acquiring feedstock (municipal solid waste, sludge, low-cost agricultural waste) and the relatively low costs of infrastructure. IEA reports that by 2040 global biomethane supply will reach 1,000 Mtoe (over 25 percent of global gas use in 2022) under 14 USD/GJ (IEA, 2020). However, since feedstock availability is limited, the market price will depend on the market forces. Increased demand for zero emission fuels from multiple sectors will put pressure on prices, although competition with e-fuels will set the upper bound on biomethane prices. At the same time, some increases in production efficiency are expected in the future. Within the next 30 years a 20 percent decrease in capital costs and 25 percent increase in conversion efficiency of the biogas process is expected (Mærsk MC-Kinney Møller Center, 2022). On the other hand, biomethane production is likely to continue to take place in relatively small facilities located in the proximity of organic feedstock. Liquification plants at such facilities do not benefit from returns to scale, which contributes to relatively high transportation costs that will drive the price upwards.

E-methane: The cost of e-methane is driven by the cost of green hydrogen and renewable CO_2. Costs of hydrogen are discussed in the earlier section. Costs of direct air capture, although prohibitively high now, are expected to decrease as the technology matures. There is however significant uncertainty in the cost pathway of the technology. Kiani et al. (2021) suggest that with scaling up a tenfold decrease in production costs is possible, from nearly $1500 per ton of CO_2 to just over $100 per ton of CO_2. However, even with those costs, costs of carbon would constitute nearly 20 percent of methane production costs (at 2.4$ per 1kg of hydrogen), estimated at over $30/GJ.

Biomethane receives score 3, although transportation to harbors may be costly due to decentralized production of biogas. Based on the above discussion, fuel cost is seen as a moderate barrier for adoption of methane as fuel. E-methane on the other hand receives score 2, lower than carbon-free e-fuels, as the need for carbon capturing increases the cost and creates a major economic barrier for e-methane.

4.3.2 Onshore

This section describes the onshore KPIs for methane fuel. We differentiate between biomethane and e-methane pathways, as there are differences to be highlighted. The table below illustrates the scores given to each of the onshore KPIs for the use of methane as a marine fuel.

Table 18: Onshore KPIs and score for methane

CATEGORY	KPI	BIOMETHANE	E-METHANE
Technical	*Infrastructure (Storage, bunkering & transportation)*	🟨	🟩
	Fuel production technology	🟨	🟧
	Production scalability	🟧	🟨
Fuel scalability & interaction	*Feedstock availability*	🟥	🟩
	Interaction with other sectors	🟧	🟩

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Infrastructure (storage, bunkering & transport): Due to low density at atmospheric pressure, methane is liquefied and stored at cryogenic temperatures for efficient storage and transport. Based on an expert assessment, liquid state is the most realistic and effective way of storing methane, due to its higher energy density and similar characteristics to liquified natural gas. Liquified methane can be stored at much warmer temperatures than for example hydrogen at -161,6 degrees Celsius. The cryogenic tanks for methane do not need as much insulation, making them lighter and cheaper, in addition to being smaller[57]. Increasing integration of decentralized biomethane feed-in into the existing gas grid is a new situation for the gas grid infrastructure with new challenges. New gas sources and therefore new paths make grid adaptations at all pressure levels

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[57] *https://science.nasa.gov/science-news/science-at-nasa/2007/04may_methaneblast, retrieved 17.08.2022*

necessary. An advantage of liquified methane is that it can be dispensed to either LNG or CNG vessels (Krich, et al., 2005) [58].

Methane can be distributed to its ultimate point of consumption by one of several options, depending on its point of origin. Distribution can occur via dedicated methane pipelines, via natural gas pipelines or by trucks as either gas or liquid. If the point of consumption (harbor, bunkering point) is relatively close to the production site, methane would typically be distributed via dedicated pipelines. These pipelines can be both buried and placed above ground. Another distribution method is via existing natural gas pipeline networks, which offers a potentially unlimited storage and distribution system for methane. Once the methane is injected into the natural gas pipeline network, it can be used as a direct substitute for natural gas by any piece of equipment connected to the natural gas grid.

Methane can also use existing gas grid distribution, and over-the-road transportation is an alternative both in a gaseous or liquid state. The energy density of methane is extremely low at ambient pressure and as a result it must be compressed to relatively high pressures to be transported economically. This is done by bulk transport vehicles. Liquification allows for even higher energy density and addresses many of the infrastructural issues associated with methane distribution. One of the key advantages of liquified methane is that the distribution infrastructure and market already exist in form of the existing LNG network.

Production location of biomethane is dependent on the supply of organic feedstock used[59]. On the other hand, the supply of feedstock used in e-methane production opens for greater potential areas of production, implying fewer transportation-related challenges.

Methane (both bio and e) can to a large extent exploit existing infrastructure and bunkering facilities. Given that methane is the main constituent of LNG, e-methane does not represent any fundamental challenge in fuel logistics, and e-methane production can occur in more remote locations. However, the potential negative climate effects from methane slips call for increased investments in prevention systems. Additionally, the placement of production plants for biomethane production (like HVO) is more restricted. For this reason, we are scoring biomethane to 3, and e-methane to 4.

Fuel production technology: Biomethane can be produced from biogas that is derived from organic matter such as human waste/sewage, food waste, distillery waste or agricultural materials (Frigon & Guiot, 2010). Biomethane can be produced by either "upgrading" biogas by a process in which any CO_2 and other contaminants are removed, or by gasification of the solid biomass followed by a methanation process[60]. E-methane on the other hand can be produced using electricity made from renewable sources – otherwise known as power-to-gas process[61].

The production method for biomethane, which consists of anaerobic digestion, is a well-established process. However, the technology is limited to mostly agricultural residues and residential waste, and proper liquefication

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[58] *LNG: Liquified natural gas. CNG: Compressed natural gas.*

[59] *https://www.biomethane.org.uk/how-biomethane-is-produced.html, retrieved 17.08.2022*

[60] *https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/an-introduction-to-biogas-and-biomethane, retrieved 17.08.2022*

[61] *https://www.rolls-royce.com/media/press-releases/2021/18-03-2021-use-of-green-methane-in-transport-and-power-generation.aspx, retrieved 17.08.2022*

of biomethane is currently not in place (Ghimire, Bakke, & Bergland, 2021). Additionally, the gasifiers used in the production process of biomethane are not able to cope with all sorts of organic matter feedstock.

The production process for methane synthesis was discovered in 1897 and it has become a well-established fuel. However, current mature electrolyzers (such as alkaline and PEM) are too expensive and inefficient to make e-methane competitive with other sustainable zero carbon fuels and fossil fuels. The production capacity is not ready, and the size of e-methane plants is currently restricted by the technologies used to capture CO_2, diminishing economies of scale and thus increasing cost (Mærsk MC-Kinney Møller Center, 2022).

Liquefaction of methane follows the same process as LNG and occurs in separate plants. The gas is pretreated to remove any contaminants and water. CO_2 is then absorbed and removed. The purified methane is compressed and pre-cooled in a chiller. Since this cooling process is not enough to fully liquify the methane, the process is repeated two or three times, which allows the methane to reach optimal temperatures for liquid storage[62].

The technologies used to produce biomethane are considered mature and have been used for several years. However, the main bottleneck for biomethane is the inefficiency and lack of advancement of current procedures. On the other hand, e-methane production is proving to be viable. However, the production processes are currently restricted by inefficient electrolyzers and immature technologies for direct air capture of CO_2.

Due to the fact that biomethane has been produced for several years, the technology is standardized, but suffering from inefficiency. Therefore biomethane production technology is scored to 3. Additionally, as with e-ammonia and green hydrogen, e-methane is experiencing several of the same challenges. However, e-methane is mainly restricted by immature DAC-related technologies that are needed to realize e-methane production. Hence scoring e-methane to 2.

Production scalability: The scalability of biomethane is highly dependent on geographical location, as most plants are located at farms and other small-scale facilities. While this has several co-benefits for rural communities, it creates challenges related to upscaling, as larger plants require more sophisticated co-operative models and are also more exposed to the variability of different waste streams. Alternatively, biomethane can be produced through thermal gasification of biomass. While there are several biomass gasification plants in operation, these are mostly only on a demonstration scale (IEA, 2020).

The current methods of producing biomethane are based on natural gas or coal gasification, which is considered a mature technology. However, using renewable electricity as the main driver is new and costly. The global electrolyzer production capacity is not ready for massive roll-out in large scale (Mærsk MC-Kinney Møller Center, 2022). Additionally, the scale of e-methane production sites is likely to be dependent on the scale of captured CO_2 and its supply, potentially diminishing economies of scale for e-methane[63].

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[62] *https://ecospray.eu/wp-content/uploads/2022/06/Liquefazione_ProductCard_ENG_web_220622.pdf, retrieved 17.08.2022*

[63] *https://www.zerocarbonshipping.com/energy-carriers/e-methane/?section=feedstock-availability, retrieved 17.08.2022*

Liquefaction of methane is important in making the fuel as energy-dense by volume as possible. Liquefaction of methane is an expensive process and has large economies of scale potential, making liquefaction of methane at smaller scale challenging[64].

The scalability of several fuels in this assessment is restricted by the technology for capturing CO_2, such as blue hydrogen. While biomethane has the potential to be produced in smaller scale, the need for adequate space and supply of inputs means the plants are restricted to farming-related activities. Hence, scoring biomethane's scalability to 2.

E-methane has the potential to be produced at small scale. However, the efficiency of current CO_2 capturing systems and electrolyzers restricts its real-world potential, hence, scoring e-methane to 3.

Feedstock availability: All types of biomass feedstock can essentially be used in biomethane production. A distinction is often made between energy crops, agricultural residues, forestry products and residues, and aquatic biomass, which can all be used as biomethane feedstock. In a study by Delft (2020), it is estimated that the maximum conceivable supply of LBM (liquified biomethane) is larger than the demand from the maritime sector in both 2030 and 2050. However, not all biomasses will be converted into methane, and there is competing demand from other sectors for methane as well.

Biomethane supply is restricted by biomass available near existing gas grids and competition with other industries, which drives the price. Globally, the maximum potential for biomethane for all industries is limited by the amount of biomass suitable for biogas production near existing gas lines. The timing of availability is limited by the maximum roll-out speed of biogas plants, even if supply is unconstrained. Considering the maximum roll-out speed, modelled by assessing historical biofuel roll-out speeds of technologically and commercially mature technologies with government support, biomethane could grow to reach the maximum availability by 2040 (Mærsk MC-Kinney Møller Center, 2022).

Additionally, biomethane feedstock is challenged by high demand across several industries, and the current regulatory framework which does not support large-scale collection of suitable waste streams for production of biomethane. E-methane uses renewable electricity, water and renewable CO_2 in its production. Renewable electricity resources, water and renewable CO_2 are widely available (even though investment in RES-production capacity would be needed) and will only be restricted by the technology used in direct air capture (DAC) of CO_2, which is currently immature.

The feedstock availability of e-methane is scored 4, with the same reasoning as for green hydrogen and green ammonia. Hence, we score the feedstock availability of e-methane to be 4. Similarly, the feedstock availability of biomethane is challenged by the same problems as HVO, hence, scoring the feedstock availability of biomethane to be 1.

Interaction with other sectors: Methane is a highly usable gas that is in demand in several industries and markets. Methane gas is often used as an energy source for residential use. As of 2020, industrial processes, commercial and public services, as well as the transport sector stand for over 80 percent of total global

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[64] https://www.zerocarbonshipping.com/energy-carriers/bio-methane/?section=fuel-production, *retrieved 17.08.2022*

consumption. Around 12 percent of total consumption goes to other non-energy usages[65]. In industry, methane is used to produce methanol (methyl alcohol) and makes up most of today's production of hydrogen through steam-methane reforming. Other commodities can be produced from carbon deposits called *carbon* black by incomplete burning of methane. Additionally, methane is used in the production of ammonia[66]. Increased production of biomethane has the potential to cause scarcity for organic matter currently used in other sectors, due to the limited total capacity of biomass globally. The characteristics of e-methane production do not suffer from this factor, while increased demand for emission-free hydrogen and direct air capture technology from other industries will likely contribute to cost reduction in the future.

Due to the scarcity problem of biomethane feedstock, the interaction with other sectors has the potential to cause substantial negative effects. However, we do not consider the challenges to be as significant as for HVO, hence we are scoring biomethane to 2. On the other hand, e-methane developments can facilitate technological improvements in different sectors without resulting in negative impacts in those sectors, hence we score the interaction of e-methane with other sectors to 4.

4.3.3 Environment

In this part we look at the KPIs related to the environmental challenges. This includes greenhouse gas emissions, both from a well-to-tank and tank-to-wake perspective, local pollution and overall energy efficiency. Due to the fact that we are assessing the well-to-wake path, we distinguish between biomethane and e-methane within the different KPIs.

Table 19 : Environmental KPIs and score for bio- and e-methane

CATEGORY	KPI	BIOMETHANE	E-METHANE
Environment	*Greenhouse gas emissions*	🟧	🟧
	Local pollution	🟩	🟩
	Overall energy efficiency	🟩	🟧

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Greenhouse gas emissions: Methane, in contrast to hydrogen and ammonia discussed earlier, contains carbon, which inherently leads to substantial tank-to-wake CO_2 emissions. Thus, to make methane a zero-emission fuel, the carbon contained in the fuel must be extracted from the atmosphere. Carbon can be captured by plants through photosynthesis or by direct air capture technology.

Well-to-tank: Due to the difference in the production process, we will discuss well-to-wake emissions for biomethane and blue and e-methane separately.

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[65] *https://www.iea.org/data-and-statistics/charts/world-natural-gas-final-consumption-by-sector-2018, retrieved 17.08.2022*

[66] *https://www.conserve-energy-future.com/sources-uses-effects-methane-gas.php, retrieved 17.08.2022*

E-methane is produced through conversion of CO_2 and hydrogen.[67] Thus the key steps in methane production are hydrogen production, capture of CO_2 and methane synthesis. Subsequently methane needs to be liquified and transported to harbours. This step is, however, the same as for biomethane.

Emissions related to production of green hydrogen are discussed in the section on hydrogen. Direct air capture has a potential of being a zero-emissions source of feedstock for synthetic fuels production, but the process has not been yet developed on a commercial scale.[68] The infrastructure requirements also contribute to lifecycle emissions, approximately 3 g CO_2e/kWh.[69] Lower infrastructure requirements are related to biogenic CO_2 point capture, although availability of this CO_2 source is limited.[70] Renewable CO_2 can be obtained also from biogenic sources, this path, however, has not been analysed due to limited supply.

The methane synthesis process does not cause emissions. For the fuel to be considered zero-emission however, the CO_2 used in the process needs to come from a renewable source – direct air capture or point capture of CO_2 released from biogenic sources, e.g., during the production of biomethane or pulp and paper. Fossil CO_2 can also be captured through point capture at industrial plants; however, we do not consider this source as potentially zero emission and do not include it in the analysis.

Biomethane is produced from the decomposition of organic materials. The feedstock used in the process can come from various sources such as plant and animal by-products and organic waste from households and industry. However, biogas can also be produced from so-called energy crops, i.e., low cost and low maintenance crops grown solely for energy production rather than food. Use of energy crops causes indirect emissions through land-use impacts. Production of biogas from biomass also releases CO_2, which has been previously captured by plants used as a feedstock, thus those emissions are neutral from a life-cycle perspective. Methane, regardless of its origin, requires liquefaction before shipment and regasification before use onboard a ship. Emissions at existing fossil natural gas liquefaction plants are significant,[71] but those can be significantly reduced if not eliminated if renewable energy is used in the process.

Furthermore, for all types of methane, emissions from fugitive leaks throughout the transportation and bunkering process are to be accounted for.

Tank-to-wake: Combustion of methane leads to CO_2 emissions, but since the varieties discussed in this section are produced using captured carbon, those emissions are neutral from a life-cycle perspective. However, use of methane in combustion engines is associated with methane slip – the release of unburned methane due to incomplete combustion or fugitive leaks (e.g., through valves or pipe connections). Engine producers claim that

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[67] *Methanation process at elevated temperatures and pressure in the presence of suitable catalysts such as nickel (Kiani, Lejeune, Li, Patel, & Feron, 2021).*

[68] *As of November 2021, there were only 19 DAC small scale/pilot plants operating worldwide, capturing more than 0.01 Mt CO_2/year (IEA, 2021b). This creates uncertainty in existing real life cycle assessments.*

[69] *A study based on existing small-scale plants suggests that the key infrastructure elements – absorbents and plant construction – are associated with approximately 6g CO_2e per 1kg of captured CO_2 (Deutz & Bardow, 2021). This accounts to approximately 3g CO_2e/kWh assuming 11.85 kWh/ 1kg methane and 2.75 kg CO_2 per kg CH_4 and 45 percent engine efficiency.*

[70] *CO_2 point capture can also be implemented at industrial plants to capture CO_2 from industrial processes (e.g., cement kilns), however, as this source of CO_2 is not renewable, we do not include it in the analysis.*

[71] *Existing studies based on fossil fuel powered liquefaction plants estimate emissions from that process at over 50 g CO_2e/kWh (Abrahams, Samaras, Griffin, & Matthews, 2015).*

methane slip can be reduced to 25 g CO_2e/kWh or even below (MAN Energy Solutions, 2021; Wärtsilä, 2020). In older engines, however, methane slip can amount to 300 g CO_2e/kWh (Nielsen & Stenersen, 2010).

We award score 2 to all types of methane discussed in this section. The relatively low score, lower than in the case of other fuels discussed earlier, is due to the risk of fugitive leaks and methane slips throughout the entire lifecycle. Those leaks occur throughout multiple stages, making them difficult to eliminate. This relatively low score is awarded even though production of e-methane has a potential of becoming near zero emissions in the future, despite a more complex production process compared to other e-fuels discussed earlier.

Local pollution: ICE engines operating at high temperatures produce high quantities of nitrogen oxides (NOx), Studies show however that NOx, SOx as well as PM emissions of biomethane are below 20 percent of those created by HFO (Brynolf, Fridell, & Andersson, 2014). Data on e-methane is not available. But one can expect potentially lower pollution levels with e-methane (except for NOx, which is related to the combustion process rather than the fuel properties) due to higher purity of the synthetic fuels.

In the future, local emissions related to methane use may be eliminated thanks to development of direct methane fuel cells. In those fuel cells methane is used directly, without being converted into hydrogen first. This would also produce energy more efficiently than combustion-based methods.

Overall, relatively low emissions and the potential to eliminate emissions through the use of fuel cells justify score 3 for methane. However, some barriers need to be addressed to scale up that technology. The score is lower than for hydrogen and electricity, higher than for HVO and on par with other fuels in the analysis.

Overall energy efficiency: Production of green methane requires the energy intensive process of carbon capture. The energy intensity varies depending on whether the source is point capture from biomass or direct air capture, with the latter requiring as much as 7.3-8.9 MJ / kg CO_2 (McQueen, Desmond, Socolow, Psarras, & Wilcox, 2021). Carbon capture amounts to approximately 12.5 percent of total energy required (Pawelec, 2020). Consequently, use of green methane as fuel requires between 4.7 and 6.2 units of primary energy for a unit of propulsion (Pawelec, 2020; Lindstad, Lagemann, Rialland, Gamlem, & Valland, 2021).

Total energy required for one kWh of propulsion using biomethane is estimated to around 4 kWh (Lindstad, Lagemann, Rialland, Gamlem, & Valland, 2021; Brynolf, Fridell, & Andersson, 2014).

The energy requirement per unit of propulsion makes us conclude that score 3 is appropriate for biomethane and score 2 for e-methane, similar to other carbon-based fuels in the assessment. Biomethane scores similarly to ammonia and hydrogen.

4.3.4 Maritime rules and regulations

Table 20: Rules and regulations KPIs and score for methane

CATEGORY	KPI	BIOMETHANE	E-METHANE
Rules and regulations	*Maturity of maritime rules and regulations*	⬢	⬢

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Maturity of rules and regulations: Methane is a non-toxic gas and creates no hazard when inhaled in limited quantities. Larger amounts of methane can displace air, which may lead to suffocation. Since methane is flammable when mixed with air, the main hazard related to this fuel is fire and explosion risk. It is common to add distinctive odors to methane for people to smell its presence.

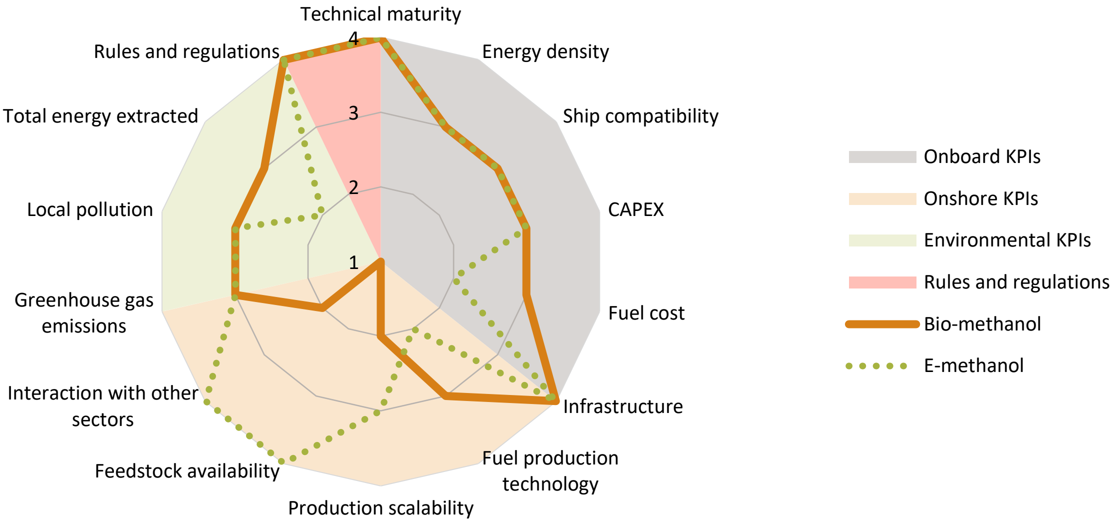
There is extensive experience in terms of handling methane onboard and onshore, stemming from shipping LNG as a commodity. A new era started when four-stroke gas engines (dual-fuel or gas only) were adopted from 2000 onwards, allowing use of LNG. Until the dual-fuel engines were introduced in the early 2000s, LNG was used only by LNG carriers capable of burning boil-off-gas in their steam turbines. In 2011, high-pressure two-stroke dual-fuel engines were introduced, allowing use of either LNG or HFO/MGO (DNV, 2019d). The maturity level of safe handling of methane has increased significantly during this time, and the use of methane onboard is mainly regulated by IGF code, "International code of safety for ships using gases or other low-flashpoint fuels", which has particular focus on using LNG as fuel. The code came into force in 2017.

As methane has been used as a marine fuel for two decades now, rules and regulations with regards to using methane as marine fuel are seen as mature and methane is given the highest score, 4.

4.4 Methanol

Methanol will play an important role in decarbonizing the Nordic ship traffic and has the potential to become near zero emission in a life-cycle perspective in the future. Methanol is already being used as a marine fuel, but most of the vessels that use methanol as fuel are methanol tankers. Even though methanol is available at several large ports, the bunkering options are not sufficient to meet the potential Nordic demand for methanol. Thus, there is a need for increased investments in infrastructure, bunkering and production facilities if demand for methanol in the Nordic countries increases. As with ammonia, the feasibility analysis conducted in this project shows that hydrogen could potentially cover over 80 percent of the current Nordic fuel consumption. Methanol has a relatively high compatibility with existing ships and its energy density is among the highest of the sustainable zero-carbon fuels. The cost to build new and convert existing vessels to run on methanol is significantly lower compared to the other sustainable zero-carbon fuels. The production technology is however less mature, and it is not ready to be scaled to meet the Nordic demand. Production of green e-methanol is a complex process and includes direct air capture (of carbon). This requires further development and investments to commercially scale up the production technology. For bio-methanol the emission intensity depends on the source of feedstock, which is limited. The latter becomes a major barrier if demand increases, especially as sustainable bio-feedstock is in demand from several sectors and thus a scarce resource.

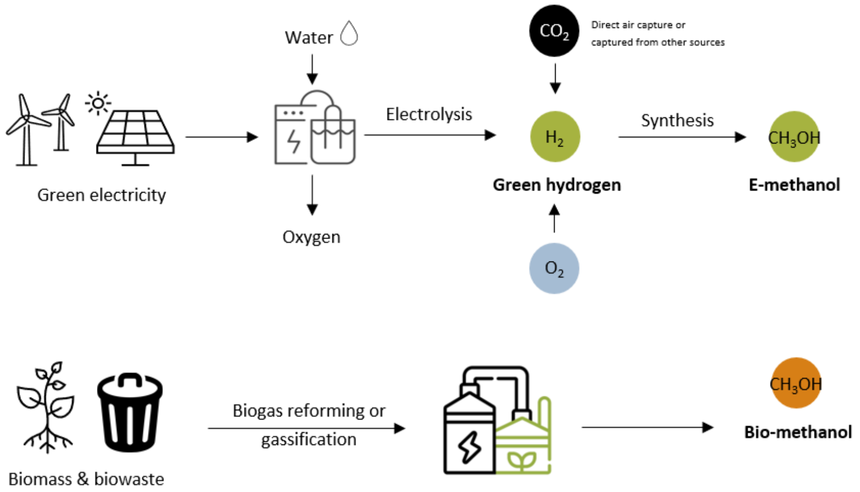
Figure 14: Scoring of onboard, onshore, environmental and safety-related KPIs for both bio- and e-methanol



Today methanol production is dominated by fossil resources as feedstock, but it can be produced sustainably as well. A transition to renewable methanol – derived from biomass or synthesized from green hydrogen and CO_2 – could expand methanol's use as a fuel and become an important factor in moving the maritime sector towards zero carbon shipping (IRENA, 2021). The focus in this report is solely on e-methanol produced via green hydrogen and bio-methanol. An alternative production pathway for blue methanol in which methanol is produced through synthesis of blue hydrogen and CO_2 is also not included in the analysis. This production pathway differs from the e-methanol pathway only in the source of hydrogen used in the production process. In the assessment, we consider only CO_2 sourced from direct air capture or organic sources in this analysis, excluding a pathway in which CO_2 is sourced from industrial processes.

Current methanol production is primarily based on hydrogenation of syngas, which is a fossil-based feedstock. However, it can also be produced sustainably. The figure below illustrates sustainable methanol production alternatives that we will be focusing on in this report. Firstly, methanol can be produced through the synthesis of green hydrogen and CO_2 captured directly from air. This production method does not cause greenhouse gas emissions. Secondly, it can be produced via synthesis of blue hydrogen and CO_2 via direct capture. This is called blue methanol, as shown in the figure below. Finally, methanol can be produced through reforming or gasification of organic material. Resulting methanol is called biomethanol and this production method is considered sustainable since the feedstock being used (biomass and biowaste) is sustainable.

Figure 15: Illustration of e-methanol and biomethanol production



The next chapters give a description of the KPIs related to the barriers and challenges of using methanol as a marine fuel, from a market perspective, onboard, onshore, environmental and safety perspective.

4.4.1 Onboard

Table 21: Onboard KPIs and score for methanol

CATEGORY	KPI	BIOMETHANOL	E-METHANOL
Technical	*Technical maturity*	⬢	⬢
	Energy density	⬡	⬡
	Existing ship compatibility	⬡	⬡
Economic	*CAPEX*	⬡	⬡
	Fuel cost	⬡	🟧

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

The following chapter focuses on onboard KPIs for using methanol as fuel. As with previous fuels, we do not differentiate between biomethanol and e-methanol (both green and blue) for technical KPIs, as feedstock and production methods do not make a difference in terms of using and storing methanol onboard. For economic KPIs the differentiation is made where it is necessary.

Technical maturity: Methanol can be used in 2-stroke and 4-stroke internal combustion engines, as well as fuel cells. The internal combustion engines are already developed and have been in use since 2015. MAN has developed 2-stroke dual fuel engines that can run both on diesel and low flashpoint fuels such as methanol. The particular engine developed is called ME-LGIM, where M stands for methanol. 4-stroke engines are expected to be available mid-2022 with retrofitting a possibility in 2024.[72] Similarly, Wärtsilä has developed a methanol fuel system that is called MethanolPac, which makes retrofit applicable for many vessels[73]. Fuel cell technology on the other hand is currently under development and expected to reach maturity around 2030 (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022)[74].

Onboard storage technologies for methanol are considered to be mature given the history of methanol being shipped as commodity. In addition, methanol is liquid under ambient conditions and hence storage of methanol onboard requires less energy compared to for example liquified methane, hydrogen etc.

Methanol engines have been successfully demonstrated and taken into use in some areas since 2015, for example Stena Ferries. For this reason, we see methanol as one of the most technically mature sustainable zero carbon fuels as there are little to no technical barriers for adoption of methanol technologically.

Energy Density: Methanol has a volumetric energy density of 15.7 MJ/L (ABS, 2021). This means that methanol will require 2.5 times more space for onboard storage compared to diesel (Foretich, Zaimes, Hawkins, & Newes, 2021). Although methanol has slightly higher volumetric energy density compared to ammonia, their densities are relatively close to each other and are lower than conventional diesel and liquified methane.

For the reasons mentioned above, we score energy density of methanol as 3, same as ammonia.

Existing ship compatibility: Methanol is not compatible with conventional engine technologies, but retrofit is possible. Retrofit may require installation of new engine cylinder heads, double walled piping, and monitoring and ventilation systems for slippage (Foretich, Zaimes, Hawkins, & Newes, 2021). Existing fuel storage technologies can be used to store methanol onboard, however, as mentioned above, because of the lower volumetric energy density there will be need for bigger storage tanks or vessels will need to bunker more often.

Given the factors above, we give methanol a score of 3 in terms of existing ship compatibility, as the technical barriers related to adoption of methanol are moderate and not major.

CAPEX: Currently the main barrier to renewable methanol uptake is its higher cost compared to fossil fuel-based alternatives, and that cost differential will persist for some time to come. However, renewable methanol's value is in its emission reduction potential compared to existing options (IRENA, 2021).

Methanol is available worldwide through existing global infrastructure. The cost to build new and convert existing vessels to run on methanol is significantly less than alternate fuel conversions.[75] The additional costs of installing methanol systems on board vessels (e.g., internal combustion engine, fuel tanks, piping) is roughly one third that of the additional costs associated with LNG systems. This is because there is no need for special materials able to handle cryogenic temperatures or for pressurized fuel tanks (DNV, 2019a). Ships converted to operate on methanol can simply begin blending *renewable* methanol in the future to reduce their operational carbon footprint.

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[72] *https://www.man-es.com/marine/strategic-expertise/future-fuels/methanol, retrieved 17.08.2022*
[73] *https://www.wartsila.com/can/media/global-news/17-03-2022-wartsila-to-deliver-first-dedicated-methanol-fuel-supply-system-3068213, retrieved 17.08.2022*
[74] *https://www.alfalaval.com/media/news/investors/2021/alfa-laval-starts-testing-methanol-fuel-cell-systems-for-sustainable-marine-power-supply/, retrieved 17.08.2022*
[75] *https://www.methanex.com/about-methanol/methanol-marine-fuel, retrieved 17.08.2022*

For this reason, CAPEX for methanol is scored as 3, which is higher than that of methane and similar to CAPEX for ammonia, as CAPEX comprises a moderate barrier for methane to be adopted as marine fuel.

Fuel cost: E-methanol, similarly to e-methane, is produced from green hydrogen and captured CO_2. Compared to methane, methanol contains more CO_2 per unit of energy (70 kg CO_2 per GJ compared to 50kg per GJ in the case of methane), making production of e-methanol with direct air capture relatively more expensive.

Biomethanol, like biomethane, is produced from biomass including biogas and faces similar challenges. Biomethanol production can be integrated with paper production reducing the costs, which is especially relevant for the Nordic countries with a significant paper industry. Lundgren et al. (2017) suggest production costs of biomethanol in the Nordic region within the $15-$22/GJ range. However, the amount of available resources is unlikely to meet the demand from the maritime sector.

As in the case of methane, we award score 3 to biomethanol and score 2 to e-methanol. Despite identical scores there are some differences. Lower transportation costs will allow for better utilization of geographically spread resources in the case of biomethanol compared to biomethane. On the other hand, higher carbon content makes e-methanol likely more costly than e-methane given high and uncertain costs of direct air capture.

4.4.2 Onshore

This section describes the onshore KPIs for methanol fuel. We differentiate between biomethanol and e-methanol pathways, as there are differences to be highlighted. The table below illustrates the scores given to each of the onshore KPIs for the use of methanol as a marine fuel.

Table 22: Onshore KPIs and score for methanol

CATEGORY	KPI	BIOMETHANOL	E-METHANOL
Technical	*Infrastructure (Storage, bunkering & transportation)*	🟩	🟩
	Fuel production technology	🟨	🟧
	Production scalability	🟧	🟧
Fuel scalability & interaction	*Feedstock availability*	🟥	🟩
	Interaction with other sectors	🟧	🟩

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Infrastructure (storage, bunkering & transport): Methanol can be found in over 100 ports globally, and there is currently no difficulty in buying methanol for bunkering. Methanol is either available at or within close proximity to many ports. There are currently several global bunkering suppliers and fuel trading platforms interested in providing methanol fuel to ships (Chatterton, 2020). However, the current methanol market is significantly smaller than the bunker fuel market. Although methanol is less energy dense than traditional fuels, thus requiring larger storage space, its liquid state makes it easy to store in ballast and "slop" tanks (Methanol Institute, 2018). The installation of methanol storage tanks in existing facilities or specifically designed stations is quite straightforward and is in any case no more difficult than the installation of their gasoline counterparts. Additionally, methanol bunkering is not that dissimilar to marine gasoil bunkering[76].

Distribution of methanol to ships can be accomplished either by truck or by bunkering vessel. Methanol is one of the top five chemical commodities shipped around the world each year, implying highly mature routines for transportation and handling. Methanol is transported by railways, ships, and trucks. Railway transport is in many cases the preferred option for long-distance transportation of bulk quantities[77].

As methanol is a global commodity and has mature infrastructure technologies along with guidelines for storage, bunkering and transportation, port infrastructure regarding storage and bunkering must be significantly expanded for methanol to become a fuel for the maritime industry. Additionally, the transportation methods of methanol have several characteristics that are similar to regular gasoline or jet fuel transportation, and we therefore assess the overall challenges to be relatively small, scoring the infrastructural KPI of methanol to 4, which is on par with current HVO infrastructure maturity.

Fuel production technology: Most methanol today is produced using fossil fuel sources, mainly natural gas. On the industrial scale, biomethanol is predominantly produced using organic matter as fuel, which is then fed into a digester that produces pure methanol. This pure methanol is then purified, making biomethanol. E-methanol is produced by combining green hydrogen and captured CO_2, which then produces green methanol from methanol synthesis.

While production of methanol from fossil sources is highly mature, production of biomethanol by using gasification technologies is still at an early stage, and as with biomethane, not able to use all sorts of organic matter feedstock. However, there are several demonstration projects worldwide. Controlling for methane slips in the gasification of biomethane pathway is highly important to ensure a climate-positive impact from gasification-based production of biomethanol (Mærsk MC-Kinney Møller Center, 2022). Production of e-methanol sees challenges related to inefficient electrolyzers in green hydrogen production and inefficient and expensive DAC-technologies.

As with the production technology of e-methane, the production technology is gaining maturity. However, e-methanol also relies heavily on technologies used to directly capture CO_2 from the atmosphere. Additionally, more efficient electrolyzers are also needed, hence we score e-methanol to 2 in this assessment. Biomethanol production technology is currently at a high maturity level, but struggles with similar challenges as biomethane, and is suffering from stagnation in the technological developments. Hence, scoring the fuel's production technology of biomethanol to 3.

Production scalability: For the direct air capture (DAC) pathway, there are no feedstock constraints regarding availability to scale e-methanol. However, there are high costs for DAC feedstock and long-term competition for bio-based CO_2 feedstock (point source bio energy carbon capture). At the same time, while some production infrastructure and procedures already exist, scale is needed through investments and development of bunkering infrastructure (Gielen, Krantz, Mouftier, & Skov Christiansen, 2021).

Methanol is currently produced at large scale using fossil fuels. By decentralizing the methanol production, renewable methanol can be produced in remote locations. However, there is a need for development of new

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[76] https://www.lr.org/en/insights/articles/advancing-methanol-bunkering/, *retrieved 17.08.2022*

[77] https://www.briangwilliams.us/methanol-economy/methanol-storage-and-distribution.html, *retrieved 17.08.2022*

process configurations to avoid energy-intensive compression stages, and to ensure access to renewable hydrogen. While being feasible in theory, the technology used in production of small-scale e-methanol is highly immature, causing non-profitable operation. This implies that there is an extensive need for increased development. This implies that only large and capital-intensive facilities can ramp up the production of e-methanol (Moioli, Wötzel, & Schildhauer, 2022).

While there are some existing biomethanol production plants, the main challenge with regard to the scalability of production is the capacity for constructing new biomethanol production facilities. Additionally, high production costs and capital investments required for biomethanol production limit its commercial application. It is suggested that economies of scale play an important role for some biomethanol production pathways (IEA-ETSAP and IRENA, 2013).

Small-scale production of e-methanol is theoretically feasible, but at present not technologically possible. Additionally, the current technologies used favor large-scale facilities. The need for renewable hydrogen complicates production further, scoring e-methanol lower than hydrogen, hence scoring the scalability of e-methanol to 2.

The current production facilities for biomethanol are large-scale facilities, and there are technological restrictions for production at smaller scale, as for bio-based methane. Large investments to utilize economies of scale are needed to make biomethanol production viable. The challenges of biomethanol production are similar to those of HVO, hence we score biomethanol's scalability to 2.

Feedstock availability: The feedstocks used in biomethanol production are waste streams of organic matter, such as manure, agricultural waste and food waste. Additionally, woody biomass can be used as feedstock in production of biomethanol. For e-methanol, the main feedstocks consist of renewable electricity, water and CO_2.

While the supply of organic matter for use in production of biomethanol is ever increasing, the supply will be challenged by high demand from several sectors. Additionally, even the fastest roll-out of biomethanol supply will not be sufficient to meet future demand. On the other hand, the availability of feedstock for production of e-methanol is close to unlimited, only restricted by high investments needed to extract the necessary feedstocks. In this case, scaling of both renewable electricity and renewable CO_2 will be vital.

Feedstock used in production of biomethanol is subject to high demand from several sectors, making it challenging to scale production to meet demand from the maritime industry. Biomethanol is therefore troubled by the same challenges as other included bio-based fuels in this assessment and given a score of 1. On the other hand, the availability of feedstock for e-methanol production is close to unlimited and only constrained by the investment level needed for extraction. We do not find this to be a significant barrier for the Nordic countries, hence we are scoring the feedstock availability of e-methanol to 4 in our assessment.

Interaction with other sectors: The global methanol production was approximately 100 million tonnes in 2020, twice the amount of 2010 (Alvarado, 2020). 30 percent of all methanol is used in North America, Western Europe and the Middle East. Methanol is used in thousands of products, including plastics, paints, cosmetics and fuels. Methanol is also used in essential products for cars, and the production of other valuable chemicals such as pharmaceuticals (Britannica, T. Editors of Encyclopaedia, 2019).

Methanol currently serves several industries and purposes and sees cross-industry competition. The primary driver of the methanol industry is the usage of petrochemicals in end-use sectors such as automotive and construction. Growing interest in clean-burning fuels and regulatory changes are one of the main drivers for the use of methanol as fuel. Manufacturers of methanol are currently focusing on expanding their production capabilities to meet growing market demand.

The increased interest in low-emission fuel will furthermore expand the future growth of the methanol market (Data Bridge - Market Research, 2022). The competition with other energy intensive sectors will increase the demand for low-emission fuels, such as the aviation sector (Frelle-Petersen, Howard, Poulsen, & Hansen, 2021).

E-Methanol's interaction with other sectors creates positive technology synergies, which is similar as with green hydrogen, e-methane, and green ammonia. Hence, scoring e-methanol to 4 in this assessment. Biomethanol's extensive use of organic matter as input in production has the potential to cause scarcities/shortages in other sectors, implying significant barriers for the use of biomethanol in the maritime industry, which causes the same negative effects as HVO and other bio-based fuels. Hence, scoring biomethanol's interaction with other sectors to 2 in this assessment.

4.4.3 Environment

In this part we look at the KPIs related to the environmental challenges. This includes greenhouse gas emissions, both from a well-to-tank and tank-to-wake perspective, local pollution and overall energy efficiency. Due to the fact that we are assessing the well-to-wake path, we distinguish between biomethanol and e-methanol within the different KPIs.

Table 23: Environmental KPIs for bio- and e-methanol

CATEGORY	KPI	BIOMETHANOL	E-METHANOL
Environment	*Greenhouse gas emissions*	🟩	🟩
	Local pollution	🟩	🟩
	Overall energy efficiency	🟩	🟧

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Greenhouse gas emissions: Methanol can be used in ICEs as well as fuel cells, either directly in direct methanol fuel cells or after cracking in hydrogen fuel cells, though fuel cell technology has not yet reached commercial maturity. Different onboard uses of methanol are associated with different levels of energy efficiency and upstream emissions.

Well-to-tank: Due to the difference in production process we will discuss well-to-wake emissions for biomethanol and e-methanol separately.

Biomethanol is produced from the decomposition of organic materials. Biomethanol production can use biogas as a feedstock, thus competing for resources with biomethane or forestry and paper industry waste (black liquor). Existing studies summarised by Schröder et al. (Schröder, et al., 2020) suggest that well-to-wake emissions are between 10 and 80 g CO_2/kWh for methanol based on wood, waste wood or black liquor and over 100 g CO_2/kWh for the biogas production path. Those studies however do not account for indirect emissions through land use change.

E-methanol is produced through conversion of hydrogen and CO_2.[78] To produce one tonne of methanol, about 1.38 t of CO_2 and 0.19 t of hydrogen are needed (IRENA, 2021). If the feedstock is to be provided from direct air capture (CO_2) and water electrolysis (H_2), 30 GJ are required to produce hydrogen and 8.4 GJ to produce the required CO_2[79] with DAC, while a further 1.6 GJ is required for the methanol synthesis (Stefansson, 2015). Matzen & Demirel (2016) estimate the emissions related to production of e-methanol from green hydrogen and point capture of biogenic CO_2 to 45 g CO_2/kWh. In this case also, indirect emissions through land use change are not accounted for.

Tank-to-wake: Combustion of methanol leads to CO_2 emissions, but since both biomethanol and e-methane are produced using captured carbon, those emissions are neutral from a life-cycle perspective.

Production of green e-methanol has potential of becoming near zero emissions in the future. However, the fuel has a complex production process which also includes direct air capture. Several barriers must be addressed to commercially scale up that technology, thus score 3 is awarded. Biomethanol's emission intensity depends on the source of feedstock. Since the availability of low emissions feedstock is limited, a score of 3 is awarded, similar to the score of blue hydrogen and ammonia.

Local pollution: ICE engines operating at high temperatures produce high quantities of nitrogen oxides (NOx). Unlike ammonia and HFO, methanol is not very toxic to fish and aquatic invertebrates (Cames, Wissner, & Sutter, 2021). SOx, NOx and PM emissions of biomethanol are comparable to emissions from biomethane, thus below 20 percent of those from HFO (Brynolf, Fridell, & Andersson, 2014), which makes them comparable to the level of local emissions for methane combustion. However, in the future, local emissions from methanol may be fully eliminated if the fuel is used in fuel cells.

Due to the low level of local pollution in methanol combustion together with the possibility to use methanol in fuel cells score 3 is awarded to both e-methanol and biomethanol, similarly to methane and ammonia.

Overall energy efficiency: Production of green methanol similarly to methane requires an energy intensive process of carbon capture. Carbon capture amounts to approximately 25 percent of total energy required (Pawelec, 2020). Consequently, use of green methanol as fuel requires between 6.2 and 6.5 units of primary energy for a unit of propulsion (Pawelec, 2020; Lindstad, Lagemann, Rialland, Gamlem, & Valland, 2021). Total energy required for 1 kWh propulsion using biomethanol is estimated around 5.2 kWh (Lindstad, Lagemann, Rialland, Gamlem, & Valland, 2021; Brynolf, Fridell, & Andersson, 2014).

The energy requirement per unit of propulsion makes us conclude that score 3 should be awarded to biomethanol and score 2 to e-methanol, similarly to other carbon-based fuels in the assessment. Biomethanol scores similarly to ammonia and hydrogen.

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[78] *Methanation process at elevated temperatures and pressure in the presence of suitable catalysts such as nickel (Kiani, Lejeune, Li, Patel, & Feron, 2021).*

[79] *Assuming 6,09 GJ/t CO_2 in line with (IEA, 2021b).*

4.4.4 Maritime rules and regulations

Table 24: Rules and regulations KPIs and score for methanol

CATEGORY	KPI	BIOMETHANE	E-METHANE
Rules and regulations	*Maturity of maritime rules and regulations*	⬢	⬢

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

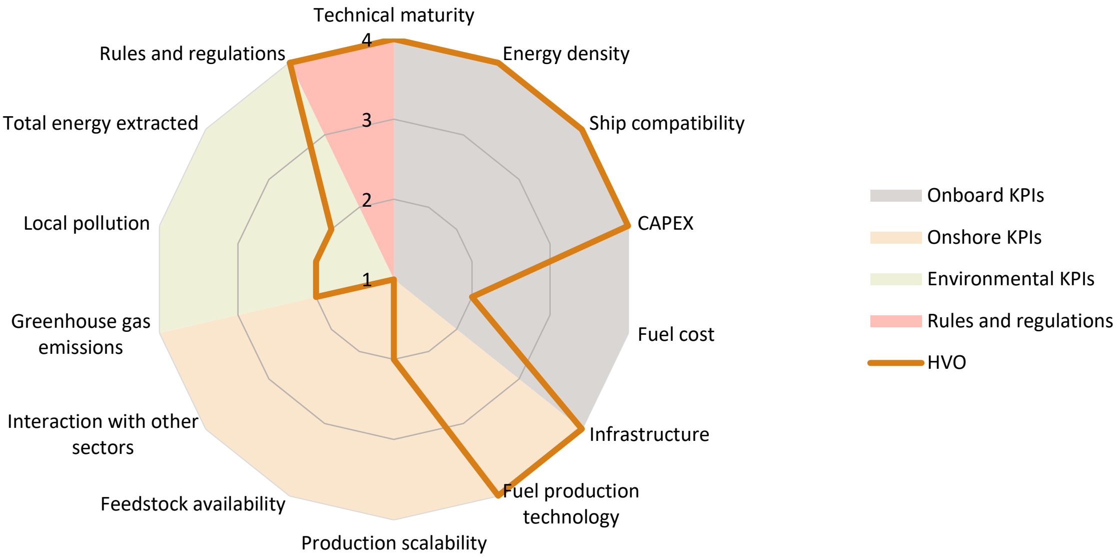
Because methanol is one of the top five chemical commodities being shipped around the world annually, the safety and regulatory framework regarding how to safely transport and handle methanol has been developed through several years. Additionally, methanol has to some extent been used as a marine fuel since 2015, and the experiences gained are crucial to uncover further challenges related to the usage of methanol as fuel. Main rules and regulations that govern use of methanol as marine fuel are adopted by IMO's "Interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel". In addition, class societies have adopted class rules related to methanol being used as marine fuel.

Methanol has been used safely as a fuel for maritime applications for some years, and guidelines and regulations for use were developed, but experience with using methanol as marine fuel is limited. For this reason, methanol is scored 3 in terms of maturity of rules and regulations.

4.5 HVO

HVO is frequently used as a fuel today. It has the highest energy density of all the fuels covered by this analysis and can, from a technical perspective, cover all the current traffic in the Nordics. Transportation and bunkering can be done using the existing onshore infrastructure and the fuel is highly compatible with current engine systems. Even though fuel costs are high, HVO is therefore deemed very mature technically and commercially both onshore and onboard. The main challenge with HVO compared to the other fuels assessed in this analysis is related to feedstock availability. Emissions from biobased fuels depend on feedstock used in fuel production. A limited sustainable feedstock availability makes it harder to scale production without competing for renewable energy sources with other sectors. On the other hand, given that HVO is highly compatible with current vessels, it is a preferred option as a drop-in fuel today, and can play an important role as a transitory fuel going forward.

Figure 16: Scoring of onboard, onshore, environmental and safety-related KPIs for HVO fuel



4.5.1 Onboard

The following chapter focuses on onboard KPIs regarding using HVO as fuel. The table below summarizes the findings.

Table 25: Onboard KPIs and score for HVO

CATEGORY	KPI	HVO
Technical	*Technical maturity*	🟩
	Energy density	🟩
	Existing ship compatibility	🟩
Economic	*CAPEX*	🟩
	Fuel cost	🟧

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Technical maturity: HVO can be used in internal combustion engines. It can be used in existing vessels as a drop-in fuel without further modifications. Similarly onboard storage systems are suitable for using HVO with no modification needed.

For this reason, the technology to use HVO as marine fuel is the most mature compared to other sustainable zero-carbon fuels and it faces little to no barriers technologically.

Energy Density: HVO has a volumetric energy density of 33.3–35.7 MJ/L, which is closest to the energy density of conventional diesel fuel. Hence onboard storage of HVO does not require more space than that of conventional diesel and it is more space-efficient compared to all other marine fuel and energy carrier alternatives discussed in this report. *For this reason, we score HVO 4 on this KPI.*

Existing ship compatibility: Existing fuel storage systems onboard are suitable for storing and using HVO as a fuel. Similarly, existing marine engines can utilize HVO as fuel without modification (Frelle-Petersen, Howard, Poulsen, & Hansen, 2021). Since HVO can be used in existing vessels without modifications, the fuel is scored highest in terms of existing ship compatibility. *Therefore, HVO is scored 4.*

CAPEX: There are estimated little to no additional costs reported when switching to HVO, *therefore this KPI receives the highest possible score, 4.*

Fuel cost: Since HVO can be produced using existing oil refinery infrastructure, which with decreasing demand for fossil fuels would have been idle otherwise, capital costs of HVO production are lower than in case of other fuels discussed in the analysis. At the same time, the narrower feedstock base that can be used for fuel production compared to biomethane and biomethanol implies that the feedstock costs are likely to be higher in the case of HVO. IEA Bioenergy (2020) estimates costs of HVO at approximately $18-$30/GJ.

Due to lower feedstock availability and higher cost estimates for existing feedstock than in the case of other biofuels, HVO is scored 2. This is the lowest score among the sustainable zero-carbon fuels, the same score as e-methane and e-methanol, as fuel price constitutes a major economic barrier for using HVO as marine fuel.

4.5.2 Onshore

This section describes the onshore KPIs for hydrotreated vegetable oil (HVO) fuel. The table below illustrates the scores given to each of the onshore KPIs for the use of methanol as a marine fuel.

Table 26: Onshore KPIs and score for HVO

CATEGORY	KPI	HVO
Technical	*Infrastructure (Storage, bunkering & transportation)*	🟩
	Fuel production technology	🟩
	Production scalability	🟧
Fuel scalability & interaction	*Feedstock availability*	🟥
	Interaction with other sectors	🟥

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Infrastructure (storage, bunkering & transport): HVO is a high-quality fuel in which the oxygen has been removed using hydrogen, which results in long-term stability. The fuel has characteristics that make it suitable as a drop-in fuel, substituting fossil-based fuels. The suitability as drop-in fuel makes HVO relatively compatible in existing infrastructure and engine systems, subject to approval by the manufacturer. While much of the existing infrastructure can be utilized, minor modifications may in some cases be required (Aatola, Larmi, Sarjovaara, & Mikkonen, 2008). Bunkering procedures are similar to regular diesel, and we do not find any significant barriers when going from regular diesel fuel oil to HVO. Another important consideration is that HVO has approximately 7 percent lower density than other fossil-based diesel fuels (Weber & Amundsen, 2016). This implies that a higher storage volume is required for the same level of output. However, we do not find this to be a significant barrier for the use of HVO in current storage infrastructure.

HVO fuel can be stored for periods up to 10 years, making it ideal for purposes where long-term storage is required, especially for applications such as backup generators. By the hydrogenation process, oxygen is removed from the fuel, which significantly reduces the risk of degradation or oxidation. Unlike earlier biofuels, HVO does not absorb water, and thus does not provide an environment where microbes can thrive. These advantages reduce the need for regular testing and maintenance programs to remove water from the fuel (TUFFA Tanks, 2021).

HVO is primarily transported using trucks, rail and barge. Additionally, ships are used to transport large amounts of HVO between continents, and pipelines are being explored as a more efficient means of transporting fuel across land to major markets.

HVO's characteristics make it ideal as a drop-in fuel and the similarity with conventional fuels calls for few to no infrastructural changes with regard to storage systems, bunkering and transport facilities. Hence, scoring HVO to 4, the highest score possible.

Fuel production technology: HVO production is limited to the use of vegetable oils and animal fats using hydrogen and catalysts at high pressures and temperatures (hydrogenation). HVO production can take place in existing fossil fuel refineries after some minor adjustments (ETIP Bioenergy, 2020). However, hydrogen is used to remove the oxygen from the triglyceride (vegetable oil) and integration to an existing oil refinery is therefore preferred over small plants (Aatola, Larmi, Sarjovaara, & Mikkonen, 2008). The refining process allows one to adjust the properties of the fuel under cold conditions. The production of hydrogen used in the HVO production process can be viewed in the assessment of hydrogen as fuel.

A central step in the production of HVO is the hydrotreatment process. Hydrotreatment is the reaction of organic compounds in the presence of high-pressure hydrogen to remove oxygen along with other heteroatoms[80]. The hydrotreatment process is considered one of the most mature technologies found in the refining industry[81]. The current production technologies for producing HVO are considered to have reached high maturity. However, the production techniques only consider production from selected feedstocks. Production of HVO from other feedstocks is not mature.

HVO's ability to exploit existing production infrastructure makes it a good alternative compared to traditional fuels. There are also few challenges regarding the refining process of HVO, while one of them being chlorine buildup during the hydrogenation process. However, the production process reaches high maturity. We therefore score the production technology of HVO to 4.

Production scalability: HVO is currently produced in large refineries at large scale. This is due to the high investment costs for the changes that are necessary to utilize some existing facilities to accommodate HVO's properties. The investment costs associated with HVO are far higher than for biodiesel production, which implies

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[80] *https://www.sciencedirect.com/topics/chemical-engineering/hydrotreating, retrieved 17.08.2022*
[81] *http://hassanelbanhawi.com/processes/hydrotreating-process/, retrieved 17.08.2022*

that large-scale production is needed to make production economically viable. One key advantage of HVO is that it can be produced in stand-alone production facilities, or in integrated plants together with fossil fuels[82]. These factors imply that small-scale production will not be economically viable. The reliance on bio-based-feedstock makes the fuel's scalability highly reliant on the access of feedstock, which in itself is challenging to scale.

The scalability of HVO is highly dependent on large-scale production facilities, and does not open for local production. This reduces the small-scale incremental increase in production that could be made from increased demand and brings large investment risks. Additionally, the use and accessibility of bio-based feedstock makes small-scale production of HVO more challenging than that of non-bio-based fuels, hence we score the scalability of HVO to 2.

Feedstock availability: Several kinds of vegetable oils and fats can be used in the production of HVO, e.g. rapeseed, soybean and corn oil, and tall oil. Additionally, animal fats can be utilized as feedstock for HVO production. Since the feedstock used in production of HVO is limited to only a handful of materials, some countries make up the majority of total annual production, e.g. China and Indonesia being the largest vegetable oil producers[83], and Canada being the largest rapeseed producer as of 2019[84].

As with other fuels based on renewable biomaterials as production feedstock, increased production due to growing demand implies imbalance in the supply and demand.

The feedstock used in HVO production suffers the same challenges as other bio-based fuels, implying the use of biomaterial in production of HVO, hence, scoring the feedstock availability of HVO to 1, lowest among the fuels.

Interaction with other sectors: HVO is a drop-in alternative to regular diesel. Almost all engines running on regular "white" or "red" diesel can run on HVO. Because HVO fuel can be used as drop-in replacement for diesel, its benefits can be experienced by almost every industry. The primary advantages are to all sectors that use diesel, from construction to haulage, distribution, aviation, and retail. The fuel can be used by industrial trucks and tankers, as well as boats and other similar vessels. HVO fuel has been approved by many original equipment manufacturers (OEMs) and engine manufacturers (HVO Fuel UK, u.d.). However, large upscaling in production caused by increased demand from the maritime sector will cause extensive deforestation, which has the potential to cause a substantial negative environmental impact (Vijay, L. Pimm, N. Jenkins, & J. Smith, 2016).

While HVO in many cases can replace today's use of regular diesel, the transition will call for large upscaling of production, seizing areas used for food production and other agricultural goods. Extensive use increases the risk of shortages in other sectors, and food shortages in some regions. Hence, scoring HVOs interaction with other sectors to the lowest in this assessment, to 1.

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[82] https://f3centre.se/en/fact-sheets/hefa-hvo-hydroprocessed-esters-and-fatty-acids/, *retrieved 17.08.2022*

[83] https://www.reuters.com/business/energy/global-edible-oil-markets-simmer-after-shock-indonesia-ban-2022-04-22/ , *retrieved 17.08.2022*

[84] https://www.sciencedirect.com/science/article/pii/B9780081005965000263, *retrieved 17.08.2022*

4.5.3 Environment

In this part we look at the KPIs related to the environmental challenges. This includes greenhouse gas emissions, both from a well-to-tank and tank-to-wake perspective, local pollution and overall energy efficiency.

Table 27: Environmental KPIs and score for HVO

CATEGORY	KPI	HVO
Environment	*Greenhouse gas emissions*	🟧
	Local pollution	🟧
	Overall energy efficiency	🟧

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Greenhouse gas emissions: HVO, like methane and methanol, contains carbon which is released to atmosphere in combustion. However, as in the case of the two other biofuels discussed earlier, carbon is captured by plants that are used as feedstock for fuel production.

Well-to-tank: HVO can be produced from oil crops or waste and residues. The source of the feedstock is the main determinant of the emissions intensity. According to the EU Renewable Energy Directive, in case of waste and residues none of the impact from upstream processes is allocated to the feedstock.[85,86]

If feedstock is produced from other sources than waste, e.g. oil crops, upstream agricultural emissions including land use change need to be considered in emissions estimates, which significantly increases total emissions. Existing studies show that well-to-tank HVO emissions when oil crops are used as feedstock can be as high as 240 g CO_2e/kWh for rapeseed and 160 g CO_2e/kWh for palm oil (Arvidsson, Persson, Fröling, & Svanström, 2011). Other studies (Bonomi, Klein, Chagas, & Dias Souza, 2018) suggest emission values in the range of 100 g CO_2e/kWh to 400 g CO_2e/kWh depending on the assumptions and to a lesser extent the type of feedstock. Emissions can be lowered substantially if renewable energy is used in HVO production and transportation (including transportation of feedstock for HVO production).[87]

Tank-to-wake: Combustion of HVO leads to CO_2 emissions, but since carbon is captured by plants that are used as feedstock, those emissions are neutral from a life-cycle perspective.

The determinants of the HVO score are limited availability of low emissions feedstock, high emissions intensity of HVO produced through oil crops and high demand from other sectors that are likely to put pressure on the use of high emission feedstock. Therefore, score 2 is awarded to that fuel, lowest of all fuels included in the analysis. It

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[85] *This group includes palm fatty acid distillates (PFAD), tall oil, slaughterhouse waste and used cooking oil (UCO).*

[86] *An alternative, methodologically justified approach is to assign emissions to residues proportionally to their share in total revenues from the production process* (Källmén, Andersson, & Rydberg, 2019). *The use of this approach would increase emission estimates related to HVO production.*

must be noted, however, that part of the future HVO production would be based on low emissions feedstock and would thus have low life-cycle emissions.

Local pollution: According to laboratory tests, using HVO leads to a 10-15 percent reduction in nitrogen oxides (NOx) emissions, 30 percent reduction in particulate matter and 50 percent reduction in total unburned hydrocarbons relative to traditional maritime fuels (Ushakov & Lefebvre, 2019). Furthermore, chemically hydrotreated vegetable oils (HVOs) are free of sulfur (Aatola, Larmi, Sarjovaara, & Mikkonen, 2008).

Local pollution levels associated with HVO are higher than for any other fuel included in the analysis, but lower than that of currently used maritime fuels, thus score 2 is awarded.

Overall energy efficiency: Overall energy efficiency with the use of HVO varies significantly depending on the feedstock source. Production of biofuels from oil crops requires approximately 1.1 units of energy per unit of fuel energy. This number however does not consider other resources such as arable land, which if used to generate energy in a more efficient way, e.g., using photovoltaics, would produce significantly more energy than through biofuels. For HVO produced from tall oil and used cooking oil, energy requirements are as low as 0.2-0.4 (Edwards, Larivé, & Beziat, 2011). Thus, given 40 percent engine efficiency, the energy efficiency of HVO stands between 0.5–2.75 units of primary energy per unit of propulsion.

Overall energy efficiency depends on the source of energy. If HVO is produced from waste, this fuel choice leads to relatively high overall energy efficiency. For HVO produced from crops the overall energy efficiency is low, especially when accounting for alternative land use. Thus, the overall score is 2, at the same level as carbon-based e-fuels.

4.5.4 Maritime rules and regulations

Table 28: Rules and regulations KPIs and score for HVO

CATEGORY	KPI	HVO
Rules and regulations	*Maturity of maritime rules and regulations*	⬢

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Maturity of rules and regulations: Pure hydrotreated vegetable oil is odorless, non-toxic and biodegradable. Therefore, leaks and spills of HVO have a considerably less detrimental impact on the environment than conventional diesel or kerosene fuels. The flash point of HVO is also higher than that of conventional diesel, which significantly decreases the risk of fire hazards (TUFFA Tanks, 2021).

There are several safety-related specifications for the use of paraffinic fuels in existence, which governs next generation fuels. HVO's similarities with traditional fossil-based diesel fuels make the current regulatory framework of safe handling and precautions transferable to marine applications, e.g., standard industry fire safety protocols and practices apply[88].

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[88] *https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=832943, retrieved 23.08.2022*

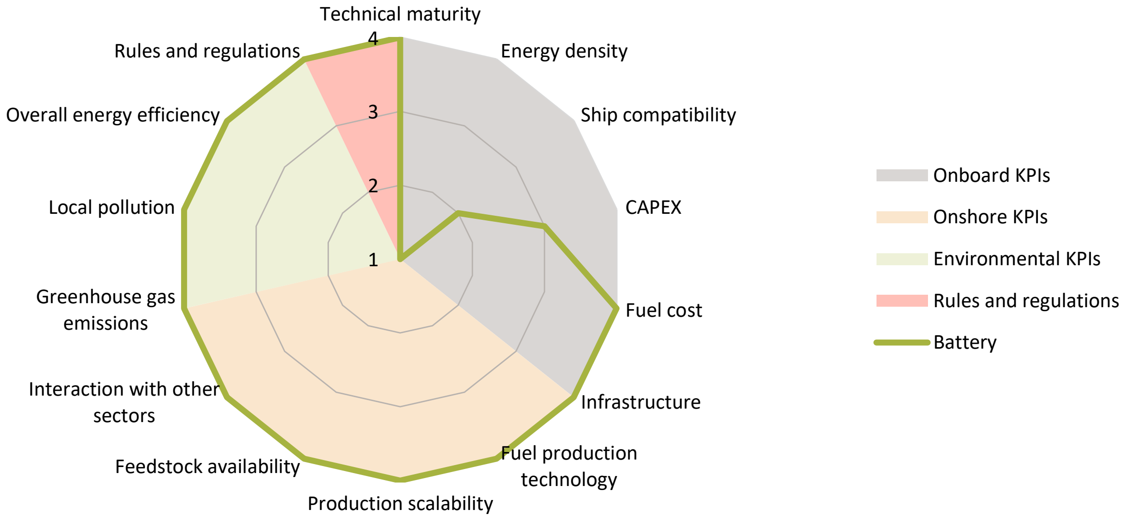
HVO's health and environmental properties have been subject to a thorough testing program in order to comply with the EU REACH regulation. HVO as such is biodegradable according to OECD test guideline 301 B. Under the EU and globally harmonized hazard classification system, HVO as such is not classified as hazardous for any other endpoint than aspiration hazard. Aspiration hazard is characteristic for all low viscosity hydrocarbons, both fossil and renewable. Odor from HVO is very weak and of paraffinic nature without any typical odor of diesel fuel. There are well known practices for handling of and safety precautions for diesel fuels. When HVO is blended into diesel fuel, well known practices used for diesel fuel apply as such for the blend (Engman, et al., 2014).

The reusability of existing regulatory framework and implementation of HVO in existing standards of use for paraffinic fuels implies a high level of safety measures for HVO fuel in marine applications, *hence, scoring the maturity to 4.*

4.6 Battery electric propulsion

There already are a number of battery-electric vessels today, especially within the ferry segment. It is a relatively mature market compared to the other sustainable zero-carbon fuels with relatively low fuel costs. In addition, the infrastructure is well established with few barriers for expanding the bunkering possibilities other than sufficient investments. The main barriers for battery electric propulsion are the low energy density and compatibility with existing ship engines. The project's feasibility study shows a potential share of 7 percent of the current domestic traffic and 3 percent of the intra Nordic traffic respectively. Still for certain segments battery-electric propulsion will be vital, it scores highly both with regards to environmental, technical, and commercial KPIs. Hybrid solutions, although not a focus of this report, also enable short-term emission reductions in the near term.

Figure 17: Scoring of onboard, onshore, environmental and safety-related KPIs for battery electric propulsion



Hybrid plug-in vessels are outside the scope of this report, as their contribution to emission reduction is completely dependent on the share of battery propulsion in their total sailing. However, hybrid solutions are expected to be a crucial part of reducing emissions, especially in the process of transitioning to the other zero fuel alternatives.

4.6.1 Onboard

In this chapter we focus on using battery electric propulsion systems and storing batteries onboard.

Table 29: Onboard KPIs and score for battery electric propulsion

CATEGORY	KPI	BATTERY ELECTRIC PROULSION
Technical	*Technical maturity*	🟩
	Energy density	🟥
	Existing ship compatibility	🟧
Economic	*CAPEX*	🟩
	Fuel cost	🟩

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Technical maturity: Battery electric propulsion systems are considered to be technically fully mature. Electric engines, batteries and battery management systems have been fully operational and used at scale the last several years, especially within the ferry segment (Clarksons Research, 2022). In addition, there is constant development in battery technologies which will be beneficial for the maritime sector in the upcoming years. *Since battery electric propulsion systems are technically mature, they face little to no technical barriers and are given the highest score 4.*

Energy density: An NMC battery cell has a volumetric energy density of 0.5 MJ/l. This is the lowest energy density across the sustainable zero-carbon fuels we have looked at in this report, which translates into lower applicability of battery propulsion systems for different sailing patterns. *This constitutes a severe economic and technical barrier for adoption of battery electric systems. Therefore, battery electric propulsion is scored the lowest in terms of energy density, a score of 1, amongst all other alternative zero carbon fuels.*

Existing ship compatibility: Batteries can be added to almost any type of ship fairly easily, which makes it possible to convert vessels with conventional propulsion systems to hybrid plug-in ships. For this reason, existing compatibility of ships with batteries can be seen as fairly easy. On the other hand, this kind of battery application is left out of the scope of this report, hence we focus solely on fully electric battery propulsion systems. A fully electric vessel will need an electric engine. While this is compatible with some vessels that are in use today, it will require installation of new engines for most of today's fleet. For this reason, *battery electric propulsion is scored 2 as compatibility is seen as a major technical barrier to achieving 100 percent battery electric propulsion.*

CAPEX: The lifetime of batteries depends on the duty cycle for which they are used, relatively to the size of the battery. Smaller batteries will have reduced CAPEX but will not last as long as larger batteries in a given application. Sizing is thus a key aspect of battery system procurement. Beyond the storage system purchase price, the total system integration costs include installation at yard, FMEA, switchboard modification, commissioning, and testing (DNV, 2019a). As batteries and fully electrical marine engines are technically mature and production of these is becoming more efficient, the low energy density of battery cells is a factor that causes batteries to perform lower when it comes to CAPEX. *For this reason, CAPEX is seen as a moderate barrier for batteries and is scored to 3. This is the same level as ammonia and methanol, and higher than hydrogen.*

Fuel cost: Fuel costs of battery-electric propulsion are fully driven by the grid electricity costs. In contrast to other fuels, which can be traded across regions, there is substantial regional variation in electricity prices. This is, however, set to decrease, with increasing integration between national grids within the EEA. For technical reasons, this integration does not apply to island nations. Despite a significant increase in electricity prices in the aftermath of the Russian invasion of Ukraine, costs of electricity in the long run are likely to be determined by the levelized cost of electricity, which is likely to be around $10-15/GJ (Stattnett, 2021) in 2050.

Even though the costs per unit of energy are higher than for some other fuels that can be produced in regions were electricity is cheapest, significantly higher energy efficiency of battery-electric propulsion implies that fuel costs are likely to be the lowest of all assessed fuels, thus score 4 is awarded.

4.6.2 Onshore

This section describes the onshore KPIs for battery electric propulsion systems. The table below illustrates the scores given to each of the onshore KPIs for the use of electricity in marine applications.

Table 30: Onshore KPIs and score for battery electric propulsion

CATEGORY	KPI	BATTERY ELECTRIC PROPULSION
Technical	*Infrastructure (Storage, bunkering & transportation)*	⬢
	Fuel production technology	⬢
	Production scalability	⬢
Fuel scalability & interaction	*Feedstock availability*	⬢
	Interaction with other sectors	⬢

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Infrastructure (storage, bunkering & transport): For fully electric systems to be a viable solution for maritime applications, increased power supply at the harbor is needed. Currently, several ports are being built with shore power, reducing the need for onboard generators to maintain operation of crucial systems, which reduces emissions from ships when they are at quay. While this solution requires large amounts of power, power for the charging of fully electric vessels will require high-voltage systems, which are not yet in place. Additionally, charging of vessels requires more time than conventional fuel bunkering, meaning ships will stay longer at quay. By staying longer at quay, the turnover rate at the harbor will be reduced, which may cause bottlenecks at some ports (Horton, et al., 2022). However, we do not find evidence for this to be a significant challenge in the Nordic setting.

systems for high voltage charging of electric vessels are currently being developed and are expected to be ramped up in parallel with the implementation of new electric vessels, and several challenges related to charging of moving ships (due to waves at quay) are being tackled with technologies such as induction charging[89].

When considering transportation to harbors, we do not consider battery transport to be relevant. However, the transportation of renewable electricity to the harbors will be vital for fully electric vessels to operate at a given port.

In the Nordic setting, we do not consider access to renewable electricity in harbors to be a significant barrier in the years to come, hence, scoring 4.

Fuel production technology: The production technologies used to produce renewable electricity span a wide range of alternatives, such as wind, solar and water (hydro and tidal). The steady development of technologies for renewable energy is constantly reducing its cost of operation, making power sources such as wind and solar highly cost-effective compared to traditional production methods, such as the burning of coal. Additionally, installation of traditional coal-based power generation plants takes a significantly longer time than that of an onshore wind farm (IRENA, 2020b).

The production of electricity has reached a high maturity level over the last decades, also making renewable energy cost-competitive with traditional power generation techniques. Hence, scoring the production technology of renewable electricity to 4, similarly as for HVO, as the techniques are considered to be of high maturity.

Production/bunkering scalability: While traditional coal power generation plants require large facilities, renewable electricity allows small-scale production in local environments, given the right conditions such as access to wind or water. Electricity generation can then be scaled incrementally and connected to the existing grid. Furthermore, batteries as an energy carrier are currently being produced at large scale all over the world, being in demand by several sectors. The wide variety of usages from household electronics to large batteries for cars and marine applications makes batteries highly applicable for several energy demanding applications.

Due to the large potential of small-scale production of renewable electricity with cost-effective incremental increases and increasingly cost-effective battery production techniques, we score the scalability of electricity and batteries to 4, only matched by green hydrogen in this assessment.

Feedstock availability: In contrast to other fuels, the feedstock needed to execute fully electric voyages consists of both materials used in the batteries themselves, and renewable electricity from the grid.

Current battery production uses materials like graphite, cobalt, lithium, manganese, nickel and to some extent recycled lithium-ion batteries. As electric vessels become more widespread, the demand for special raw materials for the vessels and, in particular, for the batteries will continue to grow in size (Backhaus, 2021). Due to the wide range of materials used in the production, some of the materials will be more readily available than others, causing bottlenecks in production. The production of raw materials used in batteries are being manufactured globally, and there are currently no significant indications of shortages in the near future from increased production, hence, scoring 4 in our assessment (Vranken, 2020).

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[89] *https://www.theexplorer.no/solutions/autonomous-charging-system-for-electric-and-hybrid-ferries/, retrieved 17.08.2022*

Additionally, an increase in fully electric vessels will increase the demand for high voltage charging infrastructure in certain ports. While this is technically feasible, the production of renewable energy must be scaled up. Our expert assessment considers the scaling of renewable energy production to be highly feasible and this is not considered a barrier in the Nordic region. However, as for other fuels depending on electricity as a feedstock, vast investments will be needed.

Interaction with other sectors: Batteries are produced worldwide, with most being produced in China (Placek, 2022). The many applications for batteries make them highly usable for several sectors. The demand for lithium-ion batteries is rising rapidly and is set to increase dramatically compared to 2020-levels in the coming years. Increased use of battery technology in other sectors will increase the technological developments across different sectors. Shared technological development across sectors also has the potential to facilitate shared infrastructural needs across the different sectors. It is expected that European countries will conquer a larger portion of the total market share of battery production in the years to come, and the increase in production is also set to meet increased market demand from the EV market and other markets that are increasing in attractivity, such as the maritime industry.

Additionally, the extensive use of renewable electricity in the transition to a carbon neutral society plays an important role in all energy intensive sectors, which will see exponential increases in demand in several sectors in the years to come.

Renewable energy will be highly relevant in each sector's path to becoming carbon neutral. Similarly as for production of all non-bio-based fuels in this assessment, we score the interaction with other sectors of batteries and renewable electricity to 4.

4.6.3 Environment

In this part we describe the environment KPIs related to battery-electric propulsion as a marine fuel.

Table 31: Environment KPIs and score for battery electric propulsion

CATEGORY	KPI	BATTERY ELECTRIC PROPULSION
Environment	*Greenhouse gas emissions*	⬢
	Local pollution	⬢
	Overall energy efficiency	⬢

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

GHG emission: Fully electric propulsion does not produce any tank-to-wake emissions while well-to-tank emissions are driven by the emissions intensity of electricity in the electric grid and upstream emissions.

Well-to-tank: Emissions intensity of electricity in the grid varies from country to country in the region, with Denmark and Finland producing electricity with a carbon footprint of 109 g CO_2e/kWh and 69 g CO_2e/kWh respectively, compared to 9 g CO_2e/kWh in Sweden[90] in 2020, 0 g CO_2e/kWh in Iceland and 18 g CO_2e/kWh in Norway.[91]

Upstream emissions related to electricity generation and transmission are also to be accounted for, but given significantly higher energy efficiency of electric propulsion compared to electro-fuels (by factor 3 to 6 depending on fuel), associated emissions are lower than in the case of most fuels included in the analysis. Furthermore, battery-electric propulsion requires batteries, a significant source of emissions. Studies suggest that life-cycle emissions from battery production can reach up 200 kg CO_2 per kWh of energy storage capacity (Ellingsen, et al., 2014). Those upstream emissions can be significantly reduced if renewable energy is used throughout the entire production cycle.

<u>Tank-to-wake:</u> Electric propulsion does not generate tank-to-wake emissions.

Overall, the battery electric propulsion in regions with close to zero emissions energy in the grid gives the lowest emissions of all fuels considered, thus score 4 is awarded.

Local emissions: Electric propulsion does not generate local emissions and generates significantly lower noise levels than internal combustion engines, thus, *the highest possible score 4 is awarded*.

Overall energy efficiency: Renewable energy provided through the grid to charge batteries onboard a ship gives the lowest energy consumption per unit of propulsion energy. Energy losses associated with energy transmission, battery charging, and discharging are estimated at around 50 percent, thus only 1.5kWh of primary energy is required per 1 kWh of propulsion (Lindstad, Lagemann, Rialland, Gamlem, & Valland, 2021). This is significantly higher than for any other propulsion system, thus, *the highest possible score 4 is awarded*.

4.6.4 Maritime rules and regulations

Table 32: Rules and regulations KPIs and score for battery electric propulsion

CATEGORY	KPI	HVO
Rules and regulations	*Maturity of maritime rules and regulations*	⬢

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Maturity of rules and regulations: Battery electric vessels use high-capacity batteries for storage of electric power for propulsion. Battery electric vessels are different from ships using traditional fuels, as the onboard and onshore systems do not have as many similarities as other fuels. This implies principal differences in both storage and bunkering. These differences imply a higher level of regulatory differences between onshore and onboard use.

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[90] *https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-9/#tab-googlechartid_googlechartid_googlechartid_chart_1111, retrieved 17.08.2022*

[91] *https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-3/assessment#:~:text=Inpercent20nonpercent2DEUpercent20EEApercent20countries,epercent2FkWhpercent20inpercent20Norway, retrieved 17.08.2022. Data for Iceland and Norway for 2018*

One of the main concerns with regard to using batteries on ships (lithium-ion batteries) is the risk of thermal runaway, which is caused by an exothermic reaction when a battery is damaged or subjected to immense heat. This causes fires in the batteries that are challenging to extinguish. However, several regulatory frameworks have been developed to ensure safe and reliable use of onboard battery systems. The regulations cover several aspects which stretch from ship design and placement of equipment to gas detection systems and practices in case of emergencies.

Safety regulations related to maintenance and operation of electrical installations are laid down by the Norwegian Directorate for Civil Protection, 28th of April 2006. The guidelines provide detailed information and framework based on well-established international standards. One of the aims of the regulations is to work towards common requirements throughout the EEA-region. The aim is that all member countries implement common methods for establishing safety measures, which will contribute to reducing the risk of unwanted incidents (Norwegian Directorate for Civil Protection, 2013).

Onshore access to renewable and high-voltage electricity is key to ensure rapid charging of incoming vessels. By having renewable energy readily available at the port, electric vessels can be charged without the need for personnel being in direct contact with the systems. Technologies are evolving, reducing the need for personnel involved in the charging connection process, reducing the risks of accidents.

The current safety regulations regarding handling of high voltage systems are well established in several sectors. However, charging of ships will require extra attention with regard to smaller movement in the ship at quay. Ships move due to waves and/or wind and will therefore require solutions that have some degree of freedom to move with the vessel. There are several projects working on wireless charging and solutions without the need to involve personnel, implying safer operation (Thorburn, Stefan, 2020).

Onshore charging of electric ships is constantly evolving, and new systems are proven to work without the need for harbor personnel being involved, implying safe operations. Additionally, the regulatory framework on handling of high-voltage systems has been developed over several years, implying a high level of maturity, *hence we score onshore battery-electric systems to 4.*

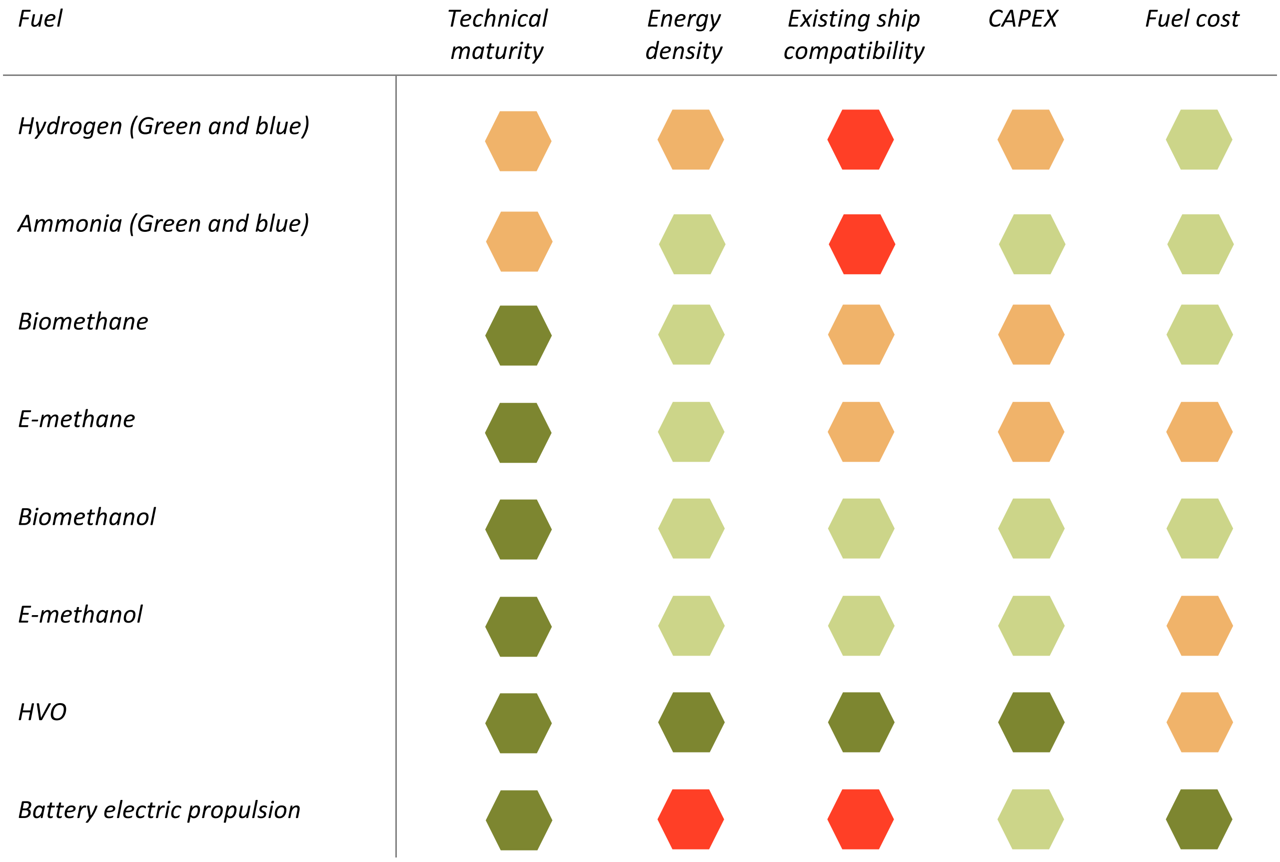
5. Comparative analysis – assessment on each KPI

In the previous chapter we presented our fuel-by-fuel assessment. In this chapter, we summarize our findings in a comparative framework for each KPI based on the previous scoring. The comparative analysis highlights how the fuels score compared to each other and makes it easier to find the fuels that are most suited for country- or region-specific barriers in the Nordics. The comparative analysis is presented based on the four main KPI categories to give a systematic overview of the most important differences.

5.1 Onboard barriers

In this part we have summed up the results from the previous chapters and made a table showing the scores for the onboard KPIs for the different fuels. This table provides a comparative analysis of the scoring.

Table 33: Comparative analysis of the onboard KPIs for the different sustainable zero-carbon fuels



Fuel	*Technical maturity*	*Energy density*	*Existing ship compatibility*	*CAPEX*	*Fuel cost*
Hydrogen (Green and blue)	🟧	🟧	🟥	🟧	🟨
Ammonia (Green and blue)	🟧	🟨	🟥	🟨	🟨
Biomethane	🟩	🟨	🟧	🟧	🟨
E-methane	🟩	🟨	🟧	🟧	🟧
Biomethanol	🟩	🟨	🟨	🟨	🟨
E-methanol	🟩	🟨	🟨	🟨	🟧
HVO	🟩	🟩	🟩	🟩	🟧
Battery electric propulsion	🟩	🟥	🟥	🟨	🟩

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Technical maturity: In terms of the KPI technical maturity onboard, methane, methanol, HVO and battery electric propulsion rate highest among the zero-carbon fuels. Methane, methanol and battery electric propulsion systems are already in use at full scale on merchant vessels. HVO is already used as a drop-in fuel and is compatible with existing propulsion systems for diesel, indicating a high maturity level as well. For hydrogen and ammonia on the other hand technical maturity is still seen as a major barrier. While there are pilots and demonstrations of hydrogen fuel cell ships, these are at very early stages and experience with hydrogen is still limited. Similarly, ammonia engines are under development. Although there is experience with shipping ammonia and onboard storage, the fact that there is no ammonia engine on the market today brings ammonia's score down to 2.

Energy density: As shown in the table, the volumetric energy densities of batteries and hydrogen in its gas form are lowest among the sustainable zero-carbon fuels. As this creates a severe economic and technical barrier for adopting battery electric systems. Even though hydrogen in its gas form has very low volumetric energy density, it can increase significantly once it is compressed or liquified so that it gets close to the level of the energy density of ammonia. For this reason, hydrogen has the potential to cover a significant share of Nordic ship traffic, hence it is scored as 2. Ammonia has a higher energy density than liquid hydrogen, and therefore gets a score of 3. The same goes for methanol and methane. Methane has a higher energy density than both ammonia and methane, but this is not seen as a major barrier for using ammonia as fuel. The highest score is given to HVO, which has an energy density of 33-35 MJ/l. This is highest among the sustainable zero-carbon fuels that we have discussed in this report, and closest to the energy density of conventional diesel with little to no barriers in terms of using it as fuel.

Existing ship compatibility: When it comes to existing ship compatibility, HVO scores highest among sustainable zero-carbon fuels, as it can be used as drop-in fuel without needing further modifications. This quality makes HVO an important transitional fuel even though it scores lower on environmental KPIs due to limited feedstock availability. Methanol is also rated relatively highly in this KPI. Methanol requires installation of new engines, but smaller modifications in terms of fuel storage onboard, which creates a relatively moderate barrier for using it as fuel. Methane rates lower due to the need for new engines and storage systems, as methane needs to be compressed or liquified for efficient onboard storage. This is a factor that creates barriers in terms of using methane as marine fuel. However, today's vessels that operate on LNG will be able to use biomethane and e-methane without requiring modifications, as LNG primarily consists of methane. This separates methane from ammonia, hydrogen and battery electric propulsion which are ranked lowest as transitional fuels. Both ammonia and hydrogen require installation of new engines and fuel storage systems, as well as additional safety measures to tackle the risks related to these fuels, i.e. flammability and explosiveness with hydrogen and toxicity with ammonia. For this reason, their compatibility with existing vessels is considered very low. Similarly, battery electric propulsion requires the installation of a new engine most of the cases, and compatibility with existing vessels is low.

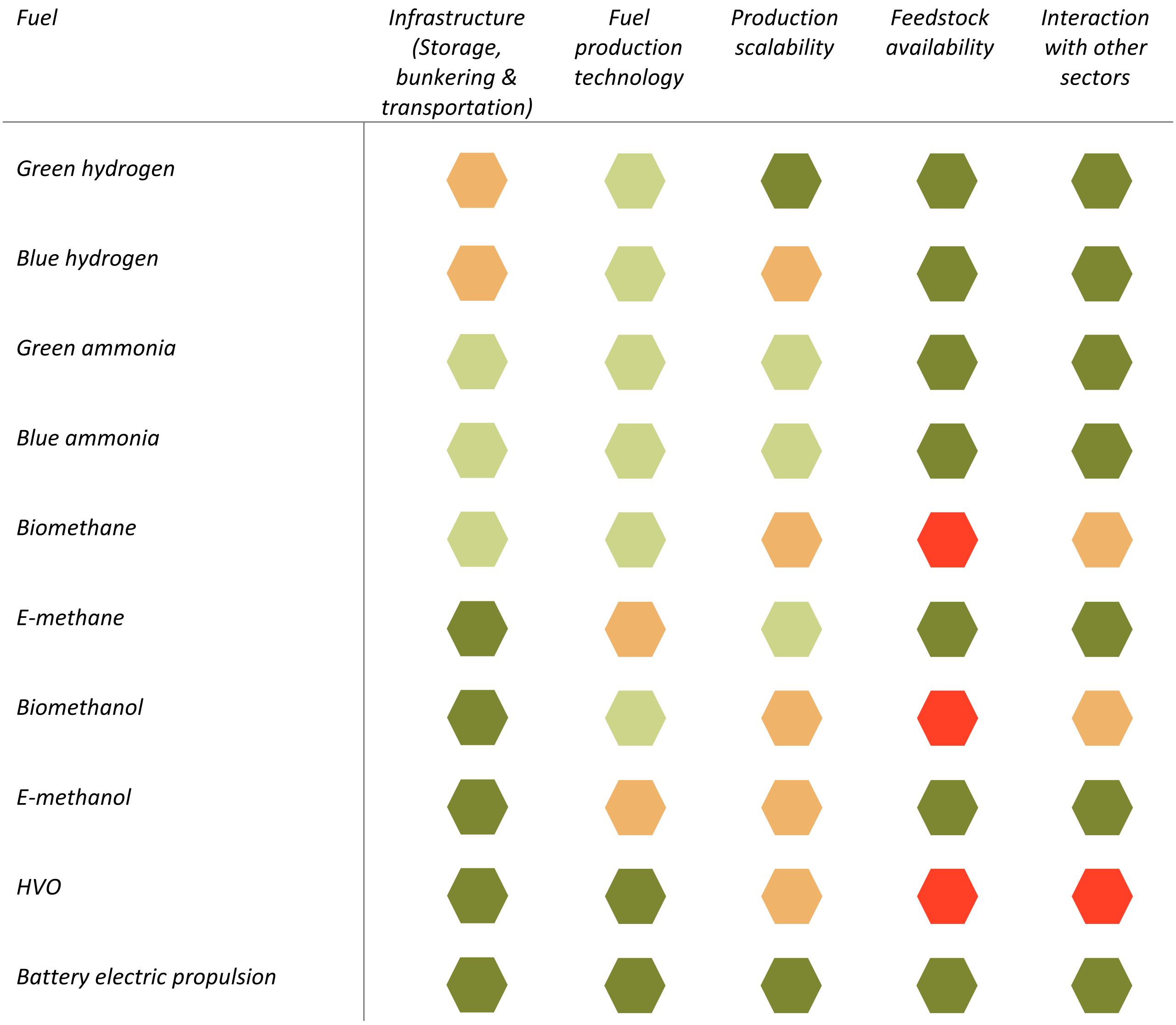
CAPEX: As seen in the table above, hydrogen and methane score the lowest on the CAPEX KPI, meaning that the cost of installing new engines and propulsion systems and costs related to handling and storage of hydrogen and methane onboard are higher compared to the other fuels. HVO is already being used in existing ship engines, where the energy density is relatively close to the energy density of conventional fuels. HVO has thereby received the highest possible score, as the CAPEX cost is lower compared to the other fuels. For both ammonia and methanol, the expected CAPEX of retrofitting or building a new vessel to run on either ammonia or methanol is expected to be lower than for both hydrogen and methane, hence a higher score. Batteries are already being used in several vessels. As batteries and fully electrical marine engines are technically mature and production of these is getting more efficient, low energy density of battery cells is a factor that causes batteries to perform lower than HVO when it comes to CAPEX.

Fuel cost: All of the sustainable zero-carbon fuels are as of today more expensive than conventional fuels. Battery-electric propulsion is the only fuel that got a score of 4 on fuel cost, as the significantly higher energy efficiency of battery-electric propulsion implies that fuel costs are likely to be the lowest of all assessed fuels. The complex economic market dynamics make fuel price projections challenging, and future prices for both conventional and sustainable zero-carbon fuels remain uncertain. For fuels with immature feedstock collection, such as for HVO, price uncertainty ranges are even wider. HVO has therefore received a score of 2, which is the lowest among the sustainable zero-carbon fuels. According to a study by DNV (2019c), the estimated prices of fuels sourced from natural gas such as LNG and methanol are associated with less future uncertainty compared to renewable sourced fuels such as hydrogen, ammonia, and biofuels. The increased price uncertainty could cause difficulties in scaling up these fuels, as economic considerations may hinder investments in the short term and consequently also the long term (Foretich, Zaimes, Hawkins, & Newes, 2021).

5.2 Onshore

In this part we have summed up the results from the previous chapters and made a table showing the scores for the onshore KPIs for the different fuels. This table gives a comparative analysis of the scoring.

Table 34: Comparative analysis of the onshore KPIs for the different sustainable zero-carbon fuels



Fuel	*Infrastructure (Storage, bunkering & transportation)*	*Fuel production technology*	*Production scalability*	*Feedstock availability*	*Interaction with other sectors*
Green hydrogen	🟧	🟨	🟩	🟩	🟩
Blue hydrogen	🟧	🟨	🟧	🟩	🟩
Green ammonia	🟨	🟨	🟨	🟩	🟩
Blue ammonia	🟨	🟨	🟨	🟩	🟩
Biomethane	🟨	🟨	🟧	🟥	🟧
E-methane	🟩	🟧	🟨	🟩	🟩
Biomethanol	🟩	🟨	🟧	🟥	🟧
E-methanol	🟩	🟧	🟧	🟩	🟩
HVO	🟩	🟩	🟧	🟥	🟥
Battery electric propulsion	🟩	🟩	🟩	🟩	🟩

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Infrastructure (storage, bunkering & transportation): The three main factors affecting this score are the fuels' ability to use the existing infrastructure, and economic and technical challenges to building new infrastructure.

There is great variation between the reusability of storage, bunkering and transportation infrastructure between the different fuels. HVO scores the best of the included fuels due to its ability to be used as a drop-in fuel and replace its fossil-based counterpart with little to no need for changes to the existing infrastructure. Hydrogen, on the other side, scores the lowest (2) due to its need for special cryogenic tanks that can withstand low temperatures to maintain liquid at atmospheric pressure. While storage systems for liquid hydrogen are technologically mature, the increased spending on new infrastructure implies high capital expenditures. Ammonia has been produced and stored as a liquid for many years and can be considered to have reached high maturity. However, ammonia is not capable of utilizing existing infrastructure for storage onshore, which implies large investments will be needed to facilitate an increased uptake in the maritime sector. Facilities for bunkering must also be addressed to fit the properties of ammonia, as the potential risks of leaks are high, implying specially made bunkering facilities. As with hydrogen, ammonia must be cooled down to a liquid for efficient storage, but ammonia does not require extreme temperatures to become a fluid.

In this assessment, methane is given a score of 3 and methanol a score of 4 in our assessment. Liquified natural gas (LNG) has well established fuel supply and logistics for both storage and bunkering and since LNG mostly consists of methane, methane has the ability to exploit most of the existing infrastructure used with LNG. While methane must be cooled to below -160 degrees Celsius to become a liquid, the already existing infrastructure implies some but few barriers for methane to be used as a fuel. Similarly, methanol is transported via ships in large quantities yearly, and is available at several ports already. While methanol requires special tanks, it can exploit much of the existing infrastructure. However, it must be significantly scaled up to meet bunker fuel demand. Expanding the storage capacity of methanol features many of the same characteristics of regular fossil-based fuels and therefore poses low barriers. Finally, battery electric propulsion receives a score of 4. Charging stations require high voltage charging facilities, which in some areas may require costly changes to electricity distribution infrastructure. However, we do not consider this to be a barrier in the Nordic setting.

Most of the included fuels have established transportation methods which have reached high maturity. However, while hydrogen can be transported in several ways, in tanks on both trucks and trains, and by pipeline, the maturity of ship transportation is low. Additionally, truck or train transportation is only viable for smaller volumes of hydrogen, meaning ports could be facing shortages as supply in practice will be restricted to pipeline transportation. Pipeline transportation also restricts placing of production facilities. Ammonia is transported globally at large quantities every year, and the methods are well established. While ammonia faces some of the same challenges as hydrogen, it can be stored as a liquid under warmer conditions, implying fewer storage related implications, which enables simpler transportation methods. Transportation-related challenges can be avoided for e-methane as production can be strategically placed to accommodate the geographic location of the end user. As methanol and HVO are fluid at ambient temperature, the transportation systems can be highly simplified, especially when comparing to hydrogen and ammonia.

Fuel production technology: Fuel production technology considers the technological maturity of fuel production and the associated processes today. Additionally, we look at whether there are barriers that need to be overcome in order for production to reach maturity and which parts of production need special attention. The technological production methods vary significantly between the fuels. Additionally, there are significant differences in production technologies used to produce greener alternatives of the same fuels. The production technologies for producing hydrogen are gaining maturity. Most hydrogen today is produced from natural gas reforming, where CO_2 is released into the atmosphere. To produce blue hydrogen, the CO_2 must be captured and stored to be carbon neutral. Blue hydrogen production is currently restricted by immature CCS technology but is still gaining maturity. Green hydrogen utilizes renewable electricity and electrolyzers, which currently are expensive and inefficient.

Blue and green ammonia is mainly dependent on whether the hydrogen used in production is blue or green. Ammonia is produced by upgrading hydrogen, and blue ammonia is therefore reliant on the CCS technologies used in the hydrogen part of production. Similarly, green ammonia is dependent on the electrolyzer technologies used in green hydrogen production. The ammonia is then produced by converting the hydrogen and nitrogen via the Haber-Bosch process, which in itself is a highly mature technology. The production technology for HVO and batteries scores the highest in our assessment, with both scoring 4. HVO production technology utilizes existing refineries and exploits many of the same processes that have been used for several years in oil and gas production. Additionally, the production of electricity is highly mature and increasingly more renewable sources are becoming cost competitive with fossil fuel-based electricity production. Similarly, production of energy carriers (batteries) has come a long way and happening at large scale across the world. We consider the production maturity of both HVO and batteries to be high.

Production of e-methane and e-methanol score lowest in our assessment when considering the production technology utilized. E-methane and e-methanol's use of electrolyzer technologies for hydrogen production are currently proving to be inefficient and too expensive for fuel production. Additionally, the need for direct air capture is proving challenging for current production. The main challenge of biomethanol and biomethane production is the reliance on specific organic matter feedstocks due to gasifiers not being able to cope with a wide variety of feedstocks.Several of the included fuels are reliant on captured and stored CO_2. These technologies are currently highly ineffective and costly. CCS is currently a limiting and costly technology for fuels such as blue hydrogen.

Production scalability: Production scalability considers whether the included fuels can be produced locally, and whether incremental (smaller) increases in production are feasible. Possible implications and whether there are constraints to some fuel's scalability is also included. Only green hydrogen and renewable electricity score 4 in our assessment of their respective scalability. Green hydrogen can be produced at both small and large scale and thus allows a far more flexible production structure than other fuels. Additionally, the barriers for grid capacity scaling in the Nordics are also considered low. Blue hydrogen and ammonia's more extensive production methods make large-scale facilities far more desirable to ensure economies of scale. The production scalability of HVO is challenged by the non-transferability of technology between small- and large-scale production of the fuels, limiting production to either small- or large-scale facilities. Additionally, the current costs of expensive technologies for methanol and methane production make local/small-scale production expensive. While methanol and methane theoretically can be produced locally, this will not be economically viable at a small scale, hence production relies on large facilities.

Feedstock availability: The availability of feedstock only considers the availability of inputs/raw materials used in production and the effect usage has on other sectors. It is important to note that this KPI does not consider the technology for access of inputs, only whether they exist in larger quantities. The availability of feedstock varies significantly between the included fuels. The main difference is between the e-based and bio-based fuels, where bio-based fuels use different sources of agricultural wastes and food waste. Producing fuels from bio-based feedstock has the potential to cause food shortages in some areas, and supply challenges in other sectors reliant on waste-based feedstock. Hydrogen, ammonia, e-methane and e-methanol use inputs such as natural gas, renewable electricity, water and renewable CO_2. The availability of all these inputs is currently high. Important to note is the variation in the technological readiness of tools to exploit all resources. Important here is the ability to extract and store CO_2, which is important for production of fuels such as blue hydrogen. Supply of renewable energy is important to operate fully electric vessels, and resources such as wind, solar and hydro are highly available in the Nordic region. Additionally, the raw materials used in batteries for fully electric vessels are being produced in large quantities and are not considered scarce resources. There is no indication of scarcity in the coming years. However, there is currently not enough renewable energy produced, which might limit the interest in hydrogen and e-fuels.

Interaction with other sectors: The fuel's interaction with other sectors is defined as the applicability of the included fuels in different sectors, and what effects their use in a marine setting will have on other sectors. Most of the included fuels have high applicability in different sectors, and their usage in different sectors can stimulate further development of the fuel technology. Increased production scale is likely to lead to a reduction in prices and increase in fuel availability. However, this argumentation applies only to fuels that are not affected by limited availability of feedstock. Due to this challenge, demand for fuels such as HVO, biomethane and biomethanol from other sectors is likely to increase prices. Furthermore, fuel producers are likely to turn to more emission intensive sources of feedstock once less emission intensive sources are fully utilized.

5.3 Environment

In this part we have summed up the results from the previous chapters and made a table showing the scores for the environmental KPIs for the different fuels. This table gives a comparative analysis of the scoring.

Table 35: Comparative analysis of the environment KPIs for the different sustainable zero-carbon fuels

Fuel	*Greenhouse gas emissions*	*Local pollution*	*Overall energy efficiency*
Green hydrogen	🟩	🟩	🟨
Blue hydrogen	🟨		
Green ammonia	🟩		
Blue ammonia	🟨		
Biomethane	🟧		
E-methane	🟧		
Biomethanol	🟨		
E-methanol	🟨		
HVO	🟧		

		🟢	🟧
		🟧	🟧
Battery electric propulsion	🟩	🟩	🟩

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

Greenhouse gas emissions: The analysed fuels differ with regard to associated greenhouse gas emissions. Vessels with battery-electric propulsion generate the lowest emissions, as long as they are powered by renewable energy from the grid which is close to reality in Norway, Sweden and Iceland. In other countries, importing zero-emission fuels, such as green hydrogen or green ammonia, is likely to offer lower emissions intensity. Those two fuels together give the highest prospects for near zero emissions shipping in the longer run, once maturity of the underlying technologies is achieved. Consequently, these fuels together with battery electric propulsion get the highest score. A necessary condition for green ammonia to attain this score is elimination of N_2O emissions that occur in combustion. E-methanol faces slightly larger barriers as it requires CO_2 from a renewable source, such a direct air capture, a technology that requires some innovation, thus score 3 is awarded.

Fuels produced from fossil fuels with carbon capture and storage, such as blue-hydrogen and blue ammonia receive lower score due to emissions from natural gas extraction and imperfect carbon capture. Although significant advancements have been made to reduce these emissions, making blue fuels potentially very low emissions fuels some progress is still needed. *As a consequence, those fuels receive score 3.*

E-methane receives score 2 due to fugitive leaks in methane transportation and methane slip onboard of a ship. Even if advancements in technology allow to significantly reduce the emissions, complete elimination of these emission sources is unlikely.

Finally, biomethanol receives score 3 while biomethane and HVO receive score 2. Actual emissions depend on the feedstock used in fuel production. The broader range of feedstock suitable for production of biomethanol justifies higher score. The same feedstock based can be used also for biomethane production, however, the lower score is driven by the significant challenges posed by methane leakage in production, transportation and use on board. In both cases, however, low-emission production possibilities are limited by availability of feedstock. Increasing production beyond the limits set by availability of waste and residues requires dedicated agricultural production which significantly increases emissions both direct and indirect through land use changes.

Local Pollution: Battery electric and fuel cell propulsion does not cause any local emissions thus hydrogen, a fuel that is currently used in fuel cells, and battery electric propulsion score 4. Combustion of ammonia, methanol and methane causes some local pollution, albeit significantly lower than in the case of traditional maritime fuels. Emissions can be further reduced through the use of fuel cells suitable for those fuels. This requires, however, further technological advancements. Thus, those fuels receive score 3. HVO scores 2 as it causes significantly more local pollution than other fuels, though still below the levels of pollution from traditional maritime fuels.

Overall energy efficiency: Battery electric propulsion is significantly more energy efficient than any other energy source considered in the analysis. It provides the lowest losses in both well-to-tank and tank-to-wake stages. Therefore score 4 is awarded. E-fuels are produced from electricity at an energy loss, first through water electrolysis to produce green hydrogen and subsequently through synthesis to produce green ammonia. Hydrogen is used in highly efficient fuel cells, while use of ammonia is mainly considered in less efficient internal combustion engines. However, there is ongoing research to use ammonia also in fuel cells, which can considerably increase energy efficiency. The overall score for green hydrogen and green ammonia is thus 3. The alternative route to producing hydrogen is through methane reforming with carbon capture and storage. This process is slightly less energy intensive, but the difference of under 10 percentage points does not justify a different score. Thus score 3 is awarded also to blue hydrogen and blue ammonia.

E-methane and e-methanol are produced through synthesis of green hydrogen; however, these fuels require also carbon from direct air capture, which substantially increases the energy intensity of the production process, or capture of carbon from limited biogenic sources sources . Thus, those fuels receive score 2.

Overall energy efficiency of biomethane and biomethanol is also relatively high, thus score 3 is awarded. The overall energy efficiency of those fuels is higher than that of e-methanol and e-methane, but still significantly lower than that of battery electric propulsion. Finally, in the case of HVO, due to limited availability of low emission feedstock we consider only the energy intensive production path from oil crops, thus score 2 is awarded.

5.4 Maturity of rules and regulations

In this part we have summed up the results from the previous chapters and made a table showing the scores for the KPIs regarding maturity of rules and regulations of the included fuels. This table gives a comparative analysis of the scoring.

Table 36: Comparative analysis of the rules and regulations KPIs for the different sustainable zero-carbon fuels

Fuel	*Maturity of maritime rules and regulations*
Hydrogen (green and blue)	🟥
Ammonia (green and blue)	🟧
Methane (biomethane and e-methane)	🟩
Methanol (biomethanol and e-methanol)	🟢
HVO	🟩
Battery electric propulsion	🟩

* Scoring scale: Dark green: 4, light green: 3, orange: 2, red: 1

The table above summarizes the scores for sustainable zero-carbon fuels regarding the maturity of rules and regulations in terms of handling and use. As seen from the table, hydrogen is the fuel scoring lowest among sustainable zero-carbon fuels. Hydrogen is explosive and highly flammable, which requires safety precautions both onboard and onshore. As experience with hydrogen shipping and using hydrogen as fuel is very limited, we consider the rules and regulations for this fuel to be the least mature. Hydrogen is followed by ammonia which scores 2. There is extensive experience and knowledge accumulated over years as ammonia is a commodity shipped around the world. However, as there are no vessels that use ammonia as fuel today, there needs to be additional learning once ammonia engines are ready to be used, as onboard handling of ammonia as fuel as well as bunkering will bring about additional safety risks. Methanol is scored as 3, as it has been newly adopted as a marine fuel and although there is experience with using it, this is limited.

Methane, HVO and batteries are scored as 4 when it comes to the maturity of rules and regulations. These are to some extent used as marine fuels and propulsion systems today in some vessel types and there is experience with handling them both onshore and onboard, which has helped to increase the maturity of rules and regulations over time.

5.5 Concluding remarks – selection of fuels for further analysis

One of the objectives of this task was to select three fuels for further analysis related to the LCA analysis (1C), infrastructure analysis (2B) and safety analysis (2b). Based on the assessment above, our recommendation is that hydrogen, ammonia and methanol are to be analyzed in all three tasks. The selection of the three fuels does not mean that they have the least barriers, but that they are considered to have significant potential with regards to sustainable zero-carbon shipping in the Nordic countries, and that their barriers are especially relevant for the in-focus points of the depth analysis.

It is important to notice that while the three fuels are assessed as the *most* promising in our assessment, a broad range of fuels will be needed on the pathway to a fully decarbonized Nordic shipping industry. In the short term, HVO and biomethane could significantly reduce emissions due to high compatibility with the existing fleet. HVO could also be vital for vessels traveling over a longer range with limited cargo capacity. However, these fuels face significant barriers due to scarcity of sustainable feedstock and competition from other sectors. Our assessment also shows that methane will struggle to meet the (near) zero-carbon criterion due to fugitive leaks and methane slips which need to be solved for methane to become fully zero-carbon even in a tank-to-wake perspective**.** Battery-electric propulsion will also play its part, but its potential impact going forward is more limited as a stand-alone zero-carbon energy carrier, with ferries that sail relatively short distances on a regular basis being the most feasible option. Hybrid systems based on electricity are will also serve as important transitory option for larger vessels, but not a part of the scope of this project.

Appendix A: Description of the different fuels

Hydrogen

Hydrogen can play an important role in the maritime industry's journey towards decarbonization. Several actors in the industry recognize hydrogen's potential, but the barriers in implementing it as a marine fuel are still substantial.

The use of hydrogen as a fuel in the maritime sector is currently quite limited. There are a few small inland boats that use hydrogen as fuel[92], but as of 2022 there are on commercial vessels of scale that operate on hydrogen in the Nordic countries. Hydrogen is a vital element for many chemical processes. Almost all existing global demand for hydrogen comes from refining (around 45 %), industrial uses (around 50 %, almost entirely as a feedstock in production of methanol and ammonia) and in steel making (around 5 %) (IEA, 2021b). The use of hydrogen for other applications, such as in fuel-cell electric vehicles or direct injection into gas grids, is negligible today.

Hydrogen is an energy carrier with a high flammability range. Hydrogen can be used directly as a fuel (in compressed or liquid form[93]) in both internal combustion engines and in fuel cells[94]. It is a chemical element that at standard conditions is a gas that is colorless, odorless, tasteless, non-toxic, and highly combustible. Hydrogen has high energy content per unit of weight but low energy content per unit of volume, making transportation of hydrogen a challenge.

Hydrogen can be extracted from fossil fuels[95] and biomass, from water, or from a mix of both. In 2020 around 90Mt of hydrogen was produced globally, around 80 % of which was produced directly from fossil fuels, mostly unabated, and another 15 % as a by-product in the (fossil-based) chemical industry (IEA, 2021b). Natural gas is the most widely used fossil fuel for hydrogen production.

Ammonia

Ammonia is a commodity that is widely traded globally. In 2020, 187 Mt of ammonia was produced worldwide, whereof 85 % is used in the agriculture sector as fertilizer, either directly or after upgrading to urea. The remaining 15 % is used as refrigerant, solvents and fuel for vehicles. Ammonia is currently not used as marine fuel since the engine technology has not yet reached sufficient maturity. Although it can be used both with fuel cell and internal combustion engines, the engines that are under development focus on internal combustion technology and are expected to be ready as early as 2023[96,97].

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[92] *https://www.offshorewind.biz/2022/08/11/hydrogen-bunkering-starts-at-dutch-port-offshore-wind-vessel-first-to-fuel-up/, retrieved 17.08.2022*

[93] *Compressed hydrogen can be stored in 350 bar or 700 bar hydrogen tanks, whereas liquified hydrogen requires storage at -253 °C or lower temperature in cryogenic storage tanks.*

[94] *Explained in more detail under propulsion systems*

[95] *Currently the majority of world hydrogen production extracts hydrogen through natural gas steam reforming, while coal gasification is the second most important source (predominantly in China)*

[96] *https://www.wartsila.com/media/news/14-07-2021-wartsila-launches-major-test-programme-towards-carbon-free-solutions-with-hydrogen-and-ammonia-2953362?utm_source=organic&utm_medium=press-release&utm_term=marine-power&utm_content=press-release&utm_campaign=ammonia-project-targets-two-and-four-stroke-marine-engine-demonstrators-by-2025, retrieved 17.08.2022*

[97] *https://www.man-es.com/discover/two-stroke-ammonia-engine, retrieved 17.08.2022*

Ammonia is a compound of nitrogen and hydrogen (denoted as NH3). Under ambient conditions it is a colorless gas with a distinct odor and toxic to humans. Exposure to ammonia can cause serious health issues and it should be handled with care. It is usually cooled down to its boiling point or lower (-33 °C) and stored in liquid state. Ammonia has a volumetric energy density of 11.5 MJ/l, approximately 30 % of diesel (DNV, 2019a). As the compound does not include any carbon atoms, use of ammonia as fuel does not cause CO_2 emissions. For this reason, ammonia is one of the important zero carbon fuel alternatives.

Methane

Methane is a hydrocarbon compound denoted as CH_4 and is the primary component of natural gas. Its boiling point is at -161 °C and for this reason it is in gas state under ambient conditions. It can be transported via pipelines, liquified to its boiling point, or compressed to transport via tankers and trucks. Methane is known to have 15-20 % lower CO_2 emissions compared to other conventional fuels and is therefore a promising marine fuel even from non-renewable sources. However, it is important to note that methane in itself is a potent greenhouse gas that is 25 times more powerful in trapping heat in the atmosphere than CO_2 (1g CH_4 = 25 g CO_2eq)[98].

Although it has lower greenhouse gas emissions, methane that is used today is primarily LNG (liquified natural gas) and it is a fossil fuel. It is a commodity that has been widely transported via tankers since the late 1950s. The LNG tanker fleet has grown 10 % from 2020 to 2021 (International Gas Union (IGU), 2022). LNG is used for power generation, heating, as well as as a maritime fuel. It is primarily transported in liquid form which requires tankers that can tolerate cryogenic temperatures. These tankers were also the first vessels that started using LNG as fuel starting from as early as the 1990s. Currently there are more than 500 vessels that use LNG as fuel, including LNG tankers and other vessel types (Clarksons Research, 2022). LNG and methane can be used both in internal combustion engines and fuel cells. Current technology that is available on the market uses internal combustion technology and is available in the form of 2-stroke and 4-stroke engines. Fuel cell technology is, on the other hand, still under development and not commercially available for shipping.

Methanol

Methanol is a hydrocarbon compound that is denoted as CH_3OH. It is liquid under ambient conditions and has a volumetric energy density of 15.6 MJ/L which corresponds to half of diesel's energy density. Methanol is one of the most transported commodities in the world. It Is used as feedstock in production of solvents, adhesives, foams etc. The fact that methanol is liquid under ambient conditions makes it a relatively easier commodity to transport and store.

Methanol is already being used as a marine fuel. Most of the vessels that use methanol as fuel are methanol tankers. In addition, Swedish Stena has retrofitted the ferry Stena Germanica to use methanol as fuel, and the ferry has been in operation since 2015. As of 2022 there are 29 vessels that will use methanol as fuel in global orderbooks, most of which consist of containerships and tankers (Clarksons Research, 2022).

Methanol can be used both in internal combustion engines and fuel cells. The current technology that is commercially available is based on internal combustion technology, which are 2-stroke engines by MAN-ES[99] and

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[98] *https://www.epa.gov/gmi/importance-methane, retrieved 17.08.2022*

[99] *https://www.man-es.com/marine/strategic-expertise/future-fuels/methanol, retrieved 17.08.2022*

4-stroke Otto-cycle engines by Wärtsilä[100]. In addition, there are other internal combustion engine technologies under development. On the other hand, fuel cell technology for methanol has not come very far and is under development (Frelle-Petersen, Howard, Poulsen, & Hansen, 2021).

HVO

HVO (hydrotreated vegetable oil) is an advanced biofuel that is produced by hydrogenation of vegetable oils such as palm oil, soybean oil, rapeseed oil, animal fats and non-food sources such as tall oil, a side product of paper pulp production. The resulting molecule is a straight chained hydrocarbon and the exact composition of these molecules depends on the feedstock and production process (European Technology and Innovation Platform, 2020). The technology to produce HVO from other organic sources such as forest residues is still under development. As with the other sustainable zero-carbon fuels, the use of biofuel is largely motivated by the goal to reduce greenhouse gases. HVO burns more cleanly than conventional diesel, and the greenhouse gas emitted in the burning process is almost entirely offset by the CO_2 absorbed while the feedstock plants grew. The greenhouse gas reductions vary depending on feedstock and production process (DNV, 2019a). Although HVO can make significant contributions to greenhouse gas reduction, for HVO to be considered sustainable, the feedstock should be coming from a source that does not contribute to deforestation or compete with food supply. Therefore, only the HVO that satisfies these criteria is considered sustainable.

HVO has a volumetric energy density of 33.3 – 35.7 MJ/L, which is closest to the energy density of conventional diesel fuel. It can be used as drop-in fuel, i.e., using it does not require further engine modifications. Similarly, bunkering and onboard and offshore storage of HVO is fully compatible with that of diesel.

Delimitations: In this report we focus on HVO produced sustainably. Other types of biofuels and HVO that is not regarded as sustainable are outside the scope of this report.

Battery electric propulsion

Fully electric ships have electric engines and batteries on board and can be charged only by using shore power. Vessels with battery electric propulsion have already been taken into use in several places. The first vessel with full-electric propulsion, "MF Ampere" was taken into service in 2015 in Norway. MF Ampere is a car ferry that is operating in Norwegian fjords. Currently, there are 44 fully electric vessels in operation globally[101], and 47 are in the orderbooks[102] (Clarksons Research, 2022). Batteries have a low energy density both in terms of volumetric energy density and gravimetric energy density. This means that batteries both take more space than conventional fuels and are heavier. The feasibility of all-electric operation for other vessels is typically limited either by the size of the required battery system or its costs (DNV, 2019a). A significant proportion of the fully electrical vessels consists of passenger and car ferries, which are known to sail relatively shorter distances and have predictable schedules. This makes these ship types suitable for battery propulsion systems, since it gives them opportunity to charge often.

Greenhouse gas emission reduction with use of battery powered ships depends on how the electricity is produced. If the electricity provided is produced by renewable sources, there will be no greenhouse gasses

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[100] *https://www.wartsila.com/marine/products/engines-and-generating-sets/wartsila-32-methanol-engine, retrieved 17.08.2022*

[101] *Excluding barge and inland vessels*

[102] *As of August 2022.*

emitted while operating and charging this type of vessel. For hybrid plug in ships, on the other hand, batteries can be installed on a ship in addition to a conventional engine. These batteries can be charged either using shore power or the conventional fuel onboard. This can help the ship to sail emission free in certain areas, for example in and out of ports, fjords etc. Although hybrid solutions are crucial to reduce local pollution, their contribution to emission reduction is completely dependent on the share of battery propulsion in their total sailing. This share is dependent on many things including the ship's size, sailing patterns etc. Ultimately, hybrid electrical propulsion systems will be a relevant way of reducing emissions until other technologies are available, however, due to its lower energy density, battery electric propulsion is less applicable to ships that sail longer distances.

Delimitations: In this report we focus only on fully electrical propulsion systems. As the emission reduction by using hybrid vessels is case specific and non-generalizable, these are outside the scope of this report.

Appendix B: Method for screening the feasibility of zero-carbon fuels

See DNVs Task 2A for more in-depth information about the AIS-analysis. This method is based on DNV's AIS-analysis, task 2A. Although there are many parameters that determine whether a fuel or technology is feasible for a given ship of a certain type and operation, the required sailing range and speed and hence the energy density is of major importance. DNV has therefore conducted an analysis of energy needed per voyage for each ship, to determine if the different fuel options are feasible for this ship. The energy consumption of each voyage will, amongst other internal and external factors, mainly depend on the ship's operational profile, weather conditions, sailing distance, engine power curve and sailing speed. By *this ship*, DNV means a ship with the same characteristics in terms of type, size and sailing pattern as the existing ship identified through the MASTER and GSCM model. It is not necessarily feasible to retrofit all existing ships to new technologies and fuels.

It should be noted that this is a simplified method for assessing fuel feasibility of a large fleet of ships, without assessing each ship and route in detail. To have a definite answer for each ship and route, more detailed feasibility analysis is typically carried out, also taking other aspects such as investment and fuel cost into account.

The most important aim of the feasibility analysis is to assess how large a part of the fleet has the potential to be battery electrified, while it is of secondary importance to assess which of the zero carbon fuels will be feasible: hydrogen, ammonia or methanol. All these fuels have hydrogen as a basis and most of the energy required in the production of these fuels is spent on producing hydrogen (Hoecke et al., 2021). Different other methods than the above have been applied in the literature for assessing the technical potential for battery electrification (UMAS, 2022) (VTI, 2021) (Kersey, 2022), and we compare our findings to these other approaches.

The screening analysis is a very high-level analysis meant to illustrate a theoretical maximum potential of alternative fuel technology based on current trade and ship activity pattern, without considering necessary changes in ship design.

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