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TECHNOLOGICAL AND ECONOMIC PERSPECTIVES ON ALTERNATIVE MARITIME FUELS

Comparison on technical feasibility and fuel production costs

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1 Introduction

1.1 Maritime transport and its share of greenhouse gas emissions

Maritime transport, including inland waterway transport, plays a key role in driving and enabling international trade. According to UNCTAD (2020), approximately 80% of world trade by volume was transported by sea in 2020 (International Maritime Organization [IMO], 2020). The energy demand of the transport sector is approximately 117 exajoules[1], which is approximately 27% of the world's energy needs.

Between 92% and 93% of the energy used by shipping, road transport, and air transport is of an oil origin. Natural gas and biofuels account for approximately 3–3.5% of this (DNV, 2020). Maritime greenhouse gas (GHG) emissions are approximately 1.1 billion tons, which is approximately 2.9% of the world's GHG emissions.

Sea transport is the lowest-emission method of transporting large quantities of goods per unit of supply. However, there are many ways to reduce the environmental impact of transport flows. The IMO has set ambitious targets for reducing emissions from shipping. The strategy, which was published in 2018, aims to reduce maritime transport emissions by 50% from 2008 levels by 2050.

To meet these goals, the IMO has introduced measures to reduce emissions; these include the EEDI (Energy Efficiency Design Index), which is already in force, and the Ship Energy Efficiency Management Plan (SEEMP), which monitors and manages ship-specific emissions.

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[1] 1 exajoule = 1 x 10^{18} joules

1.2 Prospects for maritime transport volumes and CO_2 emissions

Maritime transport volumes are projected to increase significantly in the future. At the same time, the total emissions from the sector will increase under current regulations, despite the improved energy efficiency of ships. Therefore, the IMO is preparing short- and long-term regulations to further reduce emissions.

Other international actors are also preparing their own emission reduction mechanisms. For example, the EU is planning to include shipping in its emission trading mechanism (EU ETS) as part of its Green Deal package. At the same time, the Fuel EU Maritime initiative is progressing in the EU, which aims at enhancing the use of low-carbon and carbon-neutral fuels in shipping.

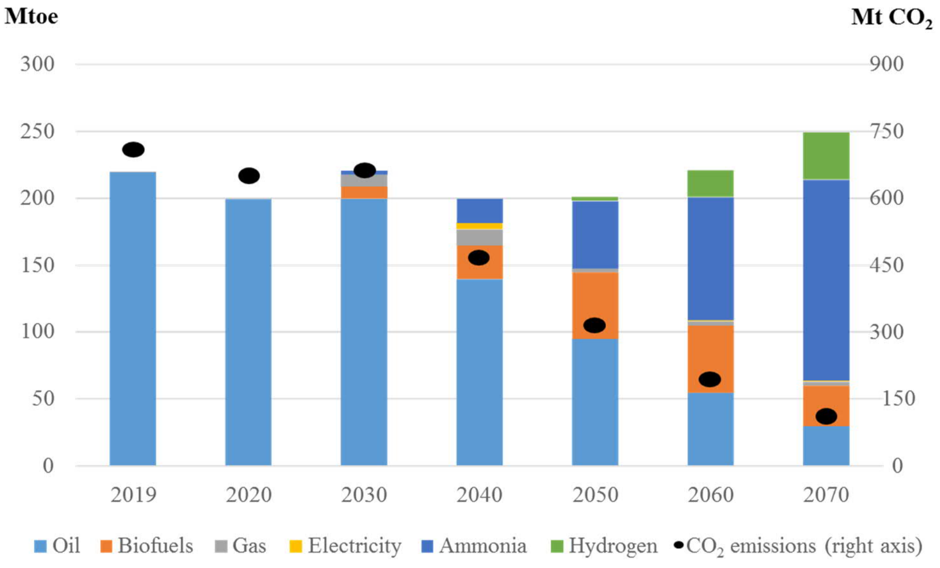

Figure 1 Energy consumption and CO_2 emissions from international maritime transport from 2019–2070 based on a sustainable development scenario (IEA, 2020)

The emission reduction decisions taken so far and the regulations put into place are mainly aimed at improving the energy efficiency of shipping. In 2019, the energy used by shipping amounted to approximately 220 million tons of oil equivalent (mtoe), of which approximately 93% is produced by oil-based (fossil) fuels (DNV GL, 2020; IEA, 2020) (Figure 1). This, combined with the projected increase in maritime volumes, means that without significant additional measures, CO_2 emissions from shipping are estimated to increase by up to 50% from current levels (IMO, 2020).

Table 1 Engine types and propulsion systems of the world's merchant fleet (2020) and vessels visiting Finland in 2018

ENGINE TYPE	WORLD MERCHANT FLEET IN 2020	VESSELS VISITING FINLAND IN 2018
BATTERIES AND DIESEL	0.07%	0.1%
DIESEL 2-STROKE	42.50%	26.9%
DIESEL 4-STROKE	55.60%	69.6%
DIESEL ELECTRICITY	1.17%	3.4%
GAS TURBINE	0.11%	0.1%
OTHERS	0.55%	
PROPULSION		
ELECTRIC	1.30%	3.5%
MECHANICAL	98.70%	96.5%

In practice, the above-mentioned developments show that to reduce emissions from shipping, the energy required for maritime transport will have to be produced with fuels that are largely different from the current ones. This is made particularly challenging by the fact that for the most part, the current fleet has such technical characteristics that their available fuel mix is limited. Table 1 presents the engine and propulsion types of the world's merchant fleet and vessels that visited Finland in 2018.

1.3 Purpose of the report

The current study compiles information from the existing academic literature and industry reports on low-carbon maritime fuel solutions. Low-carbon fuel solutions that are suitable for maritime transport can be divided into three groups (see, e.g., Lam et al., 2020):

1) Fossil-based conventional fuels with less carbon (liquefied natural gas [LNG], methanol, and its derivatives)
2) Renewable fuels based on biomass (e.g., bio-LNG, bioethanol, biodiesel, hydrogenated vegetable oil, bio-oil, and pyrolysis oil)
3) Non-bio-based renewable fuels, which would be solutions based on electricity and hydrogen carriers, as well as synthetic fuels.

Some of low-carbon fuels are already in use (in particular, first-generation biofuels). Whereas electricity or electricity-based fuels are only in very limited or test-use stages, hydrogen-based technologies are still clearly in the experimental stage.

The above-mentioned fuels are discussed in the present report from the point of view of a few key criteria (see e.g., Lam et al., 2020):

1) Current and future availability of the fuel
2) Usability
3) Technical readiness
4) CO2 emissions

The amount of energy needed for maritime transport is considerably large compared with the current production of certain fuel solutions. For example, increasing the production of biofuels is restricted by the availability of sustainable feedstock. Additionally, some fuels are also sought by other modes of transport, or there is other kind of demand for them. Historically, maritime transport has relied heavily on low-cost fuel, so the competitive situation may lead to a situation where other modes of transport with the capability of paying for the higher cost fuels take up a significant part of the potential supply.

For example, hydrogen and ammonia are currently produced mainly or entirely for purposes other than fuel. Their extensive use as marine fuels would require a significant increase in production, which may require new production methods.

For the purposes of this analysis, usability refers to the technical usability requirements related to its use both on board the ship and to the fuel distribution system. Usability is examined from the perspective of how specialized or complex technology is needed to use, store, and distribute the fuel. For example, some low-carbon fuel solutions are directly usable in existing engines (so-called drop-in fuels), while others require significant changes in the ship's engines, transmission, or tank solutions or have significant implications when it comes to, for example, the ship's cargo capacity.

Technical readiness is the stage of (technological) maturity the fuels are at from a maritime transport point of view. From the point of view of environmental impact, the aim is to take into account their emissions, especially CO_2 emissions over the entire life cycle. Local emissions from certain energy sources, such as electricity, may be very low, but their life cycle emissions depend on how the energy is produced.

From the point of view of CO_2 emissions, hydrogen and ammonia can be emission free, but both of them are produced with the help of fossil fuels, which significantly increases their emissions over the life cycle. While, on the other hand, synthetic fuels may even absorb carbon, thus reducing emissions if they are produced with renewable energy.

The possible fuel options and propulsion systems differ depending on the type of traffic in which they are used in. For this reason, when addressing the potential of fuel solutions, it is important to examine how they fit into different types of transport, that is, deep- or short-sea shipping and inland waterway transport. The requirements for these types of traffic differ significantly in terms of the size of the vessel, cargo capacity, and how much storage space can be allocated to the fuel system. For instance, fuel solutions that are not usable in short-sea shipping or ocean transport because of their energy density or storage capacity requirements may be more easily utilized in inland waterway transport.

Where feasible, the current report uses Finland as a case country to highlight the situation for a small, open economy that is highly dependent on well-functioning shipping. For example, in 2017, 86% of the value of goods imports and 80% of imports tons, as well as 80% of the value of goods exports and 92% of the exports tons, were transported by sea (Ojala et al., 2018). The maritime sector in Finland’s national economy has also been examined by Kuntze et al. (2019).

1.4 Structure of the report

Chapter 1 introduces the topic and presents the purpose and authors of the work.

The current state of the literature and industry reports on environmentally friendly and low-carbon propulsion options for vessel traffic are presented in Chapter 2.

Chapter 3 examines low-carbon fuel solutions and their availability, usability, maturity, and emissions from the perspective of the literature and industry studies on the subject; because biofuels are already in operational use in maritime transport, this chapter focuses more on electric and hydrogen-based fuel solutions and propulsion systems. Chapter 4 is based on the previous research literature, presenting a fuel cost production comparison of selected maritime fuels.

In Chapter 5, observations of the different fuel options are compiled in a strengths, weaknesses, opportunities, and threats (SWOT) analysis for different low-carbon fuel solutions. The analysis takes into account the specificities of different types of vessel traffic. Chapter 6 summarizes the main findings and conclusions of the report.

1.5 Acknowledgements

The Authors would like to thank the EU part-funded project naviSaimaa and its Project Manager Mr. Antti Vehviläinen at the Regional Council of South Carelia, Finland, for the opportunity to prepare an initial study on technological and economic perspectives on alternative maritime fuels.

This initial study was written in Finnish[2] and published in February 2021. It was focusing on the impact of ship, propulsion and fuel technologies on shipping in the Lake Saimaa region as well as shipping to and from Lake Saimaa through the Saimaa Canal that connects it with the Gulf of Finland near Vyborg, Russia.

We are also grateful for the encouragement of Mr. Vehviläinen to proceed with expanding the treatment and publish the findings in English.

Preparation of this substantially more comprehensive report in English was supported by the Finnish Shipowners´ Foundation (Varustamosäätiö) and Finnish Foundation of Seafaring (Merenkulun Säätiö). Their financial support is gratefully acknowledged.

This study is an independent academic work, and its contents, treatment of the subject or conclusions have not been influenced by the financial support received from the aforementioned organisations in any way.

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[2] Solakivi, T. and Ojala, L. (2021) ”Laivaliikenteen vähähiiliset polttoaineet ja niiden tuleva kehitys”, (Low-carbon fuels in shipping and their future development”), Project naviSaimaa, Regional Council of South Carelia.

2 State of the art of low-carbon fuels in shipping

Maritime emissions, emission targets, and emission reduction methods, including low-carbon propulsion systems, have been discussed extensively in the research literature. The key difference between the scientific research literature and industry or policy-making studies is that scientific articles typically focus on a very limited problem or topic and seek to address it in depth.

On the other hand, industry—or policy-making—studies tend to be more general in nature. These studies have sought to create an understanding of the current state of energy consumption in shipping and assess where and in what time frame shipping is developing towards new fuel alternatives. Key studies include the IMO’s reports on GHG emissions, which provides a comprehensive picture of energy consumption and emissions from shipping and future emissions development.

Other international organizations also have published reports on global energy consumption by looking at the sector and estimates of future trends. For example, the IEA’s Energy Technology Perspectives (2020) report also assesses current energy consumption in shipping and its distribution into different production methods. The development of the transport sector toward carbon neutrality is also followed, for example, by the International Transport Forum, which operates within the OECD and has published several reports on maritime transport (see, e.g., ITF, 2018, 2020)

2.1 Scenarios for the use of alternative fuels

In different scenarios, the IEA report (2020) presents the developments and technical solutions needed to reduce maritime emissions, especially in situations where maritime volumes are expected to increase.

The report is divided into short-, medium-, and long-term scenarios and is based on an assessment of the type of marine fuels and their shares in the fuel mix that the IEA estimates will be used in the short, medium, and long term.

Other organizations, such as the rating agency Det Norske Veritas (Germanischer Lloyd) in their “Energy Transition Outlook” report (DNV GL, 2020) and related “Maritime Forecast to 2050” report, also present their own assessments of the energy needs of shipping and the future operating forces of shipping.

Lloyds and UMAS (2020) present a technical and economic analysis of low-carbon and zero-carbon technologies, including investment readiness, technical readiness, and community readiness. The report approaches these issues from the perspective of different scenarios, taking into account energy demand, energy price development, and the costs of different technologies.

In addition to the above-mentioned general reports, various organizations and research institutes have also published more limited studies, such as on a single energy option or method of production. Examples include “The Future of Hydrogen,” which focuses on hydrogen technology (IEA, 2019a), “Biofuels for the Marine Shipping Sector” (Hsieh and Felby, 2017), and “On the Potential of Ammonia as Fuel for Shipping” (Hansson et al., 2020).

2.2 Emissions from shipping and the potential for their reduction

The number of research articles on marine emissions and propulsion options has increased rapidly in recent years. Thus, a complete review of the literature is impossible. Some research articles have narrowed the scope of their reviews to a single fuel option, while others have dealt with several fuel options at the same time. Some research articles do not limit the scope of the review to alternative fuels alone but draw together previous research on the potential of marine emission reduction measures more generally.

One of the most comprehensive reviews of alternative emission reduction methods is Bouman et al. (2017). The key findings of their review are presented in Table 2. In addition to Bouman et al. (2017), numerous other authors have addressed the topic, but usually from a more narrow perspective. Eide et al. (2013) have discussed the emission reduction potential of shipping and the role of alternative fuels. Other studies that discuss several fuel options include Balcombe et al. (2019), which approaches fuel options from the perspective of the decarbonization of maritime transport, reviewing the potential of different fuel options, such as biofuels, LNG, fuel cells, and methanol. Denis and Zincir (2016), on the other hand, analyze LNG, methanol, ethanol, and hydrogen from both an economic and environmental point of view.

Table 2 Potential for maritime emission reduction measures (Bouman et al., 2017)

METHOD TYPE	METHOD	BRIEF DESCRIPTION	CO_2 REDUCTION POTENTIAL
HULL DESIGN	Size of vessel	Economies of scale and improving capacity utilization	4 - 83%
	Body shape	Dimensions and shape optimization	2 - 30%
	Lighter materials	More durable steel, composite materials	.01 - 22%
	Air lubrication		1 - 15%
	Resisting devices	Other nonresistible devices to be installed	2 - 15%
	Reducing ballast	Changing the design of the vessel to reduce ballast	0 - 10%
	Coating the frame	Different types of coatings	1 - 10%
TRANSMISSION AND PROPULSION	Hybrid transmission/ propulsion	Hybrid auxiliaries and propulsion	2 - 45%
	Electricity	Electronic energy production	1 - 35%
	Devices to improve propulsion efficiency		1 - 25%
	Waste heat recovery		1 - 20%
	Boosting the energy needed on board (including lighting)		0.1 - 3%
ALTERNATIVE FUELS	Biofuels		25 - 84%
	LNG		5 - 30%
ALTERNATIVE ENERGY SOURCES	Wind power	Kites, sails	1 - 50%
	Fuel cells		2 - 20%
	Shore power		3 - 10%
	Solar energy	Solar panels on the roof	0.2 - 12%
OPERATIONAL	Speed optimization, speed reduction		1 - 60%
	Improving capacity utilization		5 - 50%
	Route optimization		0.1 - 48%
	Other operational means	Trim/draught optimization, energy management, service optimization	1 - 10%

Perčić et al. (2020) examine the different alternative fuels and their life cycle costs and emission reduction potential, in particular from the point of view of short-sea shipping, while Gilbert et al. (2018) focus on emissions during the entire life cycle of different fuel options, such as different biofuels, LNG hydrogen, and methanol. Horvath et al. (2018) aim to examine the maturity of the different fuel options and present their own scenarios for low-carbon maritime transport for 2030 and 2040.

In addition, several studies have analyzed individual fuels. Bengtsson et al. (2012) focus on biofuels, presenting two alternative pathways and the related challenges and potential to increase the use of biofuels in shipping. Mohr and Rahman (2013) deal with biofuels, especially from the perspective of how first- and second-generation biofuels differ. In particular, Bicer and Dincer (2018) focus on the environmental impact assessment of vessels powered by ammonia.

One potential way of reducing transport emissions that is frequently mentioned in the research literature is synthetic fuels, which are fuels that have their own fossil counterparts but are produced emission free (Hänggi et al., 2019). In the future, the production of renewable energy, such as wind power and solar power, is expected to increase significantly. Renewable energy production is characterized by large weather-related changes. Additionally, because energy consumption varies significantly because of seasonal, day-to-day, or occasional fluctuations, a greater imbalance between production and consumption is expected in the future. For this reason, it has been suggested (see, e.g., Create et al. 2015) that the seasonal surplus in wind and solar power production could be used for the production of synthetic fuels such as methane, methanol, dimethyl ether, or synthetic diesel.

3 The usability of low-carbon and carbon-free alternative fuels

3.1 Aspects on the life cycle of alternative fuels

When considering the technical and commercial usability of alternative fuels, the entire life cycle of each fuel should be accounted for. Key factors include the following:

- The production method of fuel and availability of raw materials required, production chains and technologies, existing production capacity, current use and distribution systems, and available capacity.
- Specificities of fuel logistics, including fuel characteristics, storage requirements, safety and fuel regulation, and necessary distribution infrastructure.
- Usability on board, including the necessary technologies (both for use and storage) and related costs.

Therefore, the availability of fuels can be determined by their physical characteristics, such as form, boiling point, flash point, energy density, and requirements related to the availability, logistics, storage, and distribution of fuels.

In addition, the development of the market price of fuels and difference in prices between alternative fuels are also very important factors for shipping operators. Demand also affects price formation, as do various national and international regulatory measures.

The regulation may relate, for example, to the taxation of fuels, content requirements of fuels, or emission limits. Lam et al. (2020) divide low-carbon fuel options into three categories:

1. Those with less carbon than fossil-based conventional fuels (LNG, methanol, and its derivatives).
2. Renewable biomass-based renewables (bio-LNG, biomethanol, biodiesel, hydrogenated vegetable oil, bio-oil, pyrolysis oil).
3. Non-bio-based renewable fuels, which are, in practice, solutions based on electricity and hydrogen carriers.

A key finding is that none of the alternative fuel options, except for environmental performance, match the performance of conventional fuels. According to Lam et al. (2020), the industry cannot achieve emission targets using fossil fuels without emission compensation from other sectors. Therefore, the use of either biofuels or hydrogen is essential. However, the sufficiency of biofuels is a problem. Biomass from sustainable sources will not be sufficient for the energy needs of shipping, especially because there is also other demand for biofuels.

Lloyd’s and UMAS (2020) have assessed the technical and economic feasibility of various low-carbon power sources compared with a conventional vessel using low-sulfur heavy fuel oil (LSHFO) fuel, here using an 82,000-ton bulk carrier as an example vessel. The aspects in the report are as follows: (1) investment readiness, such as a wider energy system and the production of future fuels; (2) technical readiness; and (3) social preparedness, including interactions with other sectors. The report does not assess safety issues, although they are mainly technical in nature.

Based on the Lloyd’s and UMAS (2020) scenarios, biofuels are competitive in the short term compared with other alternative fuels but will lose their advantage over time. The competitiveness of alternatives based on renewable electricity generation is expected to improve steadily over time because the price of this electricity is expected to decrease.

The competitiveness of new low-carbon fuel solutions and renewable electricity generation solutions depends on the development of carbon prices. The more expensive the price of CO_2 is, the faster they become profitable. According to the before mentioned report, battery-based solutions are more expensive in total cost than other alternatives. With the current technology, hydrogen has the highest storage and cargo space loss–related costs out of all the low-carbon fuel solutions.

In its own sustainable development scenario for maritime transport, the IEA (2020) expects maritime emission reductions to be implemented in three phases. In the short term, the emission reduction potential of shipping is significantly influenced by IMO sulfur regulation, which directs shipping companies to either switch to low-sulfur fuels or install sulfur scrubbers in existing equipment. However, from the point of view of CO_2 emissions, these solutions bind existing equipment to fossil fuels, thus slowing down the transition to low-emission solutions. Some of the new buildings will be LNG-powered, but their overall role in reducing CO_2 emissions is limited (8–25% compared with conventional fuels, depending on the source), especially if methane slip cannot be eliminated.

In the 2020s some of the fleet will use biofuels, at least mixed with conventional fuels, but the limited availability of biofuels and higher fuel costs compared with fossil fuels will limit their use (IEA 2020).

In the medium term, mixing biofuels with conventional fuels will play a greater role. The IEA estimates that the maritime use of biofuels will be around 25 million tons in 2040 and 50 million tons in 2050 (maritime fuel demand is currently around 210 million tons). However, the use of biofuels is limited by the amount of sustainable biomass available and the shared demand on limited overall capacity from other transport sectors, especially from aviation.

However, in the long term, the IEA sees biofuels as a temporary solution; it states that biofuel-fueled vessels will come to the end of their life cycle in the 2050s, after which they will be replaced by vessels equipped with engines and fuel systems using hydrogen or ammonia. In particular, the IEA sees significant potential for ammonia as a marine fuel in the long term (130 Mtoe in 2070), while the role of hydrogen is assumed to be lower, especially because of related storage challenges and its low-energy density. These are challenges, especially in ocean transport (deep sea), while short-sea shipping would not be affected as strongly by these challenges because of more frequent port visits.

As a fuel for maritime transport, the IEA sees the role of electricity as marginal until 2070, especially because of the challenges and high costs associated with battery technology. Electricity will mainly be seen as a hybrid solution alongside internal combustion engines and in very short-distance traffic. From the point of view of reducing emissions, the benefits of electricity will be seen in reducing emissions during shoreside electricity and in the port. When considering the potential of fuels, the entire life cycle must be taken into account. According to Lam et al. (2020), at least the following factors should be considered:

- the way in which fuel is produced
- the availability of the raw materials required,
- production chains and technologies,
- existing production capacity,
- existing operating and distribution systems,
- available capacity.

The specific characteristics of fuel logistics must also be taken into account. These include the characteristics of the fuel, storage requirements, safety, and fuel regulation, used distribution infrastructure, usability on board, including the technologies necessary for operation and storage, as well as the associated costs.

Some of the fuels under review will not yet be in extensive operational use in 2021. In addition, the current level of technological readiness, the potential obstacles to the widespread introduction of technology, the realistic timetable for the commercial uptake of technology, and economic viability must be critically assessed.

In the current report, different fuel options are examined based on fuel availability, fuel distribution logistics, usability, technical readiness, and emissions. In addition, the report briefly examines the production costs of different fuels from the present day to the 2050s.

3.2 Availability of fuels

3.2.1 Biofuels

Biofuels are typically divided into first- and second-generation biofuels. First-generation biofuels are made from food-based raw material, while second-generation biofuels are usually made from lignocellulose-containing (biomass-containing cellulose, hemicellulose, and lignin) waste.

Thus far, the use of biofuels has been limited because of the technical limitations of the existing fleet and high price of biofuels. For example, the IEA (2020) estimates that the use of biofuels in maritime transport will increase to around 50 million tons by 2050, which would represent less than a quarter of the current (around 220 Mtoe) energy needs in maritime transport. However, the increased use of biofuels will be significantly limited by the availability of sustainable biomass.

The need for maritime transport—therefore maritime energy—is expected to increase significantly in the future (see, e.g., UNCTAD, 2020). This means that sustainable biofuels would not be able to replace even the current—let alone the growing—energy demand for maritime transport. However, when assessing the potential of biofuels, the impact of other modes of transport must also be taken into account. In particular, air transport is expected to use significant quantities of biofuels in the future, thus reducing their availability for maritime transport.

3.2.2 Electricity

In 2020, world electricity production totaled 25.8 trillion kilowatt-hours. By 2050, global electricity production is expected to almost double to around 44 trillion kilowatt-hours. Just under 60% (52.8% of global electricity production in 2020) is produced with fossil fuels. Just over 10% of the world's electricity needs are generated by nuclear power, and just over 30% by renewable energy sources, including hydropower.

Most of the increased electricity generation is expected to be generated by renewable energy sources, which are estimated to increase from the current volume of around 7 trillion kWh to around 22 trillion kWh. The role of electricity as an energy solution for maritime transport depends not so much on availability but on technical characteristics, including storage capacity onboard and electricity infrastructure and distribution capacity.

3.2.3 Hydrogen and other synthetic fuels

Hydrogen can be used as a marine fuel and directly in liquefied form or in various hydrogen carriers, such as ammonia. In the production of ammonia, hydrogen is combined with nitrogen.

The production process of synthetic fuels is based on water electrolysis or other methods in which hydrogen is produced. In the production of synthetic fuels, hydrogen is combined with either carbon dioxide (CO_2) or carbon monoxide (CO) in a process called methanization. Synthetic fuels can be produced in either gas (so-called power-to-gas [PtG] fuels) or liquid form (power-to-liquid [PtL] fuels) (Urbansky, 2020).

Hydrogen or ammonia is mainly produced for other purposes, such as industrial use rather than fuel use. The world's hydrogen production is around 70 million tons a year, of which about 76% is produced from natural gas and 23% from oil. Sustainably produced hydrogen via electrolysis accounts for less than 2% of annual hydrogen production. Replacing natural gas and oil in hydrogen production would mean a significant increase in electricity consumption.

The IEA (2019) estimates that producing the current production volume (70 million tons) of hydrogen (H_2) by electrolysis would consume approximately 3,600 TWh; this corresponds to the European Union's current electricity generation capacity. There are significant variations in hydrogen production costs, depending on the method of production. The IEA (2019) estimates that the cost of conventional natural gas and oil-based production is USD 1/kg H_2. This means that the electricity price should be between USD 10 and USD 40/MWh to make the production of hydrogen by electrolysis cost-effective compared with traditional production methods.

Just like hydrogen, ammonia is mainly produced for purposes other than fuel. Around 200 million tons of ammonia are produced worldwide every year. Approximately 88% of ammonia is produced with the Haber-Bosch method, in which natural gas reacts to steam and water. Although ammonia itself does not contain carbon, the production of ammonia by current production methods is a significant source of CO_2 emissions.

The use of ammonia as a low-carbon fuel tends to be based on the electrolysis production method. The IEA (2019) also notes that synthesizing hydrogen into ammonia is not economically viable at current fuel price levels. However, according to the World Bank’s latest study (2021), hydrogen and ammonia are seen as the most prospective alternative fuels in the future for the shipping industry.

The production of synthetic liquid fuels (with current technologies) from electrolysis-produced hydrogen would mean that at the cheap electricity price of USD 20/MWh, the cost of fuel production would be set at around USD 70 per barrel (about USD 440 per ton), even when the cost of the carbon source is not taken into account. The production of synthetic gas via electrolysis would cost USD 10–12/ MBtu, or USD 370–440/m^3, according to an estimate by the IEA (2019). This implies that production technologies will need to advance remarkably, and the price of electricity will need to come down significantly for synthetic fuels to be viable. Renewable electricity prices vary depending on the location, setup, and source, but for instance, DNV GL’s (2020) renewable electricity estimate was 48–183 USD/MWh in 2020). In their estimate, a 20 USD/MWh electricity price will be reached closer to 2050.

3.3 Usability of alternative fuels

3.3.1 Biofuels

Maritime transport is an inexpensive sector from the point of view of biofuels because the requirements for the fuel quality for ships’ engines are less strict than in other transport sectors, such as road transport, particularly in air transport. In practice, this means that ships’ engines can use fuels with higher viscosity that have not been processed as much. Therefore, biofuels can be produced for maritime transport at a lower cost of production than in other sectors.

From a usability point of view, biofuels are closest to existing fuels from low-carbon fuel solutions. A significant portion of the biofuel types (biodiesel, ethanol and gas) on the market are “drop-in fuels,” that is, they can be used with existing engines and fuels without significant retrofit and conversion needs. (Eide et al. 2013)

By their very definition, biofuels must be equivalent in storage and operation to existing oil-based transport fuels. Therefore, they can be stored and transported and are accessible with the current infrastructure systems and with existing equipment. The most commonly used biofuel, bioethanol, however, is not directly usable in ship diesel engines but needs to be mixed with other fuels. Ordinary biodiesel (FAME), on the other hand, can be used in common marine diesel engines but not in other types of diesel engines.

3.3.2 Electricity

The use of electricity as a propulsion force for ships can be divided into two parts. The first group consists of fully electric vessels. For these ships, in terms of their usability, many challenges need to be addressed; these include both ship propulsion and engine technologies, the ship’s energy storage systems, and the electricity grid supplying energy to the ship. On the other hand, electricity can also be used as a propulsion power for ships as part of a hybrid solution in which energy is still produced for the ship’s engines and grid by means of diesel generators but where the ship also has battery capacity for temporary electric transport.

Some existing vessels are equipped with diesel-electric systems (Solem et al. 2015) in which the ship’s engines are electrical but their energy is produced by diesel generators. Another possible solution is a shaft generator which is installed both to provide the ship with electricity (Schøyen and Sow, 2015) but also to provide the ship with additional power when needed. Such engine and transmission solutions are typical for ships whose movement requires significant power adjustment needs. These include vessels that regularly take routes with different speed limits and ships designed for navigating ice.

From the point of view of usability, the main obstacles to the use of the electricity are the limits of current battery capacities and inadequacy of the electricity distribution infrastructure.

3.3.3 Hydrogen and other synthetic fuels

From the point of view of usability, hydrogen is still mainly in the experimental stage as a fuel for maritime transport. Although hydrogen and fuel cell technology have also been tested in maritime transport in various experimental projects for about 15 years, their widespread use is still mainly going to come in the future. The additional benefits of using hydrogen are low noise and fewer vibrations compared with internal combustion engines. When coupled with electric motors, the power loss is also low.

Key challenges for hydrogen availability are the need for storage tanks and the low vaporization point of liquefied hydrogen. Although hydrogen has a higher energy content per unit of weight than conventionally used fuels, it has the lowest energy density in terms of the volume of potential fuels. As a result, the use of hydrogen has the greatest impact on the ship's available cargo capacity within alternative fuel solutions (Horvath et al., 2018).

The low vaporization point of liquefied hydrogen means more complex fuel storage systems than conventional fuels (Balcombe et al., 2019). However, according to Denis and Zincir (2016), hydrogen has the highest flash point, which in itself makes it a safe fuel option.

Because of the low energy density of hydrogen (relative to volume), it is estimated that the most advantageous solution is to produce hydrogen on board for the use of fuel cells from various hydrogen carriers, such as ammonia.

Ammonia is a good means of transporting hydrogen; it contains no carbon at all, and it can be burned directly in diesel engines, but also like hydrogen in fuel cells (Bicer and Dincer, 2018). It can be produced with renewable energy sources and used as fuel in fuel cells or internal combustion engines. Ammonia has a higher space requirement on board compared with several other fuels, except for hydrogen, which may limit its use in long-distance traffic. Safety is also a major concern with the use of ammonia; in addition to the impact of ammonia release on water and air quality, ammonia is toxic, meaning that an internal leakage can be catastrophic for the crew (Hansson et al., 2020).

Synthetic fuels, on the other hand, are at the level of their fossil counterparts in terms of usability, but their production costs remain high.

3.4 Technical readiness

Appendix 1 provides an assessment by Lloyd's and UMAS (2020) regarding the technical readiness of the different fuel options, both in terms of fuel distribution/bunkering, tank technology, and fuel use, that is, engine and transmission technology. In the table, a technical capability is given a rating between 1 and 9, depending on the stage at which the fuel is (see also Table 3):

1. Basic principles observed
2. Technology concept formed
3. First feasible concept
4. First prototype under laboratory conditions
5. Prototype tested in the user environment

6. Preproduction prototype complete
7. Small volume pilot product introduced
8. Manufacture with a fully tested and validated product
9. Production and product in full operation

Table 3 Technical characteristics of alternative fuels (Nair, 2016)

ATTRIBUTE	HFO	MDO	LNG	RME	LBG	MEOH	ETOH
PHYSICAL STATE	**liquid**	**liquid**	**gas**	**liquid**	**gas**	**liquid**	**liquid**
DENSITY (KG/M^3)	**989**	**890**	**448.4**	**890**	**448.4**	**795.5**	**792**
FLASH POINT ^{O}C	**>60**	**>60**	**-175**	**149**	**-175**	**12**	**17**
BOILING POINT ^{O}C	**350-650**	**175**	**-161**	**369**	**-162**	**65**	**78**
BLENDABLE	**no**	**yes**	**yes**	**yes**	**yes**	**yes**	**yes**
ENGINE TYPE	**diesel**	**diesel**	**dual fuel/ otto**	**diesel**	**dual fuel/ otto**	**Dual fuel**	**Dual fuel**
TANK TYPE	**steel**	**cryo-genetic**	**steel**	**steel**	**cryo-genetic**	**special**	**special**

3.4.1 Biofuels

As far as their technical capacity is concerned, biofuels can be considered the closest replacements for oil-based fuels. Among others, Balcombe et al. (2019) note that first-generation biofuels are widely available and that the production of second-generation biofuels is also rapidly expanding.

Therefore, biofuels can be widely utilized with the engine technology already in use on existing vessels. In practice, liquid biofuels that operate either as such or mixed with oil-based fuels in compression-ignition engines are the easiest to utilize from biofuels.

Gas-based biofuels, on the other hand, require a spark-ignited engine, so the possibilities for their technical utilization in existing fleets is more limited. However, the situation is gradually improving because gas-fueled vessels are becoming more common in the world’s trading fleet. Although gas-fueled vessels accounted for only about 3% of the world’s fleet in 2020 (see, e.g., Solakivi et al. 2020a), they are more common among the younger vessels. Consequently, the use of gas-based biofuels in shipping should be easier in the future (cf. Table 3).

3.4.2 Electricity

Electricity can be used as a propulsion solution for maritime transport in many different ways. Some of these are already widely used, whereas others are either in very limited use or mainly in the test phase. According to Anwar et al. (2020), key considerations related to the use of electricity include propulsion and transmission, electrical energy storage, and the electricity network.

In 2020, just over 1% of the world's merchant fleet had a diesel-electric system, in which the ship is operated by electric motors but where electricity for the ship's engines is produced by diesel generators (CRSL, 2020). Although diesel-electric systems are more energy efficient than diesel engines because of lower power loss, the challenge in using these systems is the higher price of the system because of current oil-based fuel prices. Therefore, such systems are mainly installed on ships with an operating profile that requires, for example, significant variations in the speed of the vessel. However, in technical terms, electric motors and the utilization of electricity are already possible.

However, if electricity is considered as a fuel alternative for ships from a low-carbon perspective, this would exclude systems in which electricity and electric energy for the engines is produced with fossil fuels. The use of electricity produced by renewable energy sources requires supplying and storing the produced energy on board ships. Currently, electric energy is stored using batteries.

In road transport, especially passenger transport, electric cars are becoming more common, but their usability is also limited by the limited capacity of existing batteries and, as a result, by the limited range of the vehicles. Another limiting factor is the current charging systems, which require relatively long charging times. In maritime transport, these problems are all the more of an issue because the masses are large and distances traveled are significantly longer than in road transport.

Recently, maritime transport has started to adopt hybrid solutions in which the main propulsion of the ship is still the internal combustion engine but where the ship is able to travel for short periods with just the power of the electrical energy stored in the batteries alone. However, with current battery and charging capacities, electric-only vessels are rare and have a very limited range. To date, all-electric vessels have mainly been ferries with a short-distance itinerary, where they can be charged frequently.

Large deep-sea vessels have an engine power of more than 100,000 kW. Charging such vessels efficiently would require a completely different capacity from the electricity grid than is currently available.

The use of electricity in long-distance transport would require significant advances in battery and charging technologies, as well as major investments in the electricity distribution infrastructure.

3.4.3 Hydrogen and other synthetic fuels

The greatest potential for the use of hydrogen as a marine fuel still lies ahead. Although hydrogen has already been used as a transport fuel, especially in road transport, according to the IEA (2020), the role of hydrogen in maritime transport will be limited to individual test projects at the beginning of 2021 or as a complementary energy solution for ships.

The role of hydrogen and hydrogen carriers, such as ammonia, is still very limited in transport. The attractiveness of these solutions can be increased because of ongoing technological developments and GHG emission targets for other marine fuels. Hydrogen can be utilized not only as pure hydrogen but also by converting it into other fuels; these include synthetic methane and other synthetic fuels, as well as ammonia.

However, a number of technical issues still need to be resolved regarding hydrogen and ammonia. Although hydrogen has a higher energy content per unit of weight than conventional fuels, its low vaporizing point requires expensive and space-consuming storage on board.

Ammonia can also be used as fuel in current internal combustion engines, but proper combustion requires more efficient spark ignition systems and other technical modifications to engines (Brown, 2018). According to Hansson et al. (2020), all the experiments using ammonia as a fuel have been performed by mixing ammonia with other fuels, where the proportion of ammonia has been quite low. Also, there have been problems with both emissions and the efficiency of the system.

Many international expert organizations, such as the IEA (2020) and DNV GL (2020), have highlighted the potential of hydrogen and ammonia as a fuel for the future in their maritime transport scenarios.

The aforementioned challenges of hydrogen and ammonia also apply to their manufacturing, transportation, and storage. Most of the world’s hydrogen and ammonia production is based on coal or natural gas, resulting in significant CO_2 emissions. Hydrogen can also be produced by (water) electrolysis, but the challenge is the cost level of production, especially regarding renewable energy sources, where the cost of hydrogen production is significantly higher than with traditional coal and gas production.

The same type of cost challenge also applies to other synthetic fuels. There are two key issues to be resolved in the production of fuels: the availability of raw materials near the production site and price of the energy needed for hydrogen production. In the case of synthetic fuels, this means ensuring both cost-effective hydrogen and cost-effective access to CO_2 or carbon monoxide for the production process.

3.5 Emissions

Table 4 shows the energy content and emissions of certain in-use or test-use fuels. Regarding fuel emissions, it is essential to look at both in-use emissions and emissions related to fuel production and other life cycles. This subchapter deals with the emissions of selected low-carbon fuels from both perspectives.

Table 4 Energy content and emissions of alternative fuels (Nair, 2016)

ATTRIBUTE	HFO	MDO	LNG	RME	LBG	MEOH	ETOH
ENERGY DENSITY (MJ/KG)	**40.4**	**42.7**	**48.2**	**37.0**	**48.2**	**20.0**	**28.0**
NEED FOR TANK CAPACITY (M^3/TJ)	**25.0**	**26.3**	**46.3**	**30.4**	**46.3**	**62.9**	**45.1**
FUEL DEMAND (MT/MJ)	**24.8**	**23.4**	**20.7**	**27.0**	**20.7**	**50**	**35.7**
EMISSION FACTOR	**3.114**	**3.206**	**2.750**	**1.920**	**1.012**	**0.340**	**0.678**
EMISSIONS PER UNIT OF ENERGY PRODUCED (MJ/TJ)	**83.7**	**75.0**	**62.3**	**51.9**	**21.0**	**17.0**	**24.2**

3.5.1 Biofuels

Biofuels contain carbon, the same as fossil fuels. However, despite their fossil content, they are carbon neutral. This is because of what biofuels are made of. When fuel is used, carbon dioxide is released into the atmosphere. However, because the used biomass absorbs carbon from the atmosphere as it grows, it is seen as carbon neutral (Hanaki and Portugal-Pereira, 2018).

It is important to note that the impact of biomass farming on CO_2 emissions may vary significantly. First-generation biofuels (see, e.g., Mohr and Rahman, 2013) are produced from biomass intended for human consumption. Consequently, at worst, their production takes away the farmland intended for food production, which, in the face of the growing food demand, will then lead to the clearing of the new farmland for food and biofuel production.

In particular, there have been reports of cutting rainforests to make way for palm oil production. Figure 2 shows the CO_2 emissions of biodiesel compared with conventional fossil fuels.

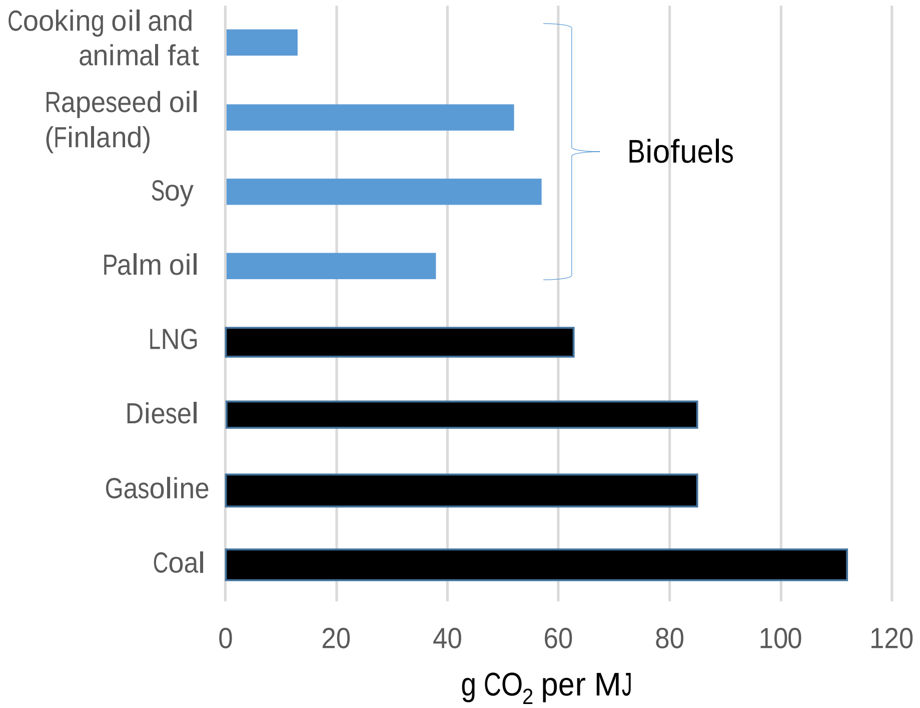

Figure 2 Biodiesel CO_2 emissions compared with fossil fuels (data source: UK Government, 2020)

The figures are based on the assumption that biodiesel has been produced in such a way that it has not led to land use changes. As can be seen from the figure, biodiesel, regardless of the source of production, has a better emission impact than conventional fuels. However, different sources of feedstock have significant implications for the level of biodiesel emissions. Although soy-based (57 g CO_2 per MJ) and rapeseed-based (52 g) biofuels are almost at the same level as LNG, the emissions of biodiesel produced from palm oil are 40% lower and biodiesel produced from recycled cooking oil is up to 80% lower than that of LNG.

If biofuels are compared with diesel, the difference is even greater. The emissions of biodiesel produced with palm oil are up to 56% and the emissions of biodiesel from cooking oil up to 85% lower than those of fossil diesel.

However, regarding biodiesel and other biofuels, it should be noted that the amount of biomass produced sustainably is limited. If the production of biofuels leads to changes in land use, and then, for example, to a reduction in carbon sinks, their impact on CO_2 emissions will be significantly reduced. In addition, possible land use changes have an impact on biodiversity. As a result, biofuels are inevitably only part of the solution to reducing emissions (IEA, 2020; DNV GL, 2020).

3.5.2 Electricity

The impact of electricity on emissions varies significantly depending on the production method. Internationally, the challenge for electricity in relation to GHG emissions is that a significant part of the world's electricity production is still based on fossil fuels.

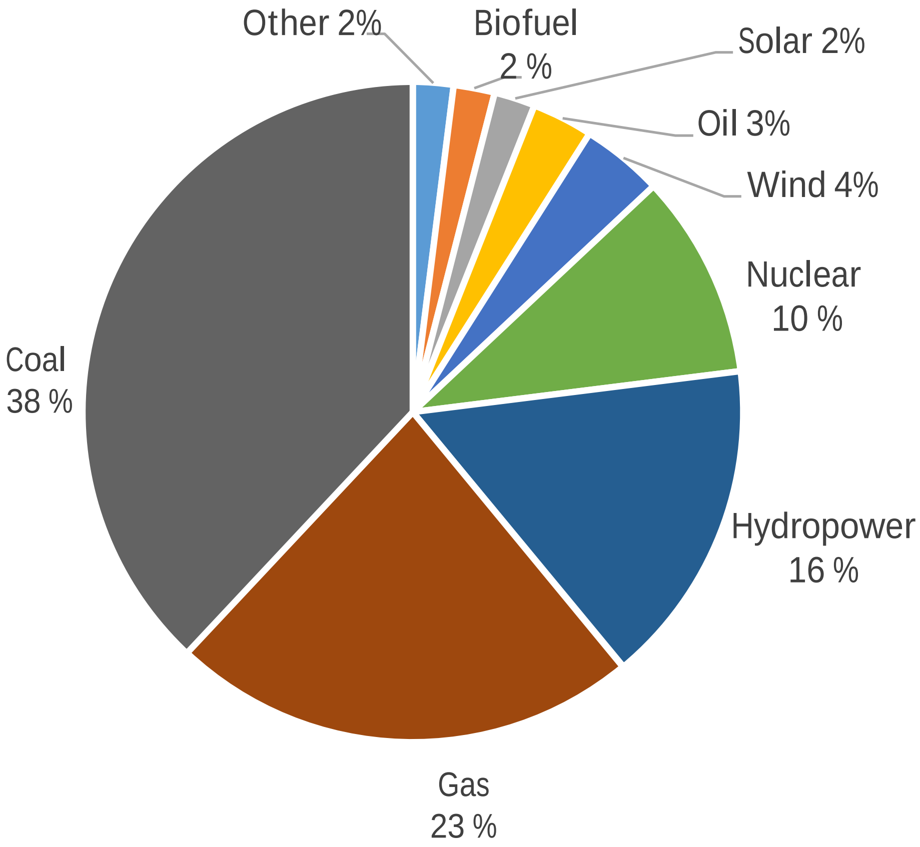

Figure 3 World electricity production by different production methods in 2017 (IEA, 2019)

According to the IEA (2019), coal accounted for approximately 38% of global electricity production in 2017. In addition, 23% of electricity was produced with gas and 3% with oil. In total, approximately two-thirds of the world's electricity production is still based on fossil fuels (Figure 4).

Table 5 presents the estimates used by the IPCC on CO_2 emissions from the different ways of generating electricity. Although CO_2 emissions from hydropower average around 4 g, wind power around 12 g, and solar energy around 22–46 g per kilowatt-hour, the corresponding emissions are 469 g for gas and 1,001 g per kWh for coal. Therefore, the way electricity is produced has a very strong impact on how low-carbon fuel solutions actually are.

Table 5 CO_2 emissions from electricity production per kWh-equivalent (Moomaw et al., 2011)

TECHNOLOGY	gCO_2/kWh_e
HYDROELECTRIC	4
WIND POWER	12
NUCLEAR POWER	16
BIOMASS	18
SOLAR ENERGY (THERMAL)	22
GEOTHERMAL ENERGY	45
SOLAR ENERGY (POLYSILICON)	46
GAS	469
COAL	1,001

When assessing the future, it is important to note that internationally, but especially nationally, the current trend of electricity production methods is trending toward low-carbon production methods. The share of renewable energies is expected to increase significantly in the future, while the share of nonrenewable fossil fuels in electricity production will fall.

3.5.3 Hydrogen carriers

The most common method to obtain hydrogen is from natural gas, but it can also be obtained from biomass and via electrolysis. The disadvantage of using hydrogen is its low storage density. Because it can be manufactured from hydrogen carriers, onboard production appears to be cheaper and more efficient than hydrogen production elsewhere.

Renewable hydrogen produced by water electrolysis, that is, the electrochemical process, in which water hydrogen and oxygen are separated by an electrical electrolysis device (Perčić et al., 2020), can be used in a fuel cell. However, whether a fuel cell is low in carbon emissions depends greatly on how the hydrogen is produced. The additional advantage of using hydrogen is its low noise and vibration compared with internal combustion engines, and coupled with an electric motor, its power loss is low. Hydrogen has a low energy density and the highest need for storage tank space from alternative fuels, limiting cargo space (Balcombe et al., 2019). Hydrogen also has the highest flash point of alternative fuels, making it safe in itself (Denis and Zincir, 2016).

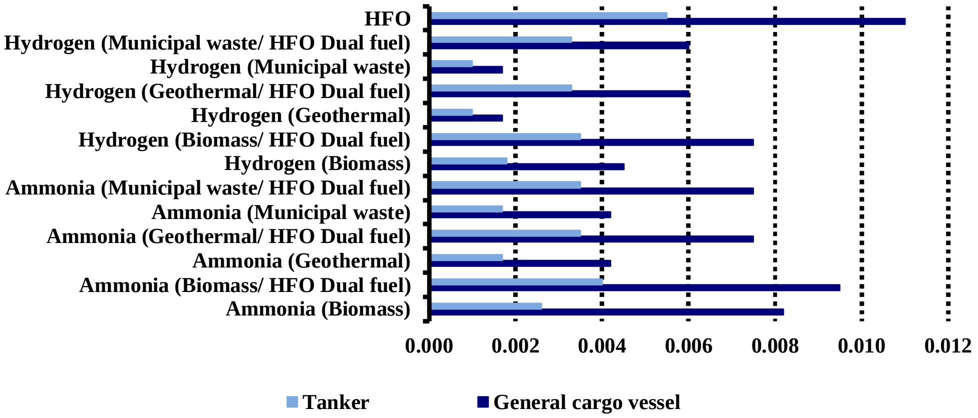

Figure 4 Greenhouse gas emissions of ammonia and hydrogen by different production methods (kg CO_2e/tkm) (Bicer and Dincer, 2018)

Hydrogen does not have operational CO_2 emissions, but it is now mainly produced from fossil fuels, so its life cycle CO_2 emissions are significantly higher compared with conventional fuels. Taking into account life cycle emissions, the benefits of hydrogen will only be realized if its CO_2 emissions from raw materials and feed-in energy are reduced, for example, by using renewable energy from solar or wind power for electrolysis (Gilbert et al., 2018; see also Figure 5).

Ammonia is a carbon-free compound that can be produced with renewable energy sources and can be used as fuel in fuel cells or internal combustion engines. Ammonia has a higher space requirement on board compared with several other fuels, with the exception of hydrogen. This may limit the use of ammonia in long-distance traffic. To date, the testing of ammonia-fueled engines has been limited to those where ammonia plays a minor role and where significant amounts of secondary fuel have been used. Safety is a major concern when considering ammonia as a fuel source. In addition to the impact of ammonia release on water and air quality, internal leakage can also be catastrophic for crews (Hansson et al., 2020).

Synthetic fuels contain the same amount of carbon as fossil fuels. Their advantage over fossil fuels is that the carbon they contain is bound during the production process from the atmosphere or another source. Thus, synthetic fuels are carbon neutral in terms of life cycle emissions if the energy used in their production is produced with renewable energy sources (Brynolf et al., 2018).

3.6 Other fuels in use

3.6.1 LNG

In 2020, approximately 3% of the world's fleet was fueled with LNG (Solakivi et al., 2020a). LNG can theoretically achieve an emission reduction of up to 20–30% compared with conventional fuels, although methane leaks reduce its real potential to around 15% (Balcombe et al., 2019). LNG has the smallest permissive variation (4–16% of fuels) in the mixing ratio and requires twice as much tank space as heavy fuel oil (HFO).

The fuel system of LNG vessels is different from those using liquid fuels. Ships need special fuel tanks, gas ventilation space, two-walled gas pipes, secure bunkering stations separating the main engine from the engine room, and a gas-safe engine compartment (Gumpel, 2012). Vessels equipped with methanol and ethanol fuel also have modifications in their main machinery (Denis and Zincir, 2016).

One LNG alternative is synthetic natural gas (SNG) produced with renewable electricity, whose emissions are about 2% compared with ordinary natural gas, mainly because of the methane emissions released in production (Horvath et al., 2019).

3.6.2 Methanol

Methanol reduces CO_2 emissions by approximately 25% compared with conventional fuels. The advantage of methanol is that it can be produced in many different ways. However, at the same time, it should be noted that depending on the method of production, emissions from methanol production vary significantly. For example, when produced from gas, emissions from methanol are 10% higher than those from HFO or MDO (Balcombe et al., 2019).

Methanol and ethanol fuel systems need additional fuel tanks or the conversion of the ship's ballast tanks into fuel tanks. Separate rooms for transfer pumps and high-pressure pumps require space (Westling, 2013). Two-walled pipes are needed to supply fuel for the main engine (MAN, 2015; Westling, 2013). Extra fuel injectors and fuel pumps are required to supply fuel for cylinders as well (MAN, 2015; Haraldson, 2014; Denis & Zincir, 2016)

The potential of methanol as a fuel is limited, at least with current production methods. Its only advantage over LNG is that it can easily replace other fuels without technical modifications to the engines (drop-in fuel). However, its life cycle CO_2

emissions with current production methods are significant. If methanol is produced from biomass, its life cycle emissions will be lower (Gilbert et al., 2018).

Because of its liquid state, methanol is very similar to conventional marine fuels. For this reason, it can be used in today’s diesel infrastructure with minor modifications, which are related to its low flash temperature (11 °C), which can be overcome by using a two-walled structure. It has a carbon content of 38%, which makes it attractive to use to comply with environmental protection regulations. By comparison, the carbon content of diesel is around 87% (Perčić et al. 2018).

4 Fuel production cost analysis based on the existing literature

The cost of fuel to the end user is dependent on multiple factors such as the price of raw-material, production costs, etc (see for example Halff et al. 2019), as well as the premium of margin the producers are able to collect, which is ultimately defined by the existing market situation. However, at least in the long term the material and production costs set a lower boundary for the price of the fuel. For this reason, cost estimates for the production of alternative maritime fuels are calculated.

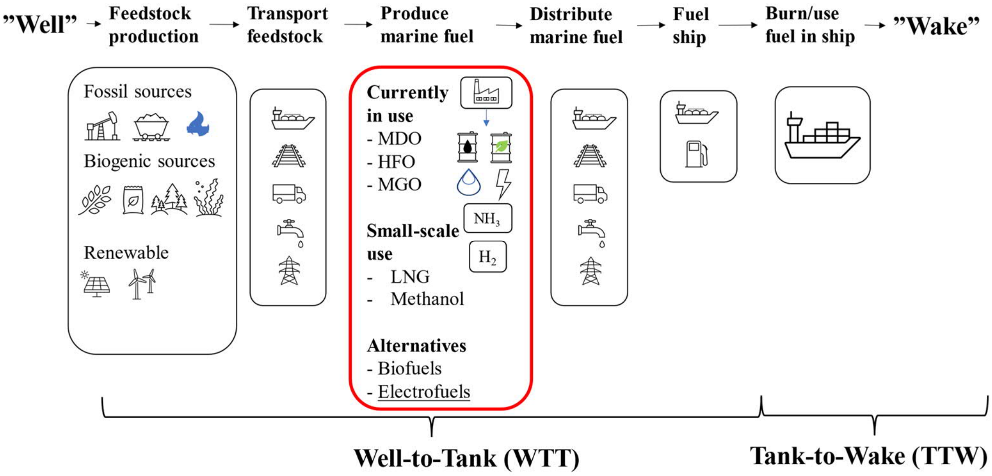

Figure 5 Illustration of a well-to-wake analysis and the focus of this study. Modified: European Commission 2016

Alternative fuels can be produced in a myriad of different pathways. A common method to comprehensively compare different production pathways is to use a “well-to-wake” (WTW) analysis. Typically, in a WTW analysis, the overall costs (production and emissions) and energy efficiency of a certain production pathway are assessed from the source “well” to the actual movement of the ship, or the “wake” (Figure 6).

The analysis can be further split into well-to-tank (WTT) and tank-to-wake (TTW) phases. In WTT, the assessment starts from a source and stops at the bunkering. This part includes the sourcing process of feedstock, transporting it to fuel production facilities and further distribution to the port and fueling (bunkering) of the ship. In TTW, the assessment focuses more on how the vessel converts the fuel internally to actual movement of the ship and to the related costs of this process.

The focus of this section is on the production phase of different maritime fuels, with an analysis based on synthesis of the existing literature and on cost calculations of a few selected electrofuels based on the total costs model (Brynolf et al., 2018).

The chosen fuels in this study are grouped into three different categories: fossil-based fuels, biomass-based fuels, and electrofuels. Fossil-based fuels include two bunkering fuels that are currently in common use (IFO380, a type of HFO, and low sulfur marine gas oil [LSMGO]) and two alternative fossil fuels (LNG and conventional methanol). To estimate the future price development of conventional fuels, different price statistics were combined.

The historical and current prices of IFO380, LSMGO and LNG were obtained from Ship & Bunker (2021) for the time period of 2009-2021. The crude oil prices for the corresponding time were obtained from Federal Reserve Bank of St. Louis (Federal Reserve, 2021). Estimates for the future prices of conventional fuels were based on long term price projections of crude oil and natural gas of the US Energy Information Administration (2021). Even as there are also other variables that affect the price of marine fuels especially in the short term, the price of marine fuels is estimated mainly to follow the price development of crude oil.

The relationship of the prices of LSMGO and IFO380 with crude oil were estimated with regression analysis, with following results:

Price of LSMGO (US$/tonne) = 150.218+8.06 (Price of Brent), where R^2:0.914,

Price of IFO380 (US$/tonne) = 40.218+5.566 (Price of Brent), R^2: 0,961.

The results of the regression analysis were then used together with the long-term price projections of Brent by the EIA to forecast the price of the respective fuels in the future. The price forecast of LNG was based on the natural gas price projection of EIA, with an assumption that the price of liquefaction would be a constant 3.31 US$ per MMBtu (Steuer, 2019).

For biomass-based fuels, three main types of fuels were chosen: biodiesel, bio-LNG, and biomethane. The variants for biodiesel are hydrotreated vegetable oil (HVO; which is produced by hydroprocessing vegetable oils), “first-generation” FAME (which is produced via transesterification), and “advanced” biofuels (which are produced via e.g. biomass-to-liquid (BtL) process). For bio-LNG, two variants are chosen: BtL and aerobic digestion.

The main difference between these two fuels is how the initial phases of the fuel production (creation of synthesis gas) is carried out. Finally, biomethanol was chosen as a comparison counterpart for the other two methanols. For more detailed explanations on the different production pathways biofuels, see, e.g., ETIP Bioenergy (2021a) and ETIP Bioenergy (2021b).

Electrofuels were chosen from Brynolf et al.’s (2018) study. As a clarification, electrofuels are synthetically produced fuels made with hydrogen from the electrolysis of water and a source of carbon dioxide (CO_2). As an additional note, pure hydrogen for fuel purposes is sometimes considered an electrofuel even though the production process itself does not require CO_2. The origin of the electricity and CO_2 dictates how sustainable and “green” the end-product is.

To distinguish different fuels from each other, a color label is often given. For instance, green ammonia is made with renewable electricity and direct air capture for the CO_2, whereas blue ammonia could use renewable electricity, but the CO_2 would be sourced via carbon capture, usage and storage (CCUS) from a fossil-based industry source. In broader terms, the term “electrofuel” refers to the process of making fuel rather than the fuel itself. More specific terms for the conversion process are power-to-X (PtX), PtG, and PtL (ETIP Bioenergy, 2021c.)

Table 6 presents a comparison of the production prices of the selected maritime fuels ($Euro_{2020}$/ton of oil equivalent [toe]) and their price projections from 2020 to 2050 based on the previous literature and the authors’ own calculations.

As stated earlier, there is great pressure to reduce the GHG emissions of the shipping industry because it produces around 3% of global GHG emissions. Shipping also emits an estimated 15% of world’s major air pollutants annually (World Bank, 2021).

Given the current price levels and projections (without extra incentives such as carbon tax), conventional fuels are the cheapest option as a maritime bunker fuel. With current projections, the average price range for conventional fuels is approximately 250–445 EUR/toe. This price range is a fraction compared with biofuels and electrofuels in their current state. Even with high bound estimates, the prices cap at 1,150 EUR/toe in the estimates.

For biofuels, the average price range was between 1,200 and 1,400 euro/toe. The prices naturally depend on the fuel in question. For example, at its cheapest, studies estimate that first-generation FAME biodiesel could be produced at 130 EUR/toe. Some of the estimates expressed an increase in the fuel production price (HVO and first genenation FAME), whereas some expressed a decreasing trend (biomethanol and both bio-LNGs and advanced biodiesel). Advanced biofuel conversion technologies have opportunities to improve either using more advanced feedstocks or via technological improvement.

As stated earlier, securing enough sustainable feedstock is a large concern for using biofuels on a larger scale to reduce the GHG gases of the shipping industry. This combined with the higher price of biofuels and competition from other transport industries hinders the usage of biofuels in shipping on a larger scale, and it is not likely that biofuels will be the long-term answer for the shipping industry.

Table 6 Production cost estimates for the selected maritime fuels in EUR_{2020}/toe

Fuel	Present (2020)	2030	2040	2050
Fossil based fuels				
IFO380	**215**	**361** (196–651)	**426** (223–742)	**463** (244–825)
LSMGO	**308**	**506** (285–901)	**596** (319–1026)	**646** (348–1,138)
LNG	**108–175**	**216** (217–225)	**223**	**228–239**
Methanol	**380** (151–530)	**180–450**	**184–459**	**186–465**
Biomass based				
Biodiesel (HVO)	**593–1058**	**612–1444**		**649–1,654**
Biodiesel (1st. Gen FAME)	**2059** (128–2,710)	**151–4417**		**163–5,149**
Biodiesel (Advanced)	**872–1,674**	**840–1875**		**771–1,806**
Biomethanol	**930** (372–1,477)	**Lower bound: 431–1,047** **Higher Bound 674–1,599**		
Bio-LNG (BtL)	**989** (853–1,116)	**954–2224**		**531–1,440**
Bio-LNG (Anaerobic digestion)	**1,175** (128–2,221)	**791–1,768**		**596–791**
Electrofuels				
Hydrogen	**2,128** (1,605–3,128)	**1,628** (1,244–2,117)	**721** (523–1,047)	**267** (186–582)
e-Methane	**2,977** (2,059–4,245)	**1,907** (1,198–2,617)	**1,256** (733–1814)	**698** (302–1,221)
e-Methanol	**3,222** (2,349–4,454)	**2,070** (1,407–2,745)	**1,477** (1,012–2,012)	**989** (640–1,465)
e-FT-liquids	**3,477** (2,535–5,117)	**2,279** (1570-3315)	**1,617** (1,082–2,489)	**1,035** (628–1,861)

Sources
Fossil-based fuels:
IFO380, LSMGO, LNG data based on EIA Annual Energy Outlook 2021
Methanol 2020: Brynolf et al. 2018 and IRENA & Methanol Institute 2020
Methanol 2030–2050: Own calculations based on EIA Annual Energy Outlook 2021; Collodi et al. 2017

Biomass-based fuels:
Biodiesel (HVO and Adv.) 2020: Brown et al. 2020
Biodiesel (HVO and Adv.) 2030–2050: Own calculations based on Brown et al. 2020; DNV GL, 2020; Xu et al. 2018
Biodiesel (1.gen FAME) 2020: Brynolf et al. 2018
Biodiesel (1.gen FAME) 2030–2050: see HVO and Adv. projection
Biomethanol 2020: Brynolf et al. 2018
Biomethanol 2030–2050: IRENA & Methanol Institute 2020 and DNV GL 2020
Bio-LNG (BtL and Anaerobic) 2020: Brynolf et al. 2018
Bio-LNG (BtL and Anaerobic) 2030–2050: CE Delft 2020 & DNV GL 2020

Electrofuels:
e-fuels: Own calculations based on Brynolf et al. 2018 total costs model.
See Appendixes 2–4 for the methodology and parameters used

Although electrofuels are currently more expensive than biofuels and conventional fuels, they are estimated to become significantly cheaper in the future. According to our estimates, given the development of alkaline electrolyzer technologies and price reductions in renewable electricity (from 70 EUR/MWh in 2020 to 20 EUR/MWh in 2050) the average production prices of electrofuels (excluding hydrogen) would decrease 72% from 3,200 EUR/toe to 900 EUR/toe. For comparison using DNV GL's (2020) electricity price estimates (average of high and low scenario; 90, 59, 49 and 39,5 EUR/MWh from 2020 to 2050) the average prices would decrease from 3,700 EUR to 1,300 EUR/toe.

Given the current estimates, it seems difficult for electrofuels to become commercially viable without having additional factors coming in to boost the beneficial side of electrofuels. For example, the development of different production technologies (e.g., proton exchange membrane [PEM] and solid oxygen electrolyzer [cell] [SOE(C)] for electrolysis process) and faster or more significant decreases in renewable electricity prices coupled with legislative changes (e.g. carbon tax) could even the price competition between conventional fuels and electrofuels.

Currently for electrofuels, the crucial element is to reduce the production price of hydrogen (electrolysis process), in which the price of electricity plays a major role (see, e.g., Zang et al., 2021; Dieterich et al., 2020). In our calculations, when electricity prices decreased to the price range of about 20–30 EUR/MWh, electrofuels were starting to become commercially viable (2040 onwards).

Another important aspect to consider when producing electrofuels is the cost and acquisition of carbon. Our calculations used general CCUS-sourced (and priced) CO_2. From the perspective of GHG emission reductions, using carbon sourced with Direct Air Capture (DAC) technologies would be more beneficial in the long-term as they are considered one of the few viable carbon negative technologies i.e., they reduce carbon from atmosphere. However, DAC-captured CO_2 is currently 4-5 times more expensive than CCUS captured CO_2. (Dieterich et al., 2020). DAC-technologies seem to have potential to reach comparable price levels to CCUS-captured CO_2 in the mid- to long-term (See e.g. Sherwin, 2021 or Fasihi et al. 2019). In our sensitivity analysis with DAC CO_2 pricing starting from 250 EUR/mt in the 2020s halving every ten years to 31.25 EUR/mt in 2050, use of DAC would increase prices of electrofuels by 20% in the 2020s but only by 6% in 2040 and 1% in 2050. For other recent estimates on electrofuels, see, for example, Dieterich et al. (2020) and CE Delft (2020).

Currently, the future is still uncertain for many alternative fuels, especially for electrofuels. Multiple production pathways exist, but some potential technologies and production pathways are still developing. Finding the optimal pathway will depend on various variables, including technological, political, and economic factors

(World Bank, 2021; Dieterich et al., 2020). Chapter 5 compares the different technologies in a SWOT analysis.

5 SWOT analysis of low-carbon fuels

The SWOT analysis of low-carbon fuel solutions is presented in Table 7. There are many types of shipping traffic, and some of the factors mentioned in the table are significant for one type of transport and less significant for others. The future energy solutions of the transport sector will at least partially differ based on the type of transport. The strengths and weaknesses of the alternatives also depend on the time frame of the review.

Some low-carbon fuels, such as biofuels, are already used by maritime transport, and some are in the final phases of the test phase. For this reason, for example, the IEA (2020) estimates that the importance of biofuels as a low-carbon fuel solution for shipping will increase, especially in the short term. Both liquid and gaseous biofuels can be utilized with existing fleets and with the main part of the engine technology currently in use.

Biofuels are currently significantly more expensive than fossil fuels. The impact of the tightening of environmental regulation (see, e.g., Solakivi et al., 2020b), the relative cost competitiveness of biofuels, and other alternative and low-carbon fuels will improve in the future. However, the increasing use of these is hindered by the limited availability of sustainably produced biomass, which, at best, is sufficient for meeting no more than a fraction of the energy needs of shipping.

In the case of biofuels, non-maritime issues can also be seen as a threat. One of these relates to the way biofuels are produced because the production of first-generation biofuels has had a detrimental effect on land use. For example, in Indonesia, Malaysia, and Brazil, part of the forest area has been cleared out for biofuels, for example, for palm oil production, partially displacing food production in favor of biofuel production. This is undesirable from the point of view of biodiversity, carbon sinks, or social sustainability, for which palm oil production in particular has been strongly criticized. These issues limit the production potential of biofuels.

Although the share of biofuels as a marine fuel is likely to increase in the short term, their limited availability will guide the industry toward other fuel solutions in the medium and long terms.

Electricity as a power solution for shipping is already a reality. Although the majority of the world's merchant fleet continues to use fossil fuels, the number of different diesel-electric and hybrid solutions has been increasing, especially in traffic that requires the ship's engines and transmission to adapt to different speeds.

As the main source of power for ships, electric motors are still rare and are mainly used for short-distance passenger transport. The biggest challenge for electric ships is the storage of electricity on board and considerably long charging times. Current battery technology cannot store enough energy for the long ranges required for shipping. Therefore, battery-powered vessels are likely to be limited to traffic where the distances between charging points are relatively short and the masses carried by the vessels and the power required for it are relatively low.

The challenge for ships powered by electric energy alone is also the adequacy of the charging and electricity transmission infrastructure and the related investments. The power requirements of ships are considerable. This is particularly true in winter shipping, where running on ice requires greater engine power from ships overall and sporadically higher power outputs.

One of the challenges of electricity as a power source is the diffused port network, which means that charging possibilities and sufficient electricity transmission infrastructure can be found in several locations. It is for these reasons that the IEA (2020) also estimates that the role of rechargeable electric ships in vessel traffic will be limited.

When assessing the potential of electricity, emissions from electricity production must also be taken into account. Although electricity does not produce local emissions, its life cycle CO_2 emissions can be high. Approximately two-thirds of the world's electricity is still produced with fossil fuels, while in Finland, the corresponding share is only around 17% (IEA, 2020; Energy Industry, 2020).

The electrification of vessel traffic is not only a matter of battery technology, but many assessments see fuel cell technology as promising, at least in the longer term. Because hydrogen and ammonia do not contain carbon, in principle, they could significantly reduce the emissions from vessel traffic. The problems of utilizing hydrogen and ammonia are mainly technical. Currently, the cost of production is also remarkably high. Although hydrogen has been used as a fuel, for example, in road transport, its use in maritime transport is still in the trial stage. The use of ammonia is also mainly limited to mixing it with other fuels in spark-ignited engines.

The energy content of hydrogen relative to weight is high but is low in relation to volume, which has a major impact on the available cargo space. This can be partially influenced by the use of ammonia or other hydrogen carriers from which hydrogen is manufactured on board. In the case of ammonia, the risks posed by its toxicity to the crew of the vessels, in addition to the challenges related to the engine technology itself, must be addressed.

The production of hydrogen and ammonia is currently mainly based on fossil fuels. If hydrogen or ammonia are to become a major propulsion option for maritime transport, the production methods must be changed and production increased significantly. According to the IEA (2020) and DNV GL (2020), this should be possible, and they expect the share of hydrogen and ammonia in marine fuels to increase, especially in the long term. The World Bank’s (2021) recent study also envisions a similar future.

Table 7 SWOT analysis of fuel alternatives

	STRENGTHS	**WEAKNESSES**	**OPPORTUNITIES**	**THREATS**
BIOFUELS	Already in operational use	Limited availability of fuels made from sustainable biomass	In the short term, the use can be expanded from the current level	Competition for supply with other modes of transport because of transport emissions targets
	Usable as traditional fuels with existing engine technologies	Currently higher price than fossil fuels	Scope of use in the short term primarily a price issue	Limited amount of sustainably produced biomass and not enough for more than a fraction of maritime energy needs
	Do not require a new, separate distribution infrastructure		Production also from domestic raw materials	In particular, the first-generation biofuels could reduce food production capacity if fuel production is preferred
ELECTRICITY	No local emissions	The world’s current electricity production largely based on fossil fuels	Renewable electricity production is becoming more common and life cycle	High energy consumption of ships, no charging with existing electricity transmission infrastructure

			emissions from electricity are falling	
	Technology exists, electric motors already in use by maritime transport	Emission reductions require expansion of renewable electricity production	New production methods reduce electricity prices, making electricity a more cost-effective propulsion	Significant investment in the construction of charging and distribution infrastructure
	Efficiency of electric motor better than internal combustion engine	Key challenge energy storage on board	The development of battery technology will enable longer ranges in the future	Battery and charging technology require development
	Technology also in use by other modes of transport; development does not rely only on maritime transport operators	Current battery technology only enables short range and is not suitable for long-distance traffic	Advances in charging technology enable shorter charging times	Significant demand for battery and their minerals also elsewhere
		Current charging technology requires long charging times		
HYDROGEN	Carbon-free fuel	Low vaporization point	Technology already in use with other modes of transport, technology transfer possible	Current hydrogen production method mainly based on fossil fuels
	Energy content of hydrogen per unit of weight greater than for other fuels	Low energy content per volume	Ongoing several development projects; technological development fast	Sustainable production requires a change in production method
	For example, water electrolyzes can be produced emission free	Maximum negative impact on cargo space	As renewable energy becomes more common, the price of electricity needed for	Current hydrogen production small compared with current

			electrolysis is expected to fall, making hydrogen a more competitive fuel	or projected energy needs of shipping
		Requires more specialized storage technology		Electrolysis-based hydrogen production is not widely used
		No existing distribution system		Current production price high compared with fossil fuels
		Fuel cell technology is not yet the main source of power in shipping; technology will not be usable until further in the future		
AMMONIA	Ammonia does not contain carbon, hence being (carbon) emission-free fuel	The scale of current production is small compared with the energy needed by maritime transport	Can be used as a hydrogen carrier	Ammonia production currently mainly based on fossil fuels
	Production technologies well known and used	Production currently mainly based on fossil fuels	Emission-free production with renewable energy sources	Use as fuel would require a significant increase in production capacity and new, zero-emission production methods
	Can be used both in fuel cells and in existing engines (with conversions) as fuel	Ammonia is toxic; leaks on board fatal to crew	Can also be utilized with existing engine technologies, which is why the transition may be easier than, for	Technology only in the test phase; the maturation of technology for large-scale use still a question

			example, the transition with hydrogen	
	Easier to store and transport than hydrogen, hence acting as a hydrogen carrier	Ammonia only at test stage as marine fuel, small quantities mixed with other fuels in experiments to date	Production methods exist	Safety in fuel used to be solved
	Impact on cargo space less than, for example, hydrogen		Transport infrastructure and storage easier to implement than with hydrogen	Requires the creation of a distribution and storage infrastructure
SYNTHETIC FUELS	Usable as traditional fuels with existing engine technologies	Currently higher price than fossil fuels or biofuels	Emission-free production with renewable energy sources	Use as a fuel would require a significant increase in production capacity and new, zero-emission production methods
	Do not require a new, separate distribution infrastructure	The production process requires significantly inexpensive, emission-free energy	Production method technically complete	Industrial-scale production does not currently exist
	No local emissions, carbon neutral even for life cycle emissions if produced with renewable energy	Energy loss during the life cycle quite high	Significant synergy with existing industry in raw material production possible in Finland	

Synthetic fuels combine the potential of biofuels to act as drop-in fuels in current engines, yet they still face challenges in their production in terms of energy intensiveness and cost levels. The weakness of synthetic fuels as a transport fuel is their significant loss of power.

For example, according to Bracker and Timpe (2017), only 13% of the total energy used to produce synthetic fuels is directed at the movement of a vehicle as a power source for a passenger car. The reason for this is the fuel production process and the poor efficiency of the internal combustion engine. Synthetic fuels are more suitable for the propulsion of maritime transport than passenger car transport.

Although the process of producing synthetic fuels is technically known (the processes of electrolysis, carbon capture, and methanization), their production is significantly more expensive than fossil fuels. For example, Brynolf et al. (2018) estimate that the production of synthetic fuels would be somewhat more expensive than biofuel production in the 2030s.

Production costs are an important factor in the increasing use of hydrogen and ammonia or synthetic fuels as a marine fuel. Currently, their use is still significantly more expensive than fossil fuels. Although growth in renewable energy production is also expected to reduce the cost of producing hydrogen and ammonia, their high (higher) price will slow down their wider uptake as transport fuel, at least until the late 2020s and probably into the 2030s.

6 Summary

This report provides an overview of the current state of low-carbon fuel solutions for shipping and their future development. It is based on the most recent literature by key players in the field. The review has focused on biofuels, electricity-based solutions, and hydrogen-based energy solutions, including solutions based on hydrogen carriers.

Greenhouse gas emissions from maritime transport

In 2019, maritime transport accounted for just under 3% of global GHG emissions. Shipping volumes and emissions are expected to increase significantly in the future under existing propulsion solutions. At the same time, key actors in maritime regulation, such as the IMO and the EU, have set important targets for reducing the GHG emissions from maritime transport.

In addition to the objectives already set, new regulations are planned. The IMO's Marine Environment Protection Committee (MEPC) is planning to tighten the energy efficiency requirements for ships and is exploring market-based measures to reduce emissions from shipping. The European Commission and the European Parliament are preparing to include shipping in the EU ETS mechanism or, alternatively, to create their own EU-wide emissions trading mechanism for shipping[3]. In addition, the Fuel EU Maritime initiative is expected to hasten the introduction of alternative low-carbon and carbon-neutral fuels in shipping.

Maritime emission reductions are unlikely to be achieved by the means currently in place, but other means are needed to supplement them. New low-carbon or carbon-neutral fuel solutions are expected to play a key role in this development.

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[3] On these, see e.g. Ojala, L. (2021) Differing impacts and interests of EU Member States regarding maritime emission solutions, A Policy Brief, Published 10 June 2021 (Available here)

Background to low-carbon propulsion solutions for maritime transport

In the current report, low-carbon propulsion solutions have been addressed, particularly from the point of view of their usability, technical readiness, emissions and costs. Based on this, the analysis carried out and the SWOT analysis show that fuel solutions are progressing at different speeds: some of the fuels are already in operational use and can be utilized using existing engine technology, while some are still at the experimental stage and require technology that is still in development.

Different fuels also have very different requirements for the distribution system, storage, and so forth. For this reason, the role of the alternatives differs depending on the timespan during which they are developed and the type of traffic they are intended and eventually used for.

Biofuels as a fuel of water transport

From all the fuel options examined, the first-generation biofuels are already in operational use. Biofuels have the same characteristics as oil-based fuels, and they can be used in engines that are commonly found on board of existing ships. Their availability can also be ensured within the current fuel distribution system.

Consequently, key players in the sector see potential in biofuels to reduce emissions from shipping, especially in the short term. The disadvantage of biofuels has thus far been their higher price than oil-based fuels; this means that biofuels have mainly been used outside maritime transport. Another factor that will limit the role of biofuels in reducing GHG emissions from shipping is their limited availability. The amount of sustainably produced biomass represents only a fraction of the amount needed to meet the need for marine energy.

In addition, the demand for liquid biofuels is also high in other modes of transport. According to some estimates, a significant proportion of sustainably produced biofuels will be used to reduce emissions from aviation. Therefore, biofuels are not expected to be a key solution in reducing shipping emissions in the medium to long term.

Electricity as a fuel for maritime transport

There are many factors associated with electricity, such as propulsion, which affect its functionality in different types of traffic. Until now, the use of electricity in shipping has been mainly limited to diesel-electric solutions, where the ship’s propulsion is powered by electric motors but where electrical energy is produced by diesel-powered generators. Because the solution is still based on oil-based fuels, it is not a low-carbon solution.

Hybrid solutions or fully rechargeable electric ships have so far been rare. The use of these types of ships has been limited by the low capacity of the batteries and limited range of the vessels, as well as the long charging times required by charging technology. The range requirements for ocean traffic and most of the short-sea shipping effectively exclude propulsion solutions based solely on battery technology. As a result, the importance of battery technology-based solutions in shipping is likely to be limited.

Currently, the battery-based ships that are currently in service, under construction, or on the drawing board are typically used in traffic in which one leg of travel is short and recharging opportunities are abound. In addition, the requirements for charging infrastructure and electricity transmission infrastructure and their relatively high investment costs must also be considered. This, combined with the limited range because of battery capacity, means that electronic solutions can also be expected to be suitable for inland waterway transport, mainly for traffic where ships take a regular short route between charging points.

Hydrogen and hydrogen carriers in shipping

In the long term, key players in the sector estimate that a significant proportion of shipping will be switched over to hydrogen and hydrogen carriers, such as ammonia. However, before we can think about their use in shipping on a large scale, a number of different issues need to be resolved. First, the technology needed for their use is mainly experimental in maritime transport. In addition, to date, fuel cell technology has been tested on ships mainly as secondary energy solutions, such as auxiliary machinery. Regarding vessel technology, maintaining hydrogen on board is also a challenge for the time being.

Although the energy content of hydrogen relative to weight is high, its low vaporization point means that the storage tank space it requires and the effect on the cargo space is greater than that of other fuels. One solution has also been to produce hydrogen on board from a hydrogen carrier, such as ammonia. However, the toxicity of ammonia causes its own storage problems.

Before the large-scale introduction of hydrogen or ammonia, the way in which they are produced must be solved. The current production method relies heavily on fossil fuels, especially gas. With these production methods, hydrogen has high life cycle emissions and, therefore, does not provide a solution for reducing GHG emissions from shipping. In addition, the current production volumes of hydrogen and ammonia are small compared with the energy needs of shipping. Production costs are also significantly higher than those of current fossil fuels.

Before hydrogen or ammonia could be made into a solution to ease emissions from shipping, the way in which they are produced and their volume and costs must change significantly. However, changes in the cost competitiveness and volume of water electrolysis-based production are expected to increase as renewable energy production becomes more common, and its costs will decrease together with economies of scale and technological development.

Synthetic fuels in water transport

A development similar to hydrogen and hydrogen carriers is also expected in the production of synthetic fuels using PtX technologies. In their production, hydrogen that is produced by water electrolysis is combined with carbon dioxide captured in methanization. The production technology of these types of fuels is technically ready, but for cost reasons, industrial-scale production has not been started.

However, industrial-scale production is being launched, and there would be opportunities for this from the point of view of both technology and access to raw materials in Finland. Although the production of synthetic fuels is currently estimated to be more expensive than fossil fuels and biofuels, it is assumed that the tightening of environmental regulations, particularly the European Union’s ambitious climate targets, will improve their relative competitive position over time.

Epilogue

Shipping and its power sources are looking to be renewed in the coming decades. There will be no single solution in the field, but the energy needs—and possible energy-saving measures—will be addressed with a solution that is suitable for the current situation and that is also economically feasible.

The quest for a low-carbon or fossil-free society goes far beyond the transport sector. Achieving this objective relies not only on technological progress but on political decisions. Decision making on regulation and incentives is hampered, for example, by the difficulty of predicting the speed of technological development, making it difficult to compare the emission-reducing effect of different measures with the costs they require.

Although estimates of the cost impacts of different measures vary greatly, it would seem that for a long time, the unit cost of CO_2 emission (€ per ton of CO_2) reductions has often been significantly lower elsewhere than in transport, especially in the energy production and energy efficiency of manufacturing processes.

Abbreviations and terms

BUNKERING	**FILLING SHIP'S FUEL TANKS**
DEEP-SEA SHIPPING	Ocean transport between continents
DRAUGHT	The depth of a loaded vessel in the water, taken from the level of the waterline to the lowest point of the hull
DROP-IN FUEL	Renewable fuel that does not require modifications to the ship’s technology. May require mixing with other fuels
DWT	Deadweight tonnage; the dead weight of the vessel, i.e.. the maximum total weight of the ship’s water supplies, supplies, fuel, cargo and persons, including its load capacity
EEDI	Energy efficiency design index; the energy efficiency index of vessels
EtOH	Abbreviation for ethanol or ethyl alcohol
FAME	Fatty acid methyl ester, one type of biodiesel
GHG	Greenhouse gases
HFO	Heavy fuel oil
IEA	International Energy Agency
IMO	International Maritime Organization, which is part of the UN system
IPCC	The Intergovernmental Panel on Climate Change, which is under the auspices of the UN
CRYOGENIC STORAGE	Storage of the product (e.g. gas) at very low temperature
kW	kilowatt
LBG	Liquefied biogas
LIGNOCELLULOSE	Plant biomass consisting of cellulose, hemicellulose, and lignin. Biofuel industry interested in using lignocellulose as bioethanol

LNG	Liquefied natural gas
LSHFO	Low-sulfur heavy-fuel oil; low-lying heavy fuels
BTU	British thermal unit equivalent to 1,055 Kilojoules of energy
MDO	Marine diesel oil; diesel for vessel use
MeOH	Abbreviation for methanol or methyl alcohol; toxic alcohol
MJ	Megajoule, i.e.10^6 Joule = 1,000 Kilojoules
Mtoe	One million tons of oil equivalent; the energy volume of the various powers has been converted to the energy volume of the oil (in metric tons)
MWh	Megawatt hour
PEM FUEL CELL SYSTEM	Proton-exchange membrane. Fuel cell system that converts hydrogen chemical energy into electricity
PROPULSION	A system used to propulsion; one of the possible driving forces of ships
RME	Rapeseed methyl ester; one type of biodiesel
SEEMP	Ship energy efficiency management plan; a vessel energy efficiency management plan
SHORT-SEA SHIPPING	Short-sea shipping, e.g., within Europe
SOEC	Solid oxide electrolyzer cell; a recently developed high-temperature water electrolysis system that uses a solid oxide and two electrodes to produce hydrogen and oxygen
SWOT	Strengths, weaknesses, opportunities, threats; four-field analysis of the strengths (S), weaknesses (W), opportunities (O), and threats (T) of the case under consideration
TEU	Twenty-foot equivalent unit; a transport unit corresponding to a standardized shipping container of 20 ft.
TJ	Terajoule, i.e., 10^{12} joule = 1,000 gigajoules or 1,000,000 megajoules
TRIM	For the purposes of this, trim refers to the position of the vessel during passage
UNCTAD	United Nations Conference on Trade and Development
USD	United States Dollar; 1 EUR was approximately USD 1.22 in mid-June 2021

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Appendix 1. Technical readiness of fuels according to Lloyd’s and UMAS (2020). Scale (see chapter 5.4.): 1 = Basic principles observed ... 9 = Production and product in full operation

	Bunkering			Storage on board					Processing and conversion			Propulsion			
combustion engine	**Equipment**	**Procedures**	**Fuel quality standards**	**Structural tank**	**Membrane containment system**	**IMO type A tank**	**IMO type B tank**	**IMO type C tank**	**Venting-system**	**Fuel supply-system**	**Reformer**	**2-stroke combustion-engine**	**4-stroke combustion-engine**	**Fuel-Cell**	**Boiler**
LSHFO (reference vessel)	**9**	**9**	**9**	**9**					**9**	**9**		**9**	**9**		**9**
Biodiesel	**9**	**9**	**9**	**9**					**9**	**9**		**9**	**9**		**9**
E-diesel	**9**	**9**	**9**	**9**					**9**	**9**		**9**	**9**		**9**
Biomethanol	**7**	**6**	**3**	**7**					**7**	**7**		**7**	**6**		**2**
E-methanol	**7**	**6**	**3**	**7**					**7**	**7**		**7**	**6**		**2**
Bio-LNG	**9**	**9**	**9**		**8**		**9**	**9**	**9**	**9**		**9**	**9**		**9**
E-LNG	**9**	**9**	**9**		**8**		**9**	**9**	**9**	**9**		**9**	**9**		**9**
E-ammonia	**7**	**2**	**2**			**7**	**7**	**7**	**3**	**7**		**3**	**2**		**2**
NG ammonia	**7**	**2**	**2**			**7**	**7**	**7**	**3**	**7**		**3**	**2**		**2**
E-hydrogen	**4**	**2**	**3**				**3**	**6**	**2**	**2**		**2**	**5**		**2**
NG hydrogen	**4**	**2**	**3**				**3**	**6**	**2**	**2**		**2**	**5**		**2**
fuel cell															
Biomethanol	**7**	**6**	**3**	**7**					**7**	**7**	**3**		**6**	**7**	**2**
E-methanol	**7**	**6**	**3**	**7**					**7**	**7**	**3**		**6**	**7**	**2**
Bio-LNG	**9**	**9**	**9**		**8**		**9**	**9**	**9**	**9**	**4**			**7**	
E-LNG	**9**	**9**	**9**		**8**		**9**	**9**	**9**	**9**	**4**			**7**	
E-ammonia	**7**	**2**	**2**			**7**	**7**	**7**	**3**	**7**	**2**		**2**	**7**	**2**
NG ammonia	**7**	**2**	**2**			**7**	**7**	**7**	**3**	**7**	**2**		**2**	**7**	**2**
E-hydrogen	**4**	**2**	**3**				**3**	**6**	**2**	**2**			**5**	**7**	**2**
NG hydrogen	**4**	**2**	**3**				**3**	**6**	**2**	**2**			**5**	**7**	**2**
Batteries	**4**	**2**	**3**				**3**	**6**	**2**	**2**			**5**	**7**	

Appendix 2 Methodology of the cost estimates presented in Table 6

Fuel	Explanation
General notes	Brynolf et al.'s (2018) results were converted from EUR/MWh to EUR/toe using 1 toe = 11,63 MWh 1 EUR_{2015} = 1,0566 $EUR0_{2020}$ All of our own USD to EUR conversions using 1 USD = EUR 0.82 (5/2021 exchange rate)
Fossil based fuels	
IFO380	Historical prices: Ship and Bunker (2021), Historical Crude Oil Prices: Federal Reserve Bank of St. Louis (2021), Crude Oil Price Forecast: EIA Annual Energy Outlook (2021). Projection based on crude oil price scenarios and estimated (historical) connection between crude oil price and IFO380 price.
LSMGO	Historical prices: Ship and Bunker (2021), Historical Crude Oil Prices: Federal Reserve Bank of St. Louis (2021), Crude Oil Price Forecast: Scenarios of EIA Annual Energy Outlook (2021). Projection based on crude oil price scenarios and estimated (historical) connection between crude oil price and IFO380 price.
LNG	LNG price forecast: EIA Annual Energy Outlook (2021). Liquefaction constant 3.31 USD/MMBtu. (Steuer, 2019)
Methanol	Production price in 2020 from Brynolf et al.'s (2018) literature compilation converted to $EUR_{2020.}$ In range with IRENA and Methanol Institute (2020). Projections based on proportional increase of feedstock price. Average feedstock (NG) portion of production cost 65% (Collodi et al., 2017, Figure 3). Feedstock price development 2020–2050 EIA Annual Energy Outlook 2020. For example, 2020–2030 estimated price increase of 18% which corresponds to 12% price increase in methanol production price (18% x 65%).
Biomass based	
Biodiesel (HVO)	Production cost range in 2020 from Brown et al. (2020) Table 12 in that study. Projections based on proportional increase of feedstock price. Average feedstock portion of production cost 74% (Brown et al., 2020, Table 3) Biomass feedstock price factor development 2020–2050 DNV

	GL 2020 Table B.3 For example, 2050 biomass price factor is 2. Price_{2050} = Price_{2020} + increase of feedstock price as portion of production cost.
Biodiesel (1st. Gen FAME)	Production price in 2020 from Brynolf et al.'s (2018) literature compilation converted to $\text{EUR}_{2020.}$ Projection done in the same way as for HVO. Average feedstock portion of production cost 90% (Xu et al., 2018, Fig. 5)
Biodiesel (Advanced)	Identical to HVO apart from average feedstock portion of production cost. Average portion for Advanced Biofuel 35% (Brown et al., 2020, Table 10). Future cost development adjusted with cautious learning curve. 10% for 2030 and 20% for 2050. Brown et al. (2020) estimates 5-27% cost reduction in mid-term.
Biomethanol	Production price in 2020 from Brynolf et al.'s (2018) literature compilation converted to $\text{EUR}_{2020.}$ In range with IRENA and Methanol Institute (2020, Annex 3). Projections: Data from IRENA & Methanol Institute (2020, Annex 3) and DNV GL (2020, Figure B.1). IRENA and Methanol Institute (2020) and DNV GL (2020) values converted using 1 toe = 41,868 GJ. Median price of high and low scenarios.
Bio-LNG (BtL)	Production price in 2020 from Brynolf et al.'s (2018) literature compilation converted to $\text{EUR}_{2020.}$ Estimates mostly in range with CE DELFT 2020. Projections: Data from CE Delft (2020, Tables 16, 34, and 35). Converted using 1 toe = 39,7 MMBtu with liquefication cost of USD 3.31/MMBtu. DNV GL 2020 values converted using 1 toe = 41,868 GJ.
Bio-LNG (Anaerobic digestion)	

Electrofuels	
Hydrogen	Calculations based on Brynolf et al.’s (2018) total costs model (p. 1897). Used parameters, see Appendix 3. $\mathbf{TC = I_{electrolyser} + O\&M_{electrolyser} + C_{stack} + C_{electricity} + C_{water} + I_{fuelsynthesis} + O\&M_{fuelsynthesis} + C_{CO2capture} - P_{heat} - P_{oxygen} + I_{plant}}$**,** where $I_{electrolyser}$ and $I_{fuelsynthesis}$ are the annualized direct investment cost of the fuel synthesis plant or the electrolyzer. O&M cost are the operation and maintenance costs as a share of the related investment cost. C_{stack} is the annualized cost of stack replacements. Stack replacements are calculated from annual operating hours, the stack lifespan, and the electrolyzer system life span. C_{stack} is calculated from share of electrolyzer cost and number of stack replacements. $C_{electricity}$ is the cost of electricity. C_{water} is the cost of water used in fuel production. $C_{CO2capture}$ is the price of CO_2 used in fuel production. P_{heat} and P_{oxygen} are profits from selling byproduct heat and oxygen. $C_{electricity}$, C_{water}, $C_{CO2capture}$, P_{heat}, and P_{oxygen} based on reference values from Brynolf et al.’s (2018) supplementary materials section B production values for 1 fuel output per MWh. I_{plant} is the annualized indirect cost for the whole plant expressed as factor of $I_{electrolyser}$ and $I_{fuelsynthesis}$. Typically, the factor ranges from 1 to 3. Includes, e.g., engineering, construction fees, project contingency costs. e-Methane liquefaction to e-LNG assumed to be constant 3.31 USD/MMBtu (Steuer, 2019).
e-LNG	
e-Methanol	
e-FT-liquids	

Appendix 3 Total cost calculation parameters

TOTAL COSTS	**$TC = I_{electrolyser} + O\&M_{electrolyser} + C_{stack} + C_{electricity} + C_{water} + I_{fuelsynthesis} + O\&M_{fuelsynthesis} + C_{CO2capture} - P_{heat} - P_{oxygen} + I_{plant}$**						
Year		2020	2030	2040	2050	**Comment**	**Source**
Electrolyzer investment ($I_{electrolyser}$)							
Electrolyzer type		Alkaline					
Electrolyzer size (MW)		5 MW				Constant parameter	Brynolf et al. 2018 (Table 3)
Electrolyzer CF (%)		80%				Constant parameter	Chosen input
O&M (%)		2-5%				Scenario dependent	Brynolf et al. 2018 (Table 3)
Electrolyzer lifetime (year)		25	30	30	30	Constant parameter	Brynolf et al. 2018 (Table 3)
Investment Cost (EUR/kW)	LOW	600	360	280	200	Estimation. Data sources see Appendix 4	
	MED	950	680	475	270		
	HIGH	1,300	855	670	490		
Stack related costs (C_{stack})							
Stack lifetime (system)		25	30	30	30	Constant parameter	See Electrolyzer lifetime
Stack lifespan (1000 h)		75	90	110	125	Constant parameter	Christensen 2020, p. 19
Stack CF (%)		80%				Constant parameter	Chosen input
Stack Replacement Cost (%)		50% of $I_{electrolyser}$				Constant parameter	Brynolf et al. 2018 (Table 3)
Stack price (EUR/kWh)		Separate calculation				Calculation based on electrolyzer investment cost	
Electricity cost (EUR/MWh)		70	50	35	20	Constant parameter	Chosen input. Compared to DNV GL (2020) and Lloyd's & UMAS (2020)
Water Cost (EUR/mt)		1				Constant parameter	Brynolf et al. 2018 (Table 7)
Fuel Synthesis ($I_{fuelsynthesis}$)							
Plant Scale		Small					
Plant Size		5 MW				Constant parameter	Brynolf et al. 2018 (Table 5)
Plant lifetime		25	30	30	30		Brynolf et al. 2018 (Table 5)
Plant CF		80%				Constant parameter	Chosen input
O&M (%)		4%				Constant parameter	Brynolf et al. 2018 (Table 5)
CO_2 Capture (EUR/mt)	LOW	35	25	25	20	Estimation based on Brynolf et al. 2018 (Table 4); Dieterich et al. 2020 (Table 3), Roussanaly et al. 2021 (Appendix A) literature compilations	
	MED	50	35	35	30		
	HIGH	70	55	55	40		

Plant investment cost, $I_{fuelsynthesis}$ (EUR/kW)			
Methane	600 (100-900)	Scenario dependent	Brynolf et al. 2018 (Table 5)
Methanol	1 000 (600-1,200)	Scenario dependent	Brynolf et al. 2018 (Table 5)
FT-liquids (gasoline and diesel)	1 300 (800-2,100)	Scenario dependent	Brynolf et al. 2018 (Table 5)
Heat sell price (EUR/MWh)	30 EUR/MWh	Constant parameter	Brynolf et al. 2018, p. 1899
Oxygen sell price (EUR/mt)	50 EUR/mt	Constant parameter	Brynolf et al. 2018, p. 1899
Indirect OPEX	100%	Constant parameter	Chosen input
Capital Cost parameters (shared for $I_{electrolyzer}$ and $If_{uelsynthesis}$)			
Interest rate	4%	Constant parameter	NREL ATB-data (2020)
Depreciation rate	Same as the lifetime of electrolyzer or the plant		Chosen input

Appendix 4 Calculated and estimated parameters

4.1 Electrolyzer investment cost (EUR$_{2020}$ / kW)				
	Present (2020)	2030	2040	2050
LOW	600	360	280	200
MED	950	680	475	270
HIGH	1,300	855	670	490

Sources: Dieterich et al. 2020, Brynolf et al. 2018, Christensen 2020, IRENA 2019, IEA 2020, and BNEF 2019 according to Christensen 2020 (Table 4.3)

4.2 Electrolyzer stack investment cost (EUR$_{2020}$ / kWh)				
	Present (2020)	2030	2040	2050
LOW	900	540	280	200
MED	1,710	1,224	570	324
HIGH	3,900	2,565	1,340	980

Source: Own calculation based on the given parameters

4.3 CO$_2$ capture price estimates (EUR/mt)				
	Present (2020)	2030	2040	2050
LOW	35	25	25	20
MED	50	35	35	30
HIGH	70	55	55	40

Source: Estimation based on Roussanaly et al. (2021), Dieterich et al.'s (2020) and Brynolf et al.'s (2018) literature compilation.

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