Pathways for Decarbonization of the Icelandic Maritime Sector

Samorka, Ministry of Industries and Innovation, Associated Icelandic Ports and Fisheries Iceland

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Objective:

The main aim of this project is to provide the most likely scenarios for the decarbonization of the Icelandic fleet and describe the fleet and energy mix in 2030, 2040 and 2050 under these scenarios. The project addresses technology replacement and considers the effects of potential policy measures on the decarbonization pathways. These scenarios are compared to a business-as-usual scenario (baseline). The scenarios for fleet and fuel mix are used to estimate the power need and required production capacity for the various years.

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Table of contents

1 EXECUTIVE SUMMARY

There are strong drivers for CO_2 emission reductions and eventually decarbonization of shipping to meet national and international emission targets. The International Maritime Organization (IMO) and the EU are considering strong policy measures like carbon pricing and required reduction in greenhouse gas intensity of fuels. Iceland's large fishing sector and domestic fleet is not directly affected by these proposed measures. However, Iceland has a goal to achieve 10 % renewable energy share before 2030 for the maritime industry and aims to be independent of fossil fuels before 2050.

In this report we have analysed the Icelandic fleet, comprising mostly fishing vessels and domestic navigation, primarily operating in Icelandic waters. Through bottom-up calculations based on traffic data and vessel information we have estimated the energy consumption for most ships in the fleet and have found total fuel consumption relatively close to the fuel sale statistics. We have used these results to evaluate the feasibility of alternative fuel technologies in the fleet. Furthermore, we have modelled scenarios towards 2050 for CO_2 emissions and use of alternative fuels, including carbon-neutral energy carriers. In the scenarios, we have modelled the effect of potential national policy measures, of which some are similar to those proposed by the EU.

As carbon-neutral energy carriers, we have evaluated electricity in batteries, e-hydrogen, e-ammonia, e-methanol and the drop-in alternatives e-MGO and advanced biodiesel (HVO). Among zero-emission technologies, battery-electric operation is the most mature. This is however feasible only for ships with shorter sailing distances and is found to cover a very limited portion of the fleet's energy consumption in 2050. Technologies for ammonia, hydrogen or methanol operation will, to varying degrees, become commercially available in the years towards 2030.

Our scenarios indicate that without strong policy measures, the energy mix will still be dominated by fossil fuels (MGO). In the scenarios where we assume strong policy measures, e-methanol and e-ammonia eventually become the dominating fuels in the energy mix. These fuels are hydrogen-based, and lead to a necessity to build up hydrogen production capacity. With strong policy measures, the fleet can be decarbonized within 2050, given that considerable onboard technology barriers are overcome, the production capacity of electro-fuels (e-fuels) is largely scaled up, and infrastructure for fuels is in place. However, the gradual pace of technology commercialization and the long lifetime of ships results in limited emission reductions before 2030 in our scenarios.

Figure 1-1 shows the expected energy mix in a scenario that meets the goal of 10 % renewable share in 2030 and independency of fossil fuels in 2050.[1] Policy measures in this scenario include both support for onboard investments, increased CO_2 tax and a gradually increased required share of carbon-neutral fuels. In this scenario, drop-in fuels (labelled *0-MGO* in the figure) constitute the largest part of the carbon-neutral fuels until the mid-30s. Drop-in fuels include advanced biodiesel/HVO and e-MGO. Among these, e-MGO is assumed to have lower price than HVO from around 2040, leading to the preferred drop-in fuel switching from HVO to e-MGO at this point. Electro-fuels requiring onboard technology investments include e-H2 (compressed hydrogen gas produced by renewable energy), e-ammonia and e-methanol. There is some limited uptake of these fuels before 2030, while they become gradually dominant towards 2040, as new ships enter the fleet and the technologies become competitive. However, some drop-in e-MGO remains in the fleet also in 2050. The total demand for electricity production in 2050 for this energy mix is around 3500 GWh.

The dominating use of drop-in fuels in the short term reflects the fact that all the alternatives ammonia, hydrogen and methanol require onboard technology investments or design modifications. Although certain amounts of these fuels can be blended with MGO in some conventional marine engines, safety regulations require that the onboard fuel system (pipes, tanks etc.) is modified, due to the physical properties of these fuels. In practice, this leads to blend-in of even smaller amounts not being straight-forward and will also come with a significant onboard technology cost.

The modelled energy mix should not be understood as the only or most likely pathway to decarbonization. Key barriers related to onboard design and safety need to be solved for ships to operate on these alternative fuels. The fuels all have

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[1] This is *Scenario 5*, as described in chapter 6.3

advantages and disadvantages, either on the supply (land) or consumption (ship) side. Especially hydrogen and to a lesser degree ammonia have limited applicability due to energy density. Both require careful design solutions to ensure onboard safety and to integrate the onboard fuel system. If for example ammonia eventually will not be considered a sufficiently safe marine fuel for fishing vessels, the share of methanol in the fuel mix will probably be higher. Methanol technology is design-wise easier to accommodate on board the ship. Both e-methanol and e-MGO however require CO_2 as a feedstock and have higher production costs than e-hydrogen and e-ammonia. To ensure carbon-neutrality and no net emissions with the use of these fuels if the CO_2 comes for instance from industrial plants, the same amount of CO_2 needs to be captured and stored elsewhere. Alternatively, the CO_2 feedstock must come from biomass or direct air capture (DAC).

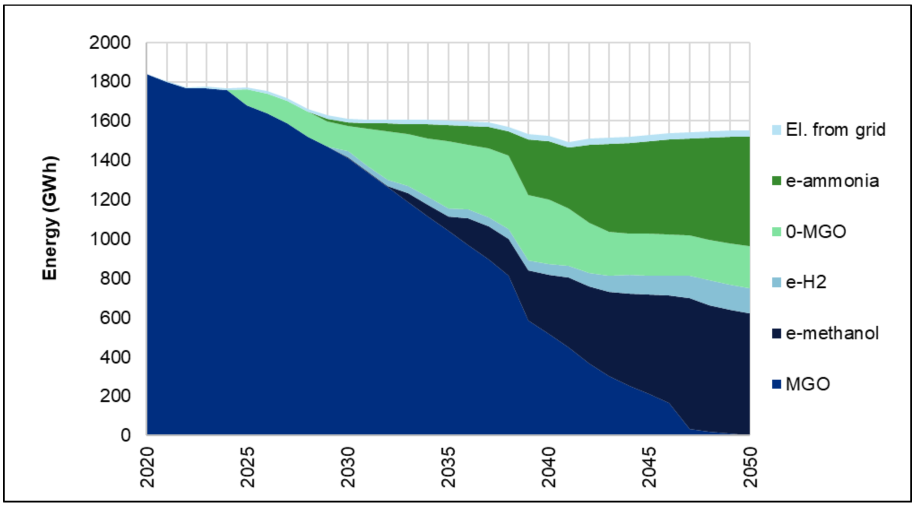


Figure 1-1: Expected energy mix in a scenario achieving 10 % renewable energy in 2030 and fossil-free Islandic maritime traffic in 2050. Policy measures in this scenario include both support for onboard investments, increased CO_2 tax and a gradually increased required share of carbon-neutral fuels. Legend: MGO - marine as oil (fossil fuel); e-H2 - compressed hydrogen gas; 0-MGO - drop-in fuel (HVO/e-MGO)

Decarbonization will come with a cost, and shipowners need to be incentivized to be able to handle these costs. Although investment subsidies are important to reduce the financial risk of developing new ship designs, the increased operational cost due to higher energy price for carbon-neutral fuels makes it difficult to ensure profitability without having an increased price on CO_2 or limiting the use of fossil fuels.

Iceland is in a unique position with its maritime sector being dominated by fishing vessels. This also poses a challenge when it comes to the introduction of alternative fuel technologies, given the fishing vessels' long sailing distances and long and sometimes unpredictable time at sea. Investment support, like modelled in this analysis, can reduce the financial risk, and valuable learning can be gained from ongoing alternative fuel pilot projects within shipping in the coming years.

Iceland also benefits from vast energy resources, and relatively cheap electricity. The access to fuels, from production to distribution and bunkering, will be essential to account for in the planning of zero-emission projects – much more than it has been with easily distributed conventional fuels. The energy transition requires large upscaling of electro-fuel production capacity, and cooperation across the value chain will therefore be imperative. The build-up of demand and production capacity will need to be coordinated since neither currently exists in Iceland. Once the first pilot projects have been commissioned a market for electro-fuels can be established to enable Iceland to become self-sufficient with energy. Furthermore, ships in international trade traditionally bunkering fuel in other countries may in the future also be served by carbon-neutral fuels produced in Iceland.

2 INTRODUCTION

Iceland has set a legal target to become carbon neutral by 2040. Key actions to be taken include a rapid clean energy transition in transport (Government of Iceland, 2020). Carbon neutrality can be obtained although some sectors still have emissions, since other sectors might play a role as carbon sinks. Iceland also has a goal to achieve 10 % renewable energy share before 2030 for the maritime industry and aims at becoming independent of fossil fuels before 2050 (Ministry of Industries and Innovation, 2020).

Fishing constitutes the major share of fuel consumption and emissions from the Icelandic maritime sector. The sector has over the past decades reduced its fuel consumption and carbon footprint considerably (The Environment Agency of Iceland, 2018), but the use of carbon neutral fuels and zero emission technology needs to be introduced for the sector to decarbonize. There are several drivers and technology development projects that may enable both the global and domestic maritime sectors to move towards decarbonization, but many steps need to be taken for carbon neutral fuels and zero emission technology to be mature, technically feasible and commercially viable for all ship types and trades. A rapid energy transition in the maritime sector is also challenging due to the long lifetime of ships.

It is uncertain what fuels will replace the currently used fossil fuels, and what will be the most likely pathways for the decarbonization of the Icelandic maritime sector. To investigate this, Samorka has together with the Ministry of Industries and Innovation, Faxafloahafnir (Associated Icelandic Ports) and Fisheries Iceland engaged DNV to develop scenarios for the decarbonization of the Icelandic domestic maritime sector and describe the fleet and energy mix towards 2050 in these scenarios. As Iceland has vast resources to produce renewable electricity, the country has the potential to produce carbon-neutral electro-fuels such as hydrogen and methanol. There is also capacity to scale up production of biodiesel in Iceland. Iceland has no fossil fuel production and is therefore entirely reliant on imports. A transition to these alternative fuels may lead to Iceland being self-sufficient with energy for use in the maritime sector. Iceland’s target of achieving carbon neutrality by 2040 and becoming independent from fossil fuels by 2050 is the underlying driver for this analysis. The analysis builds on the official fuel use forecast for 2021-2050 and presents several pathways for decarbonization in the maritime sector.

This report is structured as follows: The current Icelandic fleet and its fuel use and emissions is described in chapter 3. Chapter 4 provides an overview of emission targets and drivers for the decarbonization of shipping, both in Iceland and internationally. Chapter 5 gives a description of alternative marine fuels considered in the analysis, with current technology development trends. In chapter 6 we present an analysis of potential scenarios towards 2050, focusing on energy mix and emissions, while uncertainties are discussed in chapter 7. The findings are discussed in chapter 8.

3 CURRENT FLEET, ENERGY USE AND CO_2 EMISSIONS

3.1 Method for analysing current ship traffic and fuel consumption

We use AIS data from ship traffic in Icelandic waters to identify ships and estimate energy need and fuel consumption. The AIS data enables us to track each specific ship, identify port stays, calculate sailing distances, and estimate fuel consumption. We couple data from the official ship registry, which includes vessel size and installed engine power, with the AIS data to estimate fuel consumption for each ship. The aim is not to establish an estimate of the total fuel consumption in Icelandic waters, but to obtain representative statistics of the energy demand profile of the different ships in the fleet. The energy demand profile is important for assessing the feasibility of operation with alternative fuels as well as fuel cost for each ship in the scenario analysis (chapter 6.1). Further description of the methodology and assumptions for calculation of fuel consumption is given in Appendix B.

From the customer, we have received AIS data for Icelandic waters in 2016 and use this to analyse the ship traffic this year. The estimated fuel use is compared to official fuel sales statistics, to evaluate the robustness of the calculation methodology.

The AIS analysis starts with identifying ports. This is done by algorithms that identify locations where ships frequently lay still (the speed is given by the AIS data), and couple this with geographical shapes. The red dots in Figure 3-1 show the ports we have identified in Iceland by this approach.

When ports have been identified, we analyse all voyages carried out by ships between ports and calculate sailing distances and time at sea and estimate energy need and fuel consumption. Three different voyage types are identified, as shown in Figure 3-1:

- *Domestic voyages*: Voyages between Icelandic ports
- *International voyages*: Voyages between an Icelandic port and a port abroad
- *Passing voyages*: Voyages that intersect with the geographical area, but do not include calls in Icelandic ports

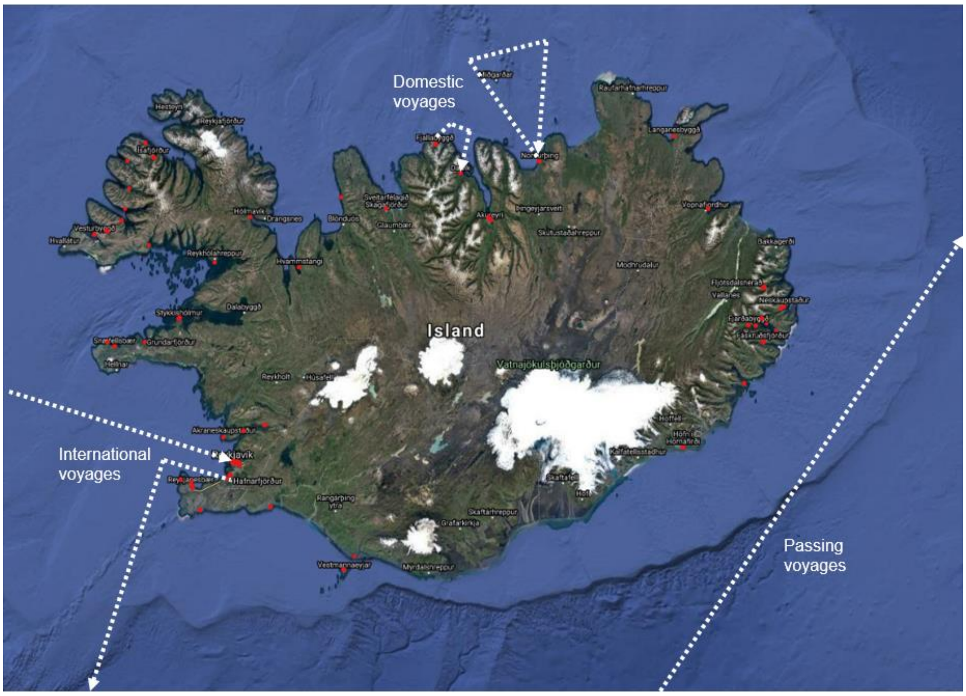


Figure 3-1: Illustration of mapping of traffic by voyage type. Identified ports are indicated with red dots

Since we have AIS data for Icelandic waters only, only the parts of international voyages and passing voyages that are within this area are included. This could imply that potential domestic voyages going out of, and then back into Icelandic waters, are registered as an international voyage. This is however assumed to be a minor issue; according to Fisheries Iceland (2017), Icelandic fishing vessels relatively seldom sail out of Icelandic waters.

After categorizing voyages, we summarize the calculated fuel consumption for all voyages during the year to obtain the domestic and international fuel consumption of the ships in the data material. This can be compared to the estimated fuel consumption of the ships with the sale statistics given in the national inventory report (The Environment Agency of Iceland, 2018).

3.2 Total fuel consumption and fleet composition

The total domestic fuel consumption from the ships in the data material is found to be 127 ktonnes for fishing vessels, and 15 ktonnes for other vessels. A comparison to official sales statistics will naturally not become a one-to-one comparison as some ships will buy the fuel in Iceland, others may buy it abroad. This likely depends on how much of the time a ship operates in Iceland. Therefore, when comparing calculated domestic and international fuel use with reported fuel consumption, we exclude the consumption of ships that have less than 50 % of their activity in domestic traffic. We assume that ships that have most of their operation in Icelandic waters are likely to bunker fuels in Iceland and that an Icelandic market for production of fuels as well as potential policy measures to reduce emissions could be targeted towards these ships. Ships that do much international sailing, may more likely bunker elsewhere and may also be affected by the EU and international regulations. For ships that have at least 50 % of their activity in domestic traffic, we estimate a total consumption of 122 ktonnes for fishing vessels, of which around 90 % is domestic. This is less than the reported statistics on fuel sales to Icelandic fishing vessels of 146 ktonnes in 2016 (Energy Forecast Committee, 2021), although the numbers cannot be compared directly due to the uncertainties related to bunkering locations described above. For domestic navigation (other ship types than fishing) we estimate 9,6 ktonnes, which is quite close to the reported sales amount of 8,7 ktonnes in 2016 (The Environment Agency of Iceland, 2018). A further discussion on fuel consumption in the past years is given in chapter 6.2.

The number of ships in the AIS data material sailing in Icelandic waters for 2016 is around 1400. From the voyage analysis a certain fraction of these is found to not visit ports in Iceland. We find 1061 ships to have at least 50 % of their activity in domestic traffic, and include these in the further analysis, distributed between ship categories as listed in Table 3-1. The Icelandic ship registry per June 2021 contains 2236 ships, of which many are smaller vessels, assumed not contained in the AIS material. In our AIS material, we however still have many ships smaller than 10 GT (gross tonnes). Although high in number, this size group contributes little to the total fuel consumption, as shown in Figure 3-2. The figure shows the expected trend of increasing average fuel consumption per ship for larger ships.

It could be assumed that the ships from the ship registry that are not present in the AIS material would have a fuel consumption in the same order of size as the smaller ships in the AIS material. Hence, our data material should comprise the ships contributing significantly to total energy consumption. It should be noted that we cannot expect this bottom-up calculation of fuel consumption to give the “correct” numbers for fuel consumption, as reported in the fuel sales statistics. In addition to the fact that the data material does not cover all ships, we must make assumptions on for example missing engine power data on some of the ships in our material, we do not have information on fishing gear for the different fishing vessels, and we may not reflect all the different operations correctly. However, the results provide adequately representative fleet statistics, and are considered sufficient for analysing the feasibility and costs of alternative fuels in the fleet.

Table 3-1: Number of ships for which at least 50 % of their sailing is domestic, whose energy consumption is the basis of this analysis

Ship type	Number of ships
Fishing vessel	828
General cargo ship	21
Leisure vessel	116
Passenger ship	65
Research/surveillance and rescue ship	11
Tug/work ship	20

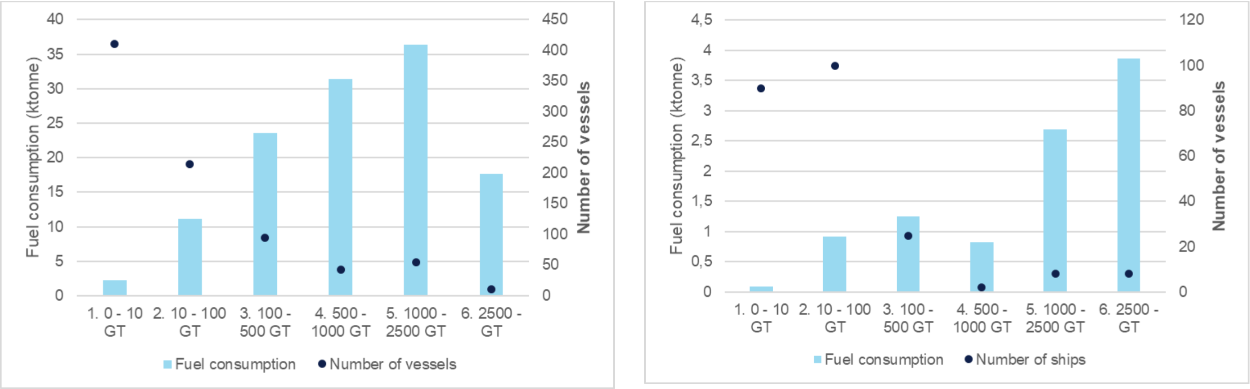


Figure 3-2: Calculated fuel consumption and number of fishing vessels (left) and other vessel types (right) of different size categories (for ships that have 50 % or more domestic sailing)

3.3 Sailing distances and energy use per sailing

From the AIS analysis we calculate the sailing distance per voyage (from port to port). Figure 3-3 shows the distribution of voyages of different sailing distances for fishing vessels overall. Shorter voyages are higher in number (left plot), while the longer contributes more to the total fuel consumption (right plot). Also, the larger ships have a bigger share of long sailing distances. Figure 3-4 shows the same for other vessel types than fishing vessels.

Our analysis identifies 61 different ports. Figure 3-5 shows the total energy consumption of all voyages of ships that depart from the different ports. The figure may indicate the share of required energy to be bunkered at each location, but a thorough analysis would be needed to determine suitable bunkering locations.

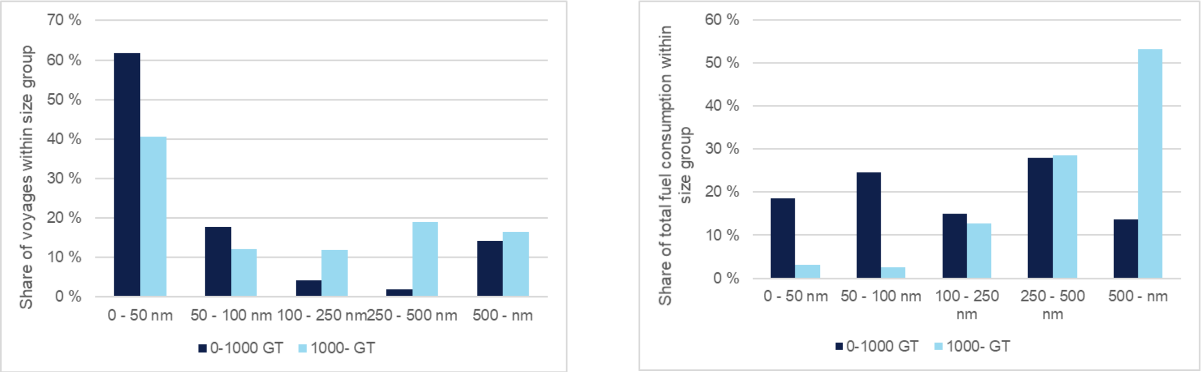


Figure 3-3: Share of voyages of different sailing distances (left) and share of total fuel consumption distributed between voyages of different sailing distances (right) for fishing vessels (for ships that have 50 % or more domestic sailing). Separate distributions are shown for vessels below 1000 GT and above 1000 GT (nm; nautical mile)

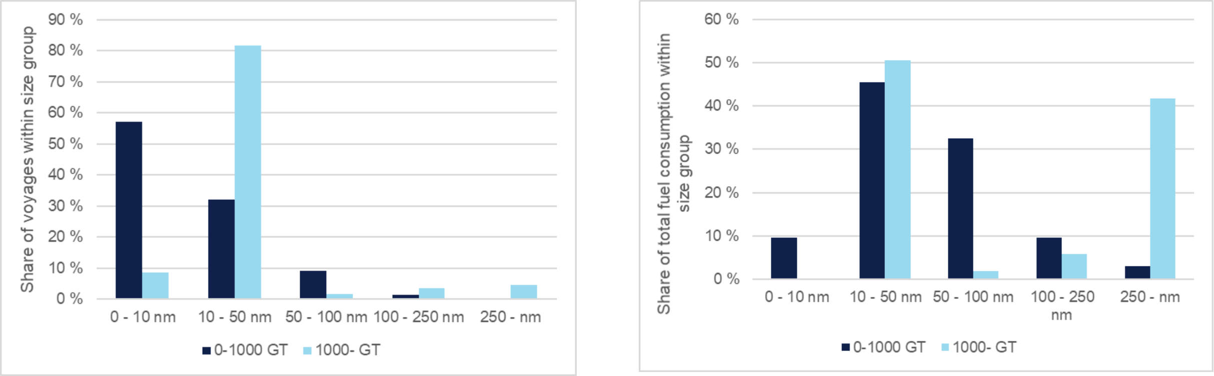


Figure 3-4: Share of voyages of different sailing distances (left) and share of total fuel consumption distributed between voyages of different sailing distances (right) for other vessel types (for ships that have 50 % or more domestic sailing). Separate distributions are shown for vessels below 1000 GT and above 1000 GT (nm; nautical mile)

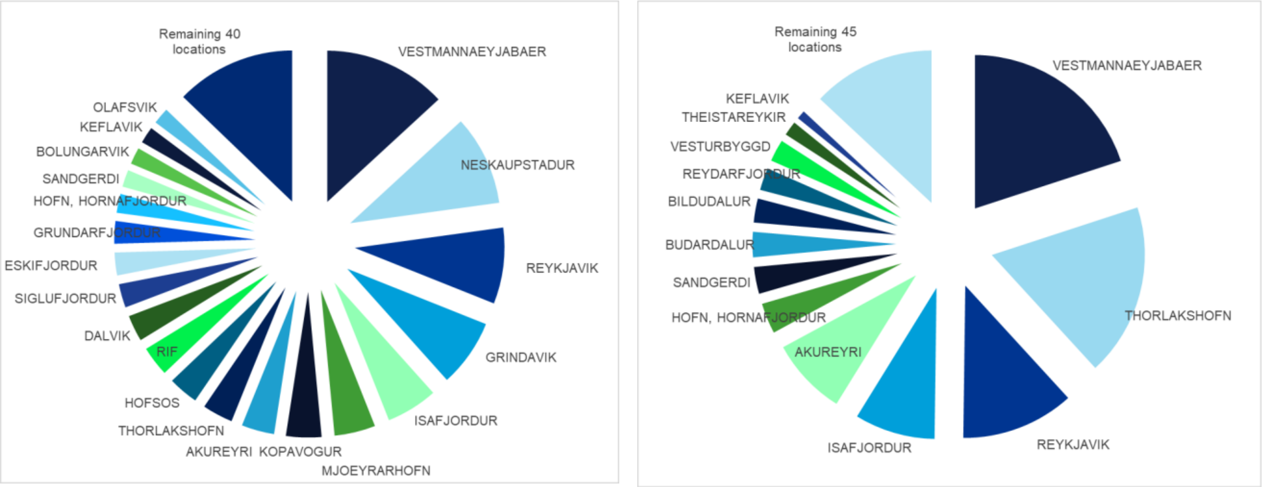
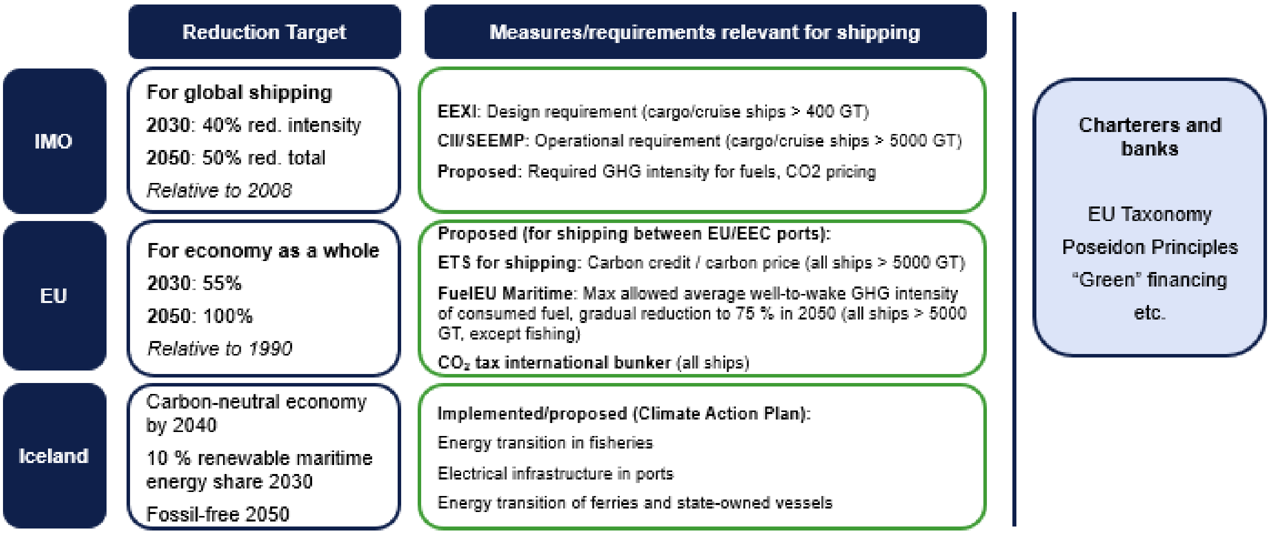


Figure 3-5: Distribution of total fuel consumption for voyages for fishing vessels (left) and other vessels (right) sailing from different ports (selected fleet of more than 50 % domestic sailing)

4 EMISSION TARGETS AND DRIVERS FOR THE DECARBONIZATION OF SHIPPING

This chapter provides a brief description of emission targets, requirements and drivers for maritime decarbonization in the IMO, the EU and Iceland. An overview is provided in Figure 4-1, and further elaborated below. It should be noted that most ships in the Icelandic domestic fleet will not be directly affected by the proposed measures and requirements from the IMO and the EU, as they are primarily targeted towards larger ships and not fishing vessels. However, these measures will lead to a gradual decarbonization of international shipping, a market for carbon-neutral fuels, and consequently also affect domestic shipping in Europe. Like Iceland's emission targets, other national targets in different European countries will also contribute to reducing emissions from domestic shipping.



	Reduction Target	Measures/requirements relevant for shipping
IMO	**For global shipping** **2030**: 40% red. intensity **2050**: 50% red. total *Relative to 2008*	**EEXI**: Design requirement (cargo/cruise ships > 400 GT) **CII/SEEMP**: Operational requirement (cargo/cruise ships > 5000 GT) **Proposed**: Required GHG intensity for fuels, CO2 pricing
EU	**For economy as a whole** **2030**: 55% **2050**: 100% *Relative to 1990*	**Proposed (for shipping between EU/EEC ports):** **ETS for shipping**: Carbon credit / carbon price (all ships > 5000 GT) **FuelEU Maritime**: Max allowed average well-to-wake GHG intensity of consumed fuel, gradual reduction to 75 % in 2050 (all ships > 5000 GT, except fishing) **CO_2 tax international bunker** (all ships)
Iceland	Carbon-neutral economy by 2040 10 % renewable maritime energy share 2030 Fossil-free 2050	**Implemented/proposed (Climate Action Plan):** Energy transition in fisheries Electrical infrastructure in ports Energy transition of ferries and state-owned vessels

Charterers and banks

EU Taxonomy
Poseidon Principles
"Green" financing
etc.

Figure 4-1: Overview of reduction targets and measures/requirements relevant for shipping

IMO

In 2018, the IMO adopted a climate strategy for international shipping, including the following ambitions:

- Obtain at least 40 % reduction of *CO_2 emission per transport work* (CO_2 intensity) in 2030, and 70 % in 2050, compared to 2008
- Obtain at least 50 % reduction of *absolute CO_2 emissions* from international shipping within 2050, compared to 2008, and work towards full decarbonization within the century

The first ambition is assumed to be met by the introduction of the technical and operational measures EEXI, CII and Enhanced SEEMP[2] (short-term measures), while further measures will be needed to reach the 2050 goal and eventually full decarbonization. Proposed measures include a global CO_2 tax or trading scheme for international shipping and required GHG intensity for fuels, similar to that proposed by the EU. These proposals will be discussed at the next MEPC (IMO's Marine Environment Protection Committee) meeting in November 2021. The measures are primarily only for larger ships (> 5000 GT).

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[2] Further description of measures and timelines can be found here: https://www.dnv.com/maritime/insights/topics/decarbonization-in-shipping/regulatory-overview.html

EU

To support the realization of the EU's reduction goals of 55 % in 2030 and carbon neutrality by 2050, the package *Fit for 55* was proposed by the EU Commission in July 2021. This has not been adopted yet, pending conclusion from other EU bodies. The key measures relevant for shipping in the EU/EEC are:

- Inclusion of shipping in the European carbon trading scheme ETS. This implies that commercial passenger and cargo ships above 5000 GT will pay for their CO_2 emissions according to the ETS carbon price, for half of the emissions on voyages between ports in EU/EEC and ports outside, and the full emissions in ports and between EU/EEC ports. A gradual phasing from 20 % of emissions in 2023 to 100 % of emissions in 2026 is proposed. This will apply only for ships larger than 5000 GT.
- Introduction of *FuelEU Maritime*, requiring stepwise reduction of well-to-wake GHG intensity of onboard energy use (g CO_2e/MJ), including shore power at port. There is a gradual reduction from 2 % in 2025 to 75 % 2050, compared to the reference level in 2020. This will apply only for ships larger than 5000 GT, and not fishing vessels.
- In addition, a CO_2 tax on all fuel bunkered for international sailing is proposed, around 37 EUR/tonne CO_2 (this applies to *all ships*).

It should be noted that especially the second measure will be important for the introduction of carbon neutral fuels. An impact assessment of Fit for 55 indicates that including shipping in the ETS will not sufficiently incentivize emission reductions and the uptake of carbon-neutral fuels (European Commission, 2020).

Iceland

In addition to the IMO and the EU, Iceland has set a national target and proposed measures for emission reduction from ships. Iceland aims to be carbon-neutral by 2040, and to have fossil fuels replaced by renewable energy sources by 2050 (Ministry of Industries and Innovation, 2020). Iceland has also set a target of achieving 10 % renewable energy share before 2030 for the maritime industry.

Charterers and banks

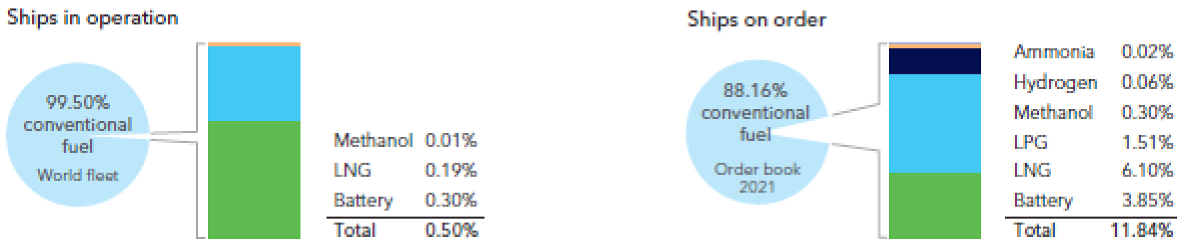
It is also worth noting that there are initiatives from charterers and financial institutions, establishing requirements for emission reductions from ships. This includes charterers that require an increasingly strict carbon intensity for the ship transport of their commercial goods, and initiatives from banks and guidelines such as the EU taxonomy providing better financial conditions for low and zero emission projects ("green" financing).

5 ALTERNATIVE MARINE FUELS

In the previous chapters, we looked at the Icelandic fleet's fuel consumption and emissions, and drivers for decarbonization. This chapter describes alternative marine fuels with the potential to decarbonize shipping. Energy efficiency measures are also key to reduce energy consumption and emissions from ships but are not discussed further in this report. With the term *alternative marine fuels*, we mean other fuels than conventional fossil fuel oil, such as MGO (marine gas oil), supplying energy on board a ship. In this chapter, we first present a short overview of the status of alternative fuels in shipping and a brief description of technology development and some selected projects. Thereafter, we describe the fuels included in this analysis. Assumed fuel prices and investment costs for alternative fuel technologies are described in chapter 6.1.

5.1 Current global development of alternative marine fuels

DNV's Alternative Fuels Insight platform[3] provides an overview of the current global uptake of alternative fuels, including batteries, in shipping. Figure 5-1 shows the current uptake of alternative fuels in ships in operation and ships on order (DNV, 2021a). It should be noted that LNG (liquefied natural gas) is a fossil fuel, and both ammonia, hydrogen and methanol can be fossil based (most current production globally is fossil). The carbon footprint of the different fuels depends on their production pathways.



Key: Liquefied natural gas (LNG); liquefied petroleum gas (LPG)
a) Sources: IHSMarkit (ihsmarkit.com) and DNV's Alternative Fuels Insights for the shipping industry – AFI platform (afi.dnv.com)

Figure 5-1: Uptake of alternative fuels for the world fleet as of June 2021 (percentage of ships in operation and on order) (DNV, 2021a)

Many of the current pilot and demonstration projects rely on governmental grants or are otherwise publicly initiated or supported. In Norway for example, environmental requirements for public purchasing of ferry services have led to rapid electrification of the ferry fleet, with more than 50 plug-in hybrid car ferries operating battery-electric.[4] In addition, one smaller hydrogen-electric ferry is expected to start operating late 2021, and two larger hydrogen-electric ferries – covering three-hour long crossings over open sea – are expected to begin operating around 2025. Internationally, there are also several zero-emission passenger ships in operation, primarily battery-electric. Currently, most zero-emission projects are ferry and passenger ships as their operational pattern is favourable for battery or hydrogen powered propulsion.

Among domestic cargo and merchant ships, there are quite a few development projects on hydrogen and ammonia powered ships that are expected to start operating within 2025. In Norway, a 5500 DWT cargo ship powered with compressed hydrogen is contracted to go into operation early 2024,[5] and a ship using liquefied hydrogen for cargo transport along the Norwegian coast is also planned for 2024.[6] This year the world's first tanker running on green

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[3] www.afi.dnvgl.com

[4] https://energiogklima.no/elektriske-bilferger-i-norge/ (in Norwegian)

[5] https://www.norwegianshipdesign.no/archive/with-orca-powered-by-nature

[6] https://www.wilhelmsen.com/media-news-and-events/press-releases/2020/wilhelmsens-topeka-hydrogen-project-awarded-nok-219-million/

ammonia is also planned to be launched.[7] Furthermore, the major container shipping company Maersk has signed a contract for 8 large container vessels to be fuelled by carbon neutral methanol.[8] The vessels are expected to start operating in 2024.

The Getting to Zero Coalition gives a comprehensive overview of maritime zero emission projects and highlights that while only two *hydrogen* projects for ships above 5000 DWT were initiated before 2020, six new projects have since begun. Similarly, while four *ammonia* projects for ships above 5000 DWT were initiated before 2020, 10 new projects have since started (Getting to Zero Coalition, 2021).

For fishing vessels, there are fewer projects with alternative fuels. According to a report by SINTEF Energy Research (2020), LNG/LBG (liquified natural gas / liquefied biogas) and biodiesel are alternative fuels technically feasible for all fishing vessel types, and hydrogen fuel cells for coastal fishing ships. There are currently quite a few newer large trawlers that have diesel electric propulsion with hybrid power supply and smaller battery packs on board (SINTEF Energy Research, 2020). Although the primary energy source is fuel oil, the use of batteries improves the engine loads and reduces the fuel consumption and can also together with a shore connection enable emission-free operation at ports. For smaller coastal fishing vessels, more shore-charged electric operation can be possible, such as the 11 m hybrid-electric Norwegian boat “Karoline” which can operate 2-3 hours on battery.

The reduced energy density of alternative fuels, limiting the tank range, compared to diesel is an obvious technical barrier for their use within the fishing sector. LNG also requires additional space compared to diesel, but recently some LNG trawlers have been delivered: the 86 m *Sunny Lady* and the 85 m *Libas* are both equipped with battery packs in addition to the LNG propulsion system.

It should be noted that most, if not all, current pilot and development projects rely on a dual fuel setup, i.e. the vessels designed for alternative fuels are also capable of operating on conventional fuel oil. This is also the case for the LNG capable trawlers mentioned above. This is further addressed in the sub-chapter below.

5.2 Fuels and technologies included in the analysis

This report analyses the feasibility and potential uptake of a range of zero-emission or carbon-neutral fuels and technologies in the Icelandic maritime sector. Some “fuels” may also be denoted *energy carrier,* for instance electricity from grid stored in batteries on board a ship. Table 5-1 presents an overview of the fuels included in the analysis. This selection is limited to conventional fuel oil/MGO, as is used in Icelandic domestic fleet today, biodiesel, electricity from grid, and a range of electro-fuels (e-fuels). Electro-fuels are synthetic fuels produced from hydrogen with renewable electricity as a basis. There is currently some biodiesel in use in Iceland, and this can (depending on the quality of the biodiesel) replace or be blended with fossil MGO on all ships with conventional technology, and as such reduce the carbon footprint of the ships without onboard technology investments. The same applies for e-MGO. The energy carriers e-hydrogen, e-ammonia, e-methanol and e-MGO are all based on hydrogen produced with renewable energy by electrolysis of water, a production pathway that is relevant for Iceland with its abundant renewable energy supply. Therefore, *blue* hydrogen and ammonia, produced from natural gas with CCS (carbon capture and storage), is not included in the analysis. E-hydrogen and e-ammonia do not contain carbon, while e-methanol and e-MGO do, and therefore emit CO_2 when combusted. Hence, for these fuels to be considered carbon-neutral, they need to be produced with carbon captured from biomass or from air (*direct air capture*; DAC).

There are also other technologies and fuels that could be relevant for emission reduction or decarbonization as well. LNG and LPG (liquefied petroleum gas) are for example gaining momentum as fuels in shipping. These are currently not used in Iceland, have limited GHG reduction potential (10-20 % reduction compared to MGO) and are not included in this analysis. Liquefied e-methane/synthetic methane or biogas would be a carbon-neutral alternative that could act as drop-in fuel on LNG fuelled vessels. The cost of onboard liquefied gas technology is assumed higher than for example

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[7] https://www.griegstar.com/grieg-and-wartsila-to-build-groundbreaking-green-ammonia-tanker/

[8] https://www.maersk.com/news/articles/2021/08/24/maersk-accelerates-fleet-decarbonisation

ammonia and methanol technology (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021), especially due to the need of cryogenic storage tanks. Also, e-methane is in most estimates more expensive than e-ammonia and comparable to or more expensive than e-methanol. For these reasons, and the fact there are no LNG vessels or infrastructure in Iceland, carbon-neutral methane is not included in this analysis. It could however be that methane produced in Iceland could be part of the future fuel mix, for example by serving gas fuelled vessels in international traffic.

Table 5-1: Overview of fuels/energy carriers and technologies

Fuel/energy carrier	Onboard technology
MGO (marine gas oil)	Conventional, fossil alternative. Internal combustion engine (mono or dual fuel), and tank system
Battery-electric/Electricity	Battery charged with electricity from grid, often in combination with redundant diesel-electric machinery and onboard tank system
Biodiesel/HVO (bio-MGO)[9]	Same as MGO, can be utilized by all ships using MGO, without onboard modifications
e-Hydrogen	Internal combustion engine (gas or dual fuel) or fuel cell system. The gas is stored in compressed or liquid form, in separate tanks.
e-Ammonia	Internal combustion engine (gas or dual fuel) or fuel cell system. The gas is stored in liquid form, in separate tanks.
e-Methanol	Internal combustion engine (liquid or dual fuel) or fuel cell system. The liquid can be stored in standard fuel tanks, with minor modifications
e-MGO	Same as MGO, can be utilized by all ships using MGO, without onboard modifications

Appendix A provides more details on the different carbon-neutral fuels.

Regarding technology maturity, battery-electric operation of ships is relatively mature for selected ship types, as described in chapter 5.1. Figure 5-2 shows a timeline for when DNV expects ammonia, hydrogen, and methanol technologies to be commercially available for use in shipping (DNV, 2021a). Although demonstration projects are implemented on ships already, it is expected that commercial application of all options is closer to 2030. Commercial application implies that enough pilot projects and early movers have implemented and tested the technology and overcome key technical barriers, so that the uptake of the technologies can be scaled up and applied on many ships within different ship segments.

In general, the ICE option for these fuels is more mature than fuel cells. According to DNV's knowledge of findings from engine tests, the efficiency of combustion engines burning ammonia, hydrogen or methanol is similar to the efficiency of conventional engines burning MGO (typically 40-45 %). The use of fuel cells has the advantage over ICE that they may reduce noise, need of maintenance and emissions of other pollutants than CO_2, as well as improve efficiency (lower energy loss than ICE; efficiency around 50-60 %, depending on type of fuel cell). However, fuels cells are more costly

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[9] A wide range of different biodiesel variants are produced, with their different sources, carbon footprint and sustainability criteria, and consequently different prices. We assume here HVO (hydrotreated vegetable oil), advanced biodiesel, which is a pure drop-in option for existing engines.

and have a shorter lifetime. The use of onboard excess/waste heat recovery systems may improve the efficiency of the fuel cell.

This timeline is used as basis in this analysis. In addition to technological maturity, economic viability and the availability of infrastructure and fuels for bunkering will be key to determine the actual uptake of the fuels and technologies in the coming decades.

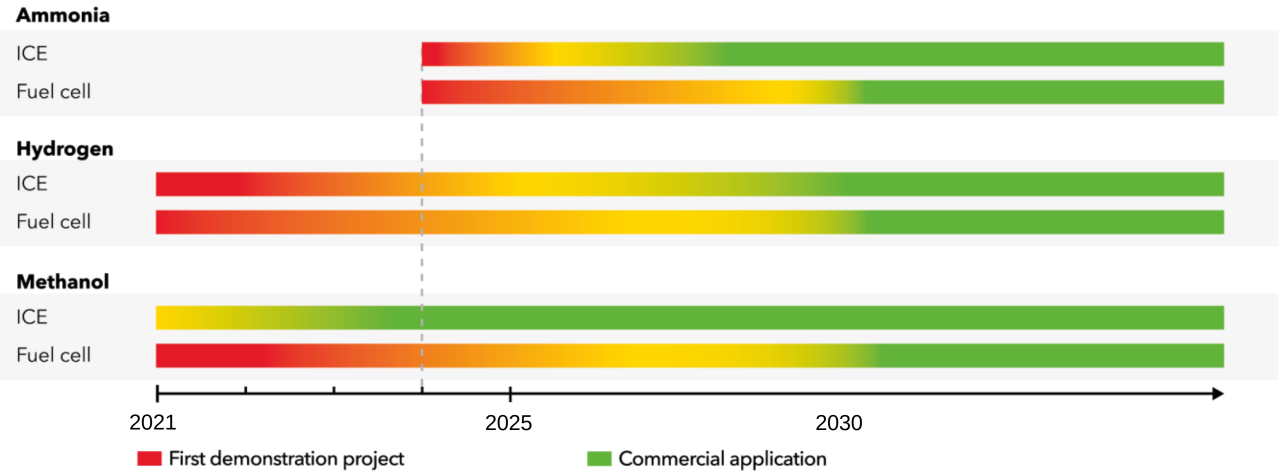

Figure 5-2: Timeline for technology maturity for the marine fuel technologies ammonia, hydrogen and methanol ICE (internal combustion engine) and fuel cell (DNV, 2021a)

5.3 Technical challenges related to the use of ammonia, hydrogen, or methanol on board ships

There are technical challenges that need to be considered when designing a ship to operate on ammonia, hydrogen, or methanol. In this chapter, we briefly discuss some of these. First, all these fuel options have lower volumetric energy density (units of energy per volume) than conventional fuel oil (diesel/MGO), as shown in Figure 5-3.

Also, the energy density *per mass* of the alternative fuel tanks is lower than for diesel tanks, although the difference in energy density per volume is larger. This lower volumetric energy density implies that more space on board needs to be allocated for storage of fuel to store the same amount of energy, compared to conventional fuels. Alternatively, the ship will have to be designed with a lower sailing range per tank bunkering.

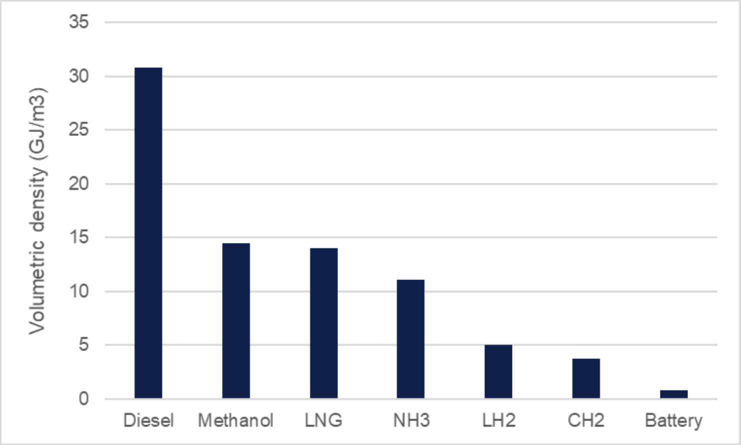

Figure 5-3: Volumetric energy density of alternative fuels[10], including tank system (LH2 – liquefied hydrogen gas, CH2 – compressed hydrogen gas, NH3 - ammonia) (MariGreen, 2018).

As described in the above chapter, the fuels can be utilized on fuel cells (FC) or internal combustion engines (ICE). The latter can be either mono fuel or dual fuel ICE. Although minor amounts of some of these fuels can be mixed into some conventional diesel engines, specific ammonia, hydrogen or methanol engines need to be used for any significant amounts of fuel. Some engines (gas or dual fuel) may be retrofitted to accommodate for these fuels[11], but in general the ship needs to be designed with new engines.

Both ammonia and methanol are low-flashpoint fuels, and their application in combustion engines typically requires a certain amount of diesel as pilot fuel, injected into the combustion chamber to ensure proper combustion. An alternative for ammonia is to crack some of the ammonia into hydrogen and use this hydrogen as pilot fuel. Further technology development will however be needed for this option to become viable. For hydrogen ICE, pilot fuel is not needed, and 100 % hydrogen use without pilot fuel is viable.[12]

DNV's *Maritime Forecast to 2050* (DNV, 2021a) sets out general guidelines to consider for the fuel system (fuel storage, supply and energy converters) when developing an ammonia-ready design for a large bulk carrier, as an example. This can be generalized to other alternative fuels and vessel types as well, and summarized as follows:

- **Fuel storage:** Evaluate optimal storage capacity and tank characteristics, establish a general arrangement, and identify structural modifications to accommodate the fuel-storage system with minimal impact on operations.
- **Power plant and fuel supply to onboard energy converters:** Evaluate the consequences of a fuel change for onboard energy converters (e.g. engines) and for the fuel supply system.
- **Integration of fuel system:** Verify acceptable trim and stability and ensure ship design is within safety requirements as set out by statutory regulations and class rules.

Safety is a key barrier for all these three fuels, especially for ammonia and hydrogen. For methanol, experience has been gained from handling this as cargo and fuel on chemical carriers. There is an IMO interim guideline for methyl/ethyl alcohols as fuel in place, providing an international standard for methanol as marine fuel and guidance for the integration of an onboard methanol fuel system. The experience on ammonia stored on board ships is however limited to carriage of ammonia in gas tankers and as a refrigerant, but not as a fuel. The toxicity of ammonia – potentially lethal in small concentrations – creates new challenges related to bunkering, storage and handling on board. International

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[10] The higher efficiency of battery-electric operation (higher energy output than ICE) is reflected in the number for battery in the figure. If fuel cell applications are used for one of these fuels, the volumetric density in terms of *energy output* for that fuel would be relatively higher than shown in the figure.

[11] https://www.wartsila.com/media/news/15-05-2020-flexibility-key-to-enabling-shipping-s-transition-to-future-fuels-2823479

[12] https://www.innio.com/en/news-media/news/press-release/new-hydrogen-engine-from-innio-ready-for-operation-after-passing-all-tests

regulations on ammonia as fuel have not been developed. DNV issued class rules for ammonia as fuel in July 2021 to support owners, shipyards, and designers in their consideration of ammonia as fuel.

There is even less experience with hydrogen on board ships, as this traditionally has not been transported on ships like ammonia has been. It is especially the low ignition energy, high flame propagation speed and consequently the explosion risk that is of concern. The risk of storage and handling of hydrogen on board ships is currently explored through research projects, but prescriptive rules / class rules are not expected in the near future.

To obtain acceptance from the flag state for the use of ammonia or hydrogen as fuel, the shipowner in practice needs to go through an alternative design process as per IMO Circ. 1455[13] and carry out a risk analysis to demonstrate that the risk is equivalent to that of a conventional diesel driven ship. The flag state can choose to accept class rules (as exists for ammonia) as a substitute to an alternative design process.

Although safety issues and implications for design can be solved on a case-by-case basis in the early projects, general guidelines and rules will most likely be needed to be in place before widespread use of ammonia or hydrogen as fuel for ships can be realized.

Some newbuilds today are built as fuel ready ships. *Fuel ready* implies that the ship is partly prepared for later conversion to one or more alternative fuels (DNV, 2021a).

Note about blend-in

Most marine internal combustion engines (ICE) will allow for a certain blend of diesel and hydrogen, ammonia, and methanol with relatively minor adjustments to their systems. Some marine ICEs can be converted to allow for running on a blend of diesel with hydrogen, ammonia, or methanol with adjustments to their systems. Even if this may seem like an attractive solution for lowering the carbon footprint of existing vessels, this is not a straight-forward option due to the regulatory implications and requirements to the vessels' fuel supply and storage systems.

At ambient pressure and temperature, both hydrogen and ammonia are gases, and will require separate fuel tanks and fuel systems in addition to the traditional diesel system. Notwithstanding the added space requirements related to these modifications, introducing fuels with a lower volumetric energy density, added requirements for safety zones and distance to heat sources, the added cost for such systems will easily add up to several million USD even for relatively small vessels. Finally, conversion kits will be available only for a small portion, and for the latest models, of marine engines. This means that generally, conversion to hybrid fuel (ammonia/diesel or hydrogen/diesel) will not be economically feasible.

Methanol may seem like an easier option, but due to the much lower flashpoint of methanol compared to diesel, there are similar practical and regulatory requirements (SOLAS/II-1/G/57 stating that ships using low-flashpoint fuels – with flashpoint lower than 60° C - shall comply with the requirements of the IGF Code[14]). Hence, for all practical purposes, the blend-in of methanol will face many of the same challenges as ammonia and hydrogen.

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[13] https://www.imorules.com/MSCCIRC_1455.html

[14] https://www.imo.org/en/OurWork/Safety/Pages/IGF-Code.aspx

6 SCENARIOS TOWARDS 2050

6.1 Modelling of future scenarios – Methodology and assumptions

To analyse the development of the Icelandic fleet, and its energy mix and emissions, we use a scenario model. The model is illustrated in Figure 6-1. We use the data of the current fleet, its calculated energy use, and model the fleet going forward in time. The model has three *analysis modules*: analysis of technology applicability, calculation of fleet development and analysis of uptake of technology and fuels. A range of parameters is input to the model, and the result is governed by what is assumed for these parameters. An economic evaluation governs the uptake of technology and fuels – each ship chooses the least costly way to be compliant with the emission target or adhere to the policy measures. The three analysis modules are further described in the sub-chapters below, together with the assumptions on fuel price and investment cost input.

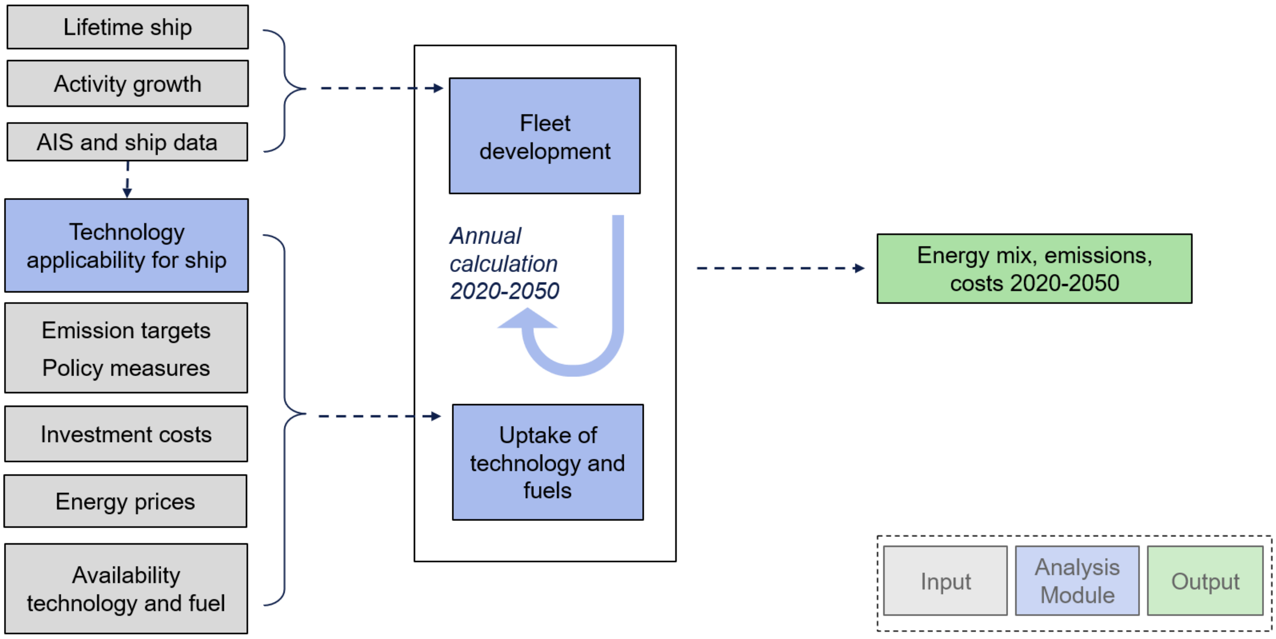

Figure 6-1: Illustration of Decarbonization Scenario Model

6.1.1 Development of the fleet

The replacement of old ships in the fleet with new ships is important when analysing possible transition to zero-emission technologies. Therefore, the number of newbuilds each year is calculated based on assumed activity growth and the age of the fleet. In the model we assume a typical lifetime of a ship of 30-50 years – the year of build of existing ships is available from the ship registry. When an old ship is scrapped, it is replaced with a newbuild. If there is activity growth, this leads to more newbuilds, while if activity level is assumed the same, the number of ships remains the same. Newbuilds that are added have the similar technical characteristics (size, engine power etc.) and operational pattern. This implies that we assume the 2016 fleet and operational pattern to be representative for the future fleet, since the model is based on the AIS analysis for this year. A further discussion on this is given in chapter 6.2.

6.1.2 Applicability of alternative fuel technologies

The alternative fuel technologies battery, hydrogen, methanol, and ammonia all have lower energy density than conventional fuels, especially energy density per volume, as described in chapter 5.3. A transition to these technologies implies that a larger part of the ship’s weight and volume will be occupied by energy storage (batteries or fuel tanks), than what is the case with conventional fuel oil.

The purpose of this part of the analysis is to find which zero-emission technologies are suitable for the ships in the fleet, comparing the space and weight of the required onboard energy storage systems to the ships' size. We first calculate the energy requirement for each individual sailing. We then find energy needs that are sufficient to cover 80% of all sailings; this then becomes the dimensioning energy requirement for the ship, i.e. the amount of energy that must be able to be stored in the tanks / battery on board. We do not make a direct assessment of where or how often the ships bunker but ensure with this approach that the energy storage on board is sufficient for several shorter trips without having to bunker (since we dimension the energy storage so that 80%[15] of the sailings are covered). How often each ship must bunker depends on how the energy consumption varies between different trips, but we find that the ships with this approach typically can carry out a couple of average trips between each bunker.

After establishing the dimensioning energy requirements, we calculate the amount of energy carrier that needs to be stored on board (installed battery capacity, stored hydrogen, stored ammonia or stored methanol). The weight and volume of this amount of energy carrier plus fuel tank is then compared with the volume of the ship (the volume is expressed by GT, gross tonnage), to determine technical suitability. It is assumed that the zero-emission fuel tank system can occupy around three times more of GT than average conventional fuel tanks, for the zero-emission technology to be technically and operationally suitable for the ship. A factor of three is arbitrarily chosen, acknowledging the fact that a transition to these fuels will lead to more onboard space being occupied by fuel storage. This is a necessary simplification to get an overall estimate of how much of the fleet is suitable for battery-electric, methanol, hydrogen or ammonia operation, without assessing each ship design in detail. More space allocated for fuel storage will lead to a changed ship design, and it is difficult to say generally how this will affect for example ship size, cargo space etc. The dual fuel LNG trawlers described in chapter 5.1 were for instance built somewhat longer than similar conventional vessels to accommodate space for LNG tanks and batteries. In the end, it must be determined in detail for the individual ship's design what is possible of weight gain and volume increase compared to conventional systems, and what implications this has for the design of the ship. It will be easier to adjust a newbuilding design for zero-emission technologies than retrofitting existing ships. The transition to zero-emission technology may also have to change the operating pattern of the ship, depending on where the relevant energy carriers are available.

6.1.3 Uptake of technology and fuels

In addition to technical-operational suitability and technological maturity, economic considerations will be key to determine whether and when there will be an uptake of zero-emission technologies and fuels. To put it simple, the feasible, allowed option with the lower total cost will be chosen. This is illustrated in Figure 6-2.

Figure 6-2: Illustration of logic determining the uptake of technology and fuels

First, an option needs to be feasible. This means it must be technologically mature, safe and technical-operationally possible for the ship to implement (determined by the analysis in 6.1.2).

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[15] The reason we do not choose the energy needs of the most energy-intensive sailing as dimensioning, is that we want to reflect the fact that the transition to zero-emission technologies will probably lead to changes in operating patterns (sailing lengths, bunkering intervals, etc.). At the same time, dimensioning to 80% of all current sailings will take into account that the operating pattern of a zero-emission ship remains "similar" as today.

Next, we can include a limitation on how much fossil fuel is *allowed*, for example by setting an annual emission target for each ship. The use of a ship-specific emission target to control the transition to zero-emission fuels in the scenarios is done in such a way to represent the effect of possible requirements and instruments that may be used to realize a national emission target, since we do not know how this will be done in practice.

We let the model calculate the cost of all feasible, allowed options each year. For each ship in the model, we calculate the total cost of the various technologies (net present value) for each year. This includes both investment costs and energy costs. One policy instrument that can be included to reduce the net present value is subsidies for investment in zero-emission technology. Each year, the option with the lowest net present value is selected. If it is cheaper to use biofuels than to make a conversion to / design newbuilds for zero-emission operation, the ship will choose this to meet the emission target. As described in chapter 6.1.5, converting existing ships with new technology will in general not be economically feasible. As long as fossil fuels (including potential taxes) are cheaper than the carbon-neutral ones, the ship will only use the amount of carbon-neutral energy carrier needed to meet the emission target.

We therefore assume that all ships that can use zero-emission technology for a period can also be operated with conventional fuel. This is probably most realistic in a transitional phase where zero-emission fuel has limited availability, and also how operation is planned in current projects with ships with zero-emission technology (by using dual fuel engine technology and two fuel tank systems).

6.1.4 Fuel prices

In principle, the price of a fuel is a function of the cost of raw material or primary energy source, production and distribution, as well as the relationship between supply and demand in the market. Fuel prices have historically seen large variations in response to changes in demand and supply, as well as changes in the price of underlying raw material used for production (e.g. crude oil and natural gas).[16] As a result, future fuel prices are hard to predict. This is especially the case for carbon-neutral fuels, where there is often no historical price data available.

Separate approaches for projecting future fuel prices have been used for carbon-neutral fuels and MGO, respectively:

1. *Carbon-neutral fuels:* Levelized cost for production and distribution has been used as a proxy for predicting future fuel bunkering prices. A literature study has been performed to derive relationships between the cost of producing carbon-neutral fuels and the cost of primary energy, i.e. cost of biomass and cost of renewable electricity. On top of this, a distribution cost has been added to reflect the additional cost of bringing the fuel to the end user. Cost reductions from improved production technologies and large-scale production are considered in the cost-estimates. The overall approach is illustrated in Figure 6-3.

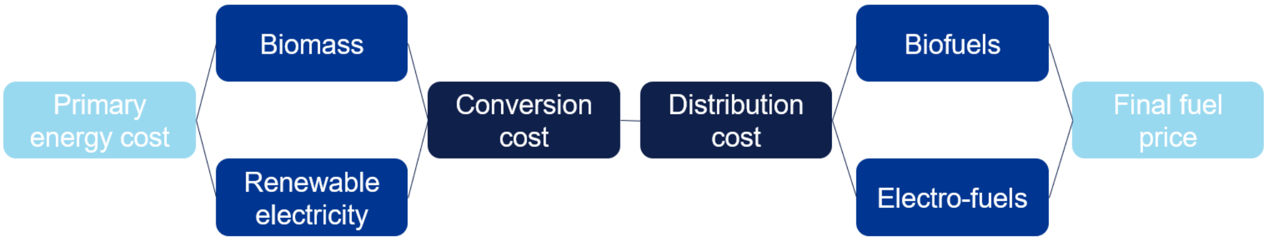

Figure 6-3: Illustration of method used for estimating bunkering prices of carbon-neutral fuels. Conversion and distribution costs will be different for the different fuels.

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[16] See for example historic price development of natural gas, crude oil, MGO, and HFO: https://www.dnv.com/maritime/insights/topics/lng-as-marine-fuel/current-price-development-oil-and-gas.html

2. *MGO:* By considering the historical relationship between bunkering prices of MGO and the price of crude oil (Brent), a constant crude oil price coefficient has been calculated for MGO. For this study, a coefficient of 1.25 has been used for MGO, meaning that on an energy basis, MGO is always 25% more expensive than the price of crude oil.

Figure 6-4 shows the estimated share of different cost components to the total price of e-methanol (left) and e-ammonia (right) in 2021 used in the study. The given cost components are *Hydrogen production*, *conversion costs*, and *distribution costs*, including cost of fuel infrastructure. The figure shows that in 2021, the distribution costs make up a relatively low share of the total price, more so for e-methanol compared to e-ammonia. For e-methanol, the cost of CO_2 capture is included in the cost of *conversion to methanol*. In the *high* fuel price scenario, cost of CO_2 reflects direct air capture (DAC), whereas in the *low* fuel price scenario, capture is assumed from combined renewable sources (e.g. CO_2 waste product in biogas-production). A range of different sources have been used to develop fuel price estimates for the different fuels. For electro-fuels, estimates for current and future production costs by IRENA (2021), Agora (2019), Concawe (2019) and Cerulogy (2017) have been used as basis.

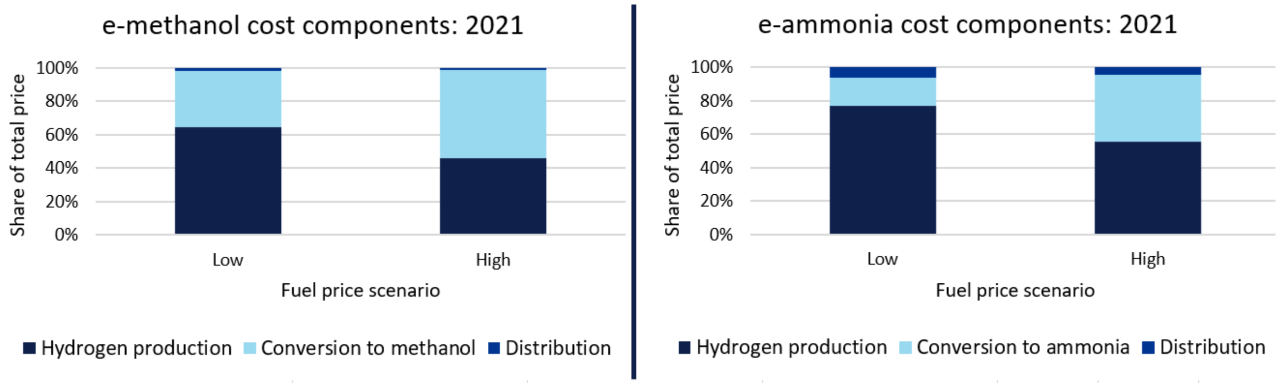

Figure 6-4: Estimated contribution of different cost components to total price of e-methanol (left) and e-ammonia (right).

Table 6-1 shows the assumed cost of primary energy sources. Representative electricity costs in Iceland are used.[17] The prices are kept constant throughout the analysis period, as agreed with the client.

Table 6-1: Assumed primary energy costs (USD/GJ)

Primary Energy Source	Scenario	2021	2025	2030	2035	2040	2045
Renewable electricity[18]	High	9,2	9,2	9,2	9,2	9,2	9,2
	Low	5,5	5,5	5,5	5,5	5,5	5,5
Crude oil[19]		11,4	9,6	10,3	11,1	11,8	11,8

A wide variety of biomass-sources can be used for production of biofuels, and as a result, it has been left out of Table 6-1. One biofuel is considered in this study:

- *Bio-MGO:* Cost of biomass assumed to grow at an annual rate of 1.5% from baseline year (2021). Prices reflect production of hydrotreated vegetable oil (HVO) via waste sources such as used cooking oil, where feedstock cost makes up a high share of total production costs.[20] Under this assumption, the price of bio-MGO is assumed decoupled from the fossil fuel price. This reflects a situation where the increased global demand for

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[17] Based on Icelandic electricity prices for tertiary power (low) and baseload power (high), agreed with the client

[18] Based on Icelandic electricity prices for tertiary power (low) and baseload power (high), agreed with the client

[19] Based on fossil energy price projections in (IEA, 2020 ed.).

[20] (IEA Bioenergy, 2020), *Advanced Biofuels – Potential for Cost Reduction*, IEA Bioenergy, p. 10.

biofuels produced from waste sources (e.g. used cooking oil) – considered a limited resource – causes the price to increase.

Figure 6-5 shows the resulting assumed fuel prices. For electro-fuels we have a high and low estimate, while for MGO and bio-MGO we use only one. In general, the projected span in fuel prices (high and low) in 2021 fall within estimated fuel production costs given the report by ICEeFuel (2021). The plots also show MGO with a CO_2 cost included, similar to the European carbon price projection towards 2050 from DNV's Energy Transition Outlook (DNV, 2021b), going from 60 USD/tonne CO_2 in 2021 to 100 USD/tonne CO_2 in 2050. It should be noted that there is currently a carbon tax for fisheries in Iceland, which is around 35 USD/tonne CO_2 (OECD, 2021), equal to around 11,7 ISK/liter fuel.

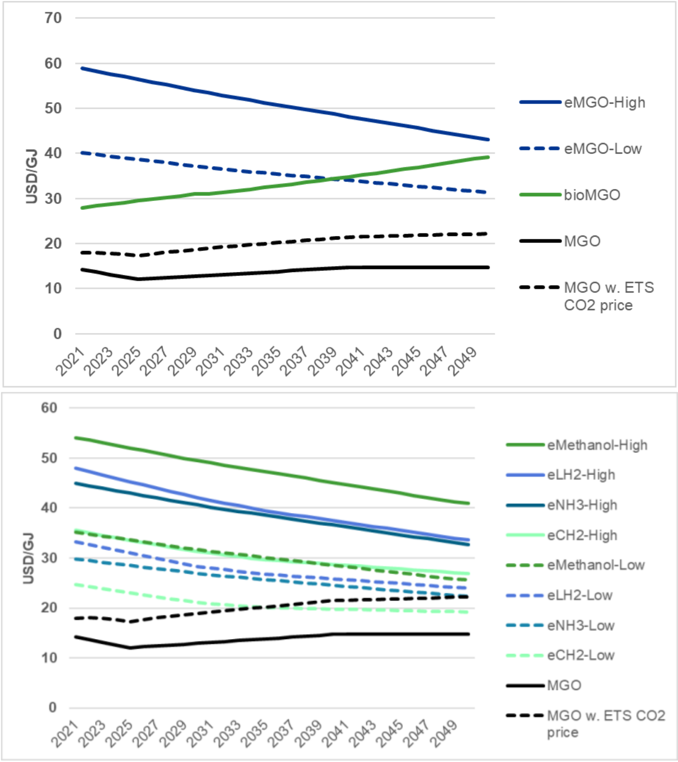

Figure 6-5: Fuel price assumptions, for MGO and drop-in fuels in upper plot and MGO and e-hydrogen (compressed; eCH2 and liquefied; eLH2), e-ammonia (eNH3) and e-methanol in lower plot

We emphasize that fuel prices are uncertain, both those of MGO and those of alternative fuels. It could for instance be argued that keeping the electricity price constant is a simplification. However, the key for the uptake of alternative fuels is how the relative difference between fuel prices will develop in time. The overall trend of decreasing production costs of electro-fuels seems well established in literature. To investigate the effect of fuel prices on the uptake of alternative fuels, we perform sensitivity analysis in chapter 7.

6.1.5 Assumptions on onboard investment costs

General assumptions

We estimate additional investment costs compared to a conventional vessel, assuming the following:

- The ship has a new tank and new gas or fuel handling system, in addition to a conventional tank system (applies both for newbuilds and conversion of existing vessels). Tank capacity for the alternative fuel is based on the estimated dimensioning energy need described in chapter 6.1.2.

- Since fuel cells have significantly higher investment costs than combustion engines, they are not assumed to be used to cover the full power requirement of the vessels. Smaller fuel cells may be used to operate more energy efficiently, but this is not included in the modelling. Both for the ammonia, hydrogen and methanol alternative, it is assumed that dual fuel combustion engines are used. For a conversion of an existing ship, the dual fuel engine is assumed to replace the existing engine. Some ships may get a converted engine to be able to run on some of these fuels, but it is uncertain to which degree this would be possible in the fleet, and this is not included in the modelling.

With this dual fuel configuration, the ships will for example be able to run on drop-in fuels (e.g. biofuel) if they are required to reduce emissions before the alternative fuel technologies become available or competitive.

To estimate investment costs, since little experience data exists, we use unit/component costs from literature review - typically converter/engine cost per installed power or tank system cost per stored energy amount.

Newbuilds

With the unit costs we estimate the following additional investment costs per vessel for newbuilds. The ranges are wide, dependent on ship size, engine power, onboard energy storage need etc.

- Compressed hydrogen: 0,5 MUSD – 14 MUSD
- Liquefied hydrogen: 0,5 MUSD – 10 MUSD
- Ammonia: 0,2 MUSD – 5 MUSD
- Methanol: 0,1 MUSD – 3 MUSD

There will presumably also be additional costs related to further development of the technologies, and piloting for the relevant ship types. The assumed investment costs are considered applicable for the technologies at a commercial stage. Since there is little experience data available, the cost estimates are tentative and uncertain.

Conversion of existing ships

The cost for retrofitting an existing ship with alternative fuel technologies is very uncertain, and it will not be possible on all ships. The feasibility and cost will be highly dependent on what changes are needed to change engine and power system, design modifications or rebuilding to accommodate tank systems etc. There is no experience data available for the alternative fuels considered here. Based on a review of known conversion projects for LNG of various ship types, the average additional cost of an LNG retrofit is at least 50 % higher than the additional cost of an LNG newbuild. A methanol conversion will be simpler to handle than LNG conversion, while it will be more challenging to convert a conventional ship to ammonia and especially hydrogen operation. For simplicity, we use a conversion addition of 100 % to the newbuild additional costs shown above. Due to the lifetime of ships and investment horizon, an expensive conversion will not be an economically viable alternative for most existing ships.

6.2 Reference scenario

It is not in the scope of this analysis to estimate the future activity of fishing vessels and other ships in Iceland. As a reference scenario we use the Energy Forecast Committee’s (2021) forecasted energy demand for the fishing sector and domestic navigation respectively. This is considered as the “Business as Usual” scenario, a reference scenario where the current trend continues with today’s fuel mix.

Although the fishing fleet in Iceland has reduced its emissions considerably, this has been due to efficiency improvements and reduced fuel use. Figures in the environmental report of Fisheries Iceland (2017) show that the fuel oil consumption of Icelandic fishing vessels decreased 35 % from 1990 to 2016. Fuel consumption of fishing vessels depends greatly on distance to fishing banks, and fuel consumption peaked in the 1990s, when much fishing was carried out on distant banks. During the past decades the size of the fishing fleet in terms of total gross tonnage (ship size) and total installed engine power has decreased. The fleet now consists of fewer and larger vessels, leading to more efficient fishing. The typical sailing distance to catch has also decreased. These reasons, together with high oil prices and advances in energy efficiency technology both for propulsion and fishing gear, have caused the reduction in fuel consumption (Fisheries Iceland, 2017).

The trend of decreasing total sailing distance is supported by AIS data that we have available for primarily larger fishing vessels, as shown in Figure 6-6 below. It should be noted that this data set includes a considerably lower number of ships than what is used in the detailed 2016 analysis, described in chapter 3. However, many of the same bigger vessels are present in this dataset, and the trend should therefore be relatively representative.

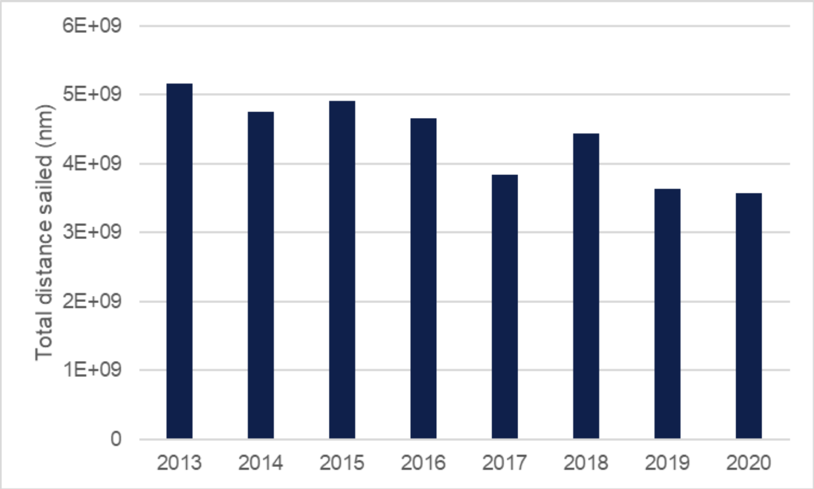

Figure 6-6: Total distance sailed by fishing vessels in the Icelandic Economic Zone, 2013-2020, calculated by AIS data (DNV data)

Figure 6-7 shows the historical and forecasted energy use in the fishing fleet and domestic shipping (Energy Forecast Committee, 2021). The development of the fuel use of the fishing fleet from 2016 to 2020 has remained quite constant, and the 2016 operational pattern as analysed in chapter 3 can therefore be assumed representative for this period. Our understanding from the forecast is that the trend described above for the fishing fleet is assumed to sustain, and the further reduction going towards 2050 is also based on energy efficiency improvements for instance due to renewal of fleet.

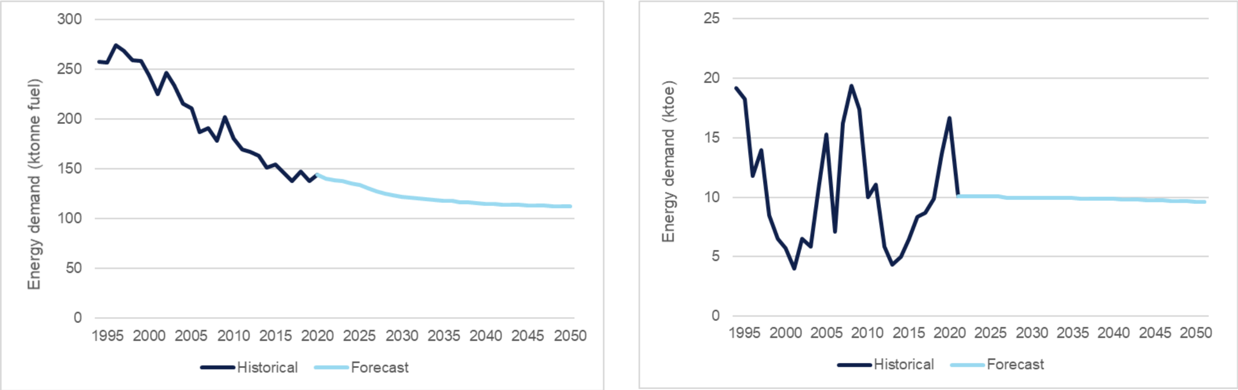

Figure 6-7: Historical and forecasted energy demand of Icelandic fishing fleet (left) and domestic navigation (right) (Energy Forecast Committee, 2021)

We use the age distribution of the current fleet to estimate the rate at which older ships are replaced by newbuilds towards 2050. The resulting development of emissions for different age categories of ships is shown in Figure 6-8. The distribution of emissions among the different age categories derives from the bottom-up estimation of fuel use on ship level, described in chapter 3, scaled to match the total fuel consumption of 2020 as given by the Energy Forecast Committee. The gradual replacement of older ships is assumed to lead to most ships older than 10 years today being phased out of the fleet by 2050, while in 2030, more than two thirds of the emissions will be from currently existing ships. This fleet development and the resulting emissions are used as reference for the modelling of decarbonization scenarios.

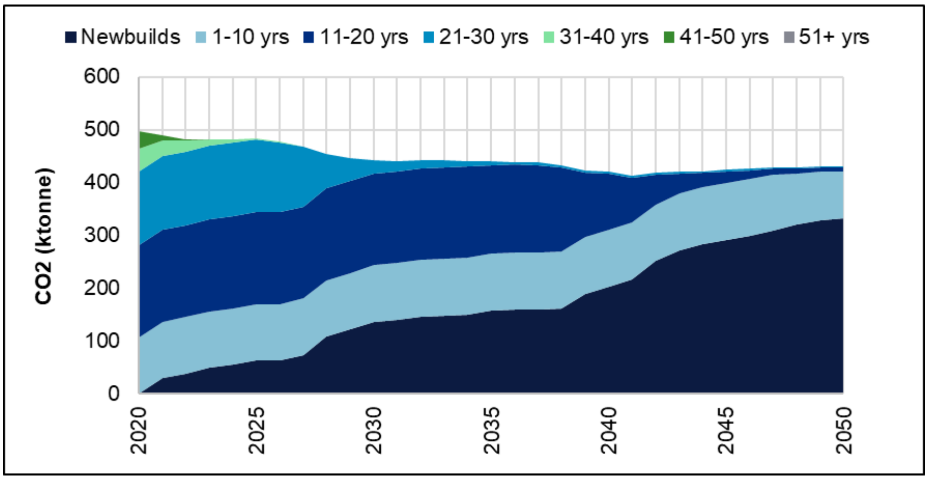

Figure 6-8: Reference emission towards 2050 distributed between age categories (categorized by the age in year 2020, and modelled newbuilds from 2021)

6.3 Decarbonization scenarios

With our scenario approach, we evaluate how the energy mix and emissions in the fleet develop under various conditions. As described in chapter 6.1.3, we have evaluated which alternative fuel technologies are applicable for the different ships in the fleet. In the scenarios, we let the different ships choose the cheapest, applicable option that meets potential regulatory requirements.

We look at three different policy measures along two different axes: economics and required share of carbon-neutral fuel, as illustrated in Figure 6-9. The measures along the economics axis – increased CO2 tax and investment support - are arbitrarily chosen and do not reflect concrete measures considered in Iceland. We base the CO_2 price on the development of the European carbon price as assumed in DNV's Energy Transition Outlook (DNV, 2021b), going from around 60 USD/tonne in 2021 to 100 USD/tonne in 2050. We add 50 % to this, simply because this is needed for the alternative fuels to become competitive to MGO with tax with the price assumptions used (chapter 6.1.4). The *investment support* is for example a governmental subsidy covering a part of the additional investment cost (CAPEX) for alternative fuel technology on board the ship. A gradually increased required share of carbon-neutral fuel reflects Iceland's target of becoming fossil-free by 2050. It is not considered here how such a policy measure would be arranged in practice.

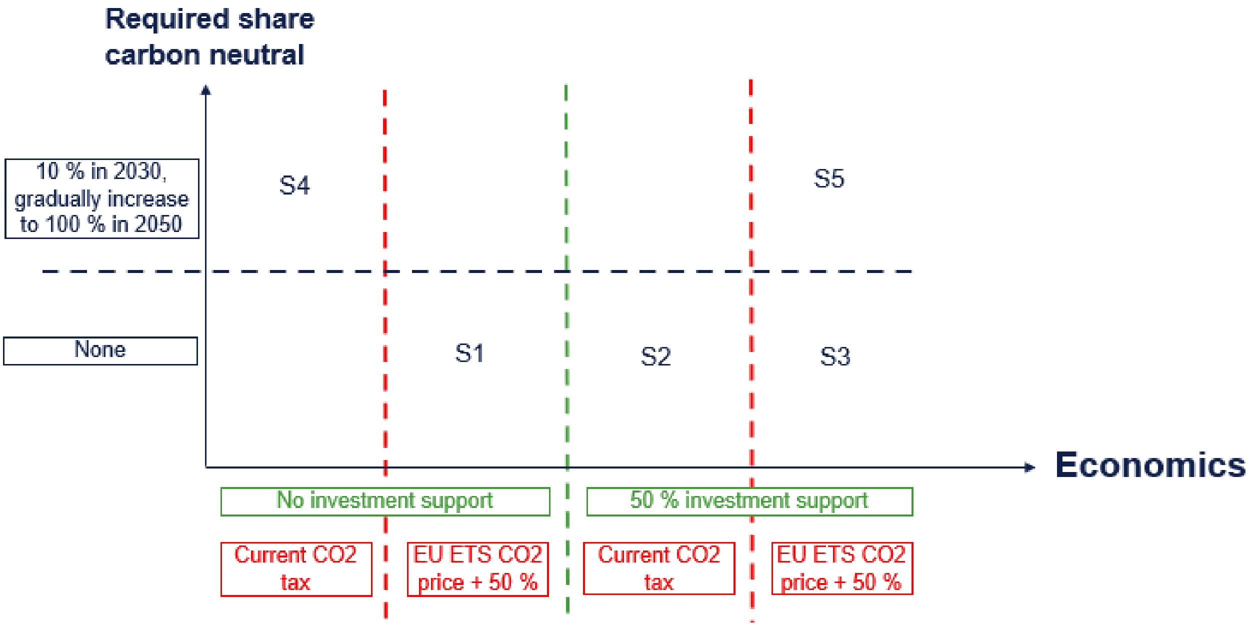

Figure 6-9: Modelled scenarios

We use the following labels for the scenarios, to ease readability:

- Scenario 1: *Tax*
- Scenario 2: *Subs.*
- Scenario 3: *Tax + subs.*
- Scenario 4: *Req. (emission targets)*
- Scenario 5: *Req. (emission targets) + tax + subs.*

In the scenarios we apply the *low* electro-fuel prices, as defined in chapter 6.1.4. Although labeled *low*, we consider these to be realistic. They reflect a low renewable electricity cost, namely off-grid tertiary power in Iceland, which is assumed to be representative for large scale electro-fuel production facilities. We do a sensitivity check on the fuel price in chapter 7. In the scenarios we assume a gradual increase of shore power to cover the energy use in port, with full coverage in 2030. The introduction of fuels and energy carriers in addition to this depends on the conditions applied in the different scenarios. In the scenario modelling, the annual energy demand of each ship as estimated in chapter 3 is used. The aggregated result is however scaled to match the forecasted energy demand as illustrated in Figure 6-7, to ensure consistency with the fuel use statistics and figures of the Energy Forecast Committee.

6.3.1 Scenario 1 – Tax

In scenario 1, a CO_2 tax equal to EU ETS CO_2 price + 50 % is imposed. There is no governmental onboard technology investment support, and no required share of carbon-neutral fuel. Figure 6-10 shows resulting CO_2 emissions and energy mix in this scenario. There is an uptake of battery-electric ships, however this contributes little to overall emission reductions. As shown in the fuel price assumptions in chapter 6.1.4, e-methanol and e-ammonia becomes competitive against MGO after 2040, with e-ammonia being the cheapest. Consequently, there is a certain amount of e-ammonia entering the energy mix closer to 2050, constituting around one fourth of the energy mix in 2050. Note that it is modeled that the ships will not start operating on the alternative fuel until it is cheaper than MGO. This implies newbuilds also before 2045 are designed ready to use ammonia while they start using it in 2045, when the price is low enough. The high investment costs, and no investment support in this scenario, lead to no uptake of hydrogen in the fleet. This scenario does not meet Iceland's official emission goals.

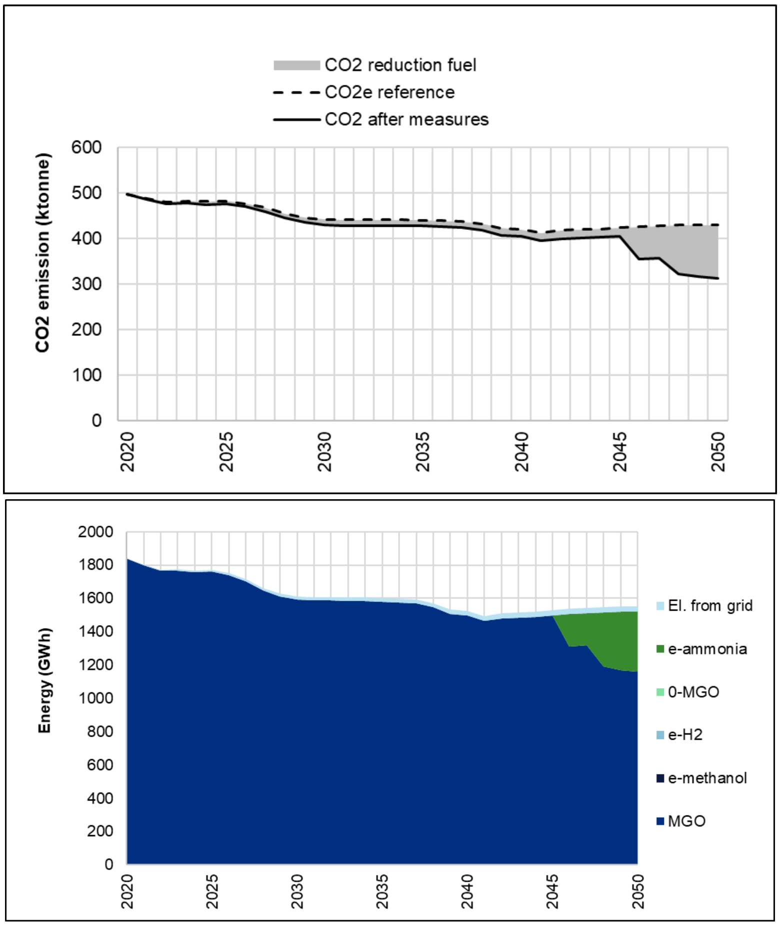

Figure 6-10: Emission trajectory (ktonne CO_2) and energy mix (GWh distributed by energy carriers) in scenario 1, with no investment support, no required carbon-neutral share but with CO_2 tax (legend: *0-MGO* denotes e-MGO or bio-MGO (HVO); *el. from grid* denotes direct use of electricity from grid; *e-H2* denotes compressed e-hydrogen gas)

6.3.2 Scenario 2 – Subs.

In scenario 2, there is no additional CO_2 tax imposed, in contrast to scenario 1. However, there is a 50 % investment support in onboard technology. Like scenario 1, this scenario does not meet Iceland's official emission goals. Figure 6-11 shows the resulting CO_2 emissions and energy mix in this scenario. Although there is investment support in place, the alternative fuels never become competitive against MGO (apart from electricity from grid). Consequently, there is no uptake of these fuels, nor significant emission reduction from the baseline. It should be mentioned that this result is quite conservative, as it could be expected that subsidies would result in more investments in energy efficiency technologies, reducing fuel consumption and as a result emissions. This is not accounted for in the modelling.

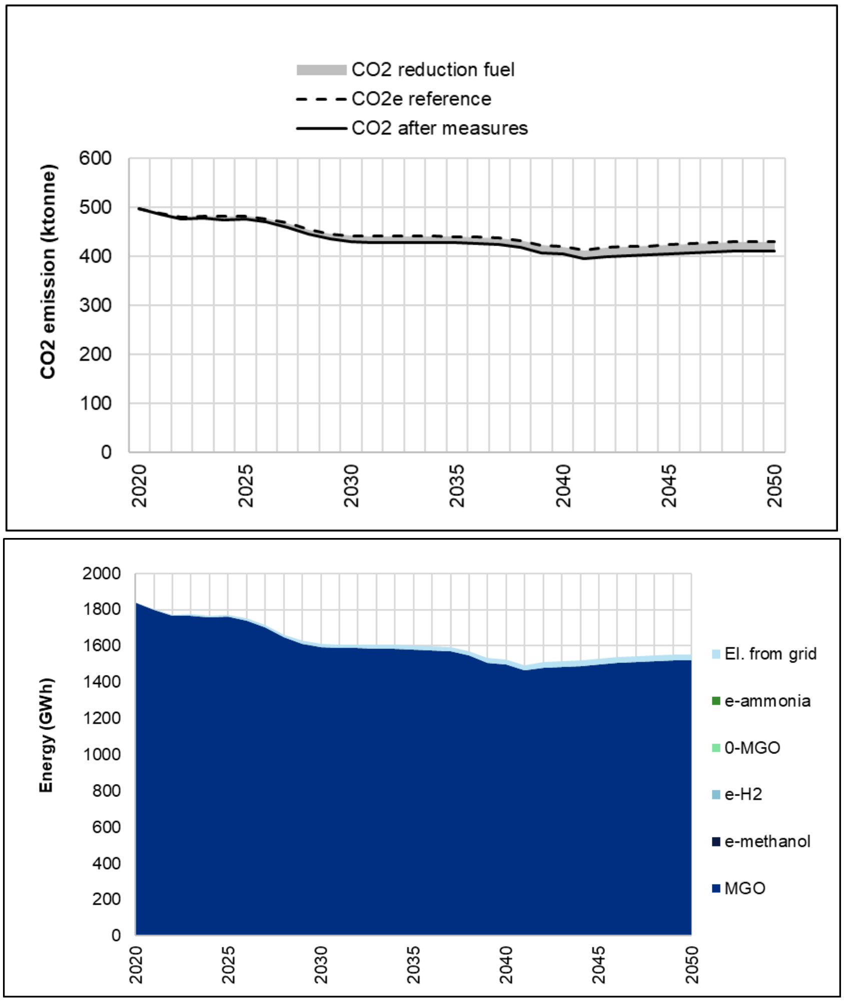

Figure 6-11: Emission trajectory (ktonne CO_2) and energy mix (GWh distributed by energy carriers) in scenario 2, with 50 % investment support, no required carbon-neutral share and no CO_2 tax (legend: *0-MGO* denotes e-MGO or bio-MGO (HVO); *el. from grid* denotes direct use of electricity from grid; *e-H2* denotes compressed e-hydrogen gas)

6.3.3 Scenario 3 – Tax + subs.

Scenario 3 includes 50 % investment support in addition to an increased CO_2 tax. As seen in Figure 6-12, e-fuels are introduced considerably earlier compared with the two first scenarios, shortly after 2030. Investment support leads to earlier investments in onboard hydrogen/ammonia/methanol technology, and once the fuels become competitive against MGO with CO_2 tax, we see a gradual increase in the number of ships sailing on these fuels. For pure hydrogen solutions, compressed hydrogen is found to be more cost-competitive than liquefied hydrogen, and there is no uptake of liquefied hydrogen in this scenario, nor in the other scenarios. The higher total cost of liquefied hydrogen and limited applicability due to energy density makes ammonia/methanol the preferred option for the large part of the fleet where compressed hydrogen is not an option due to sailing distances. In this scenario, around half of the energy mix is carbon-neutral in 2050 and the scenario does not meet Iceland’s official emission goals.

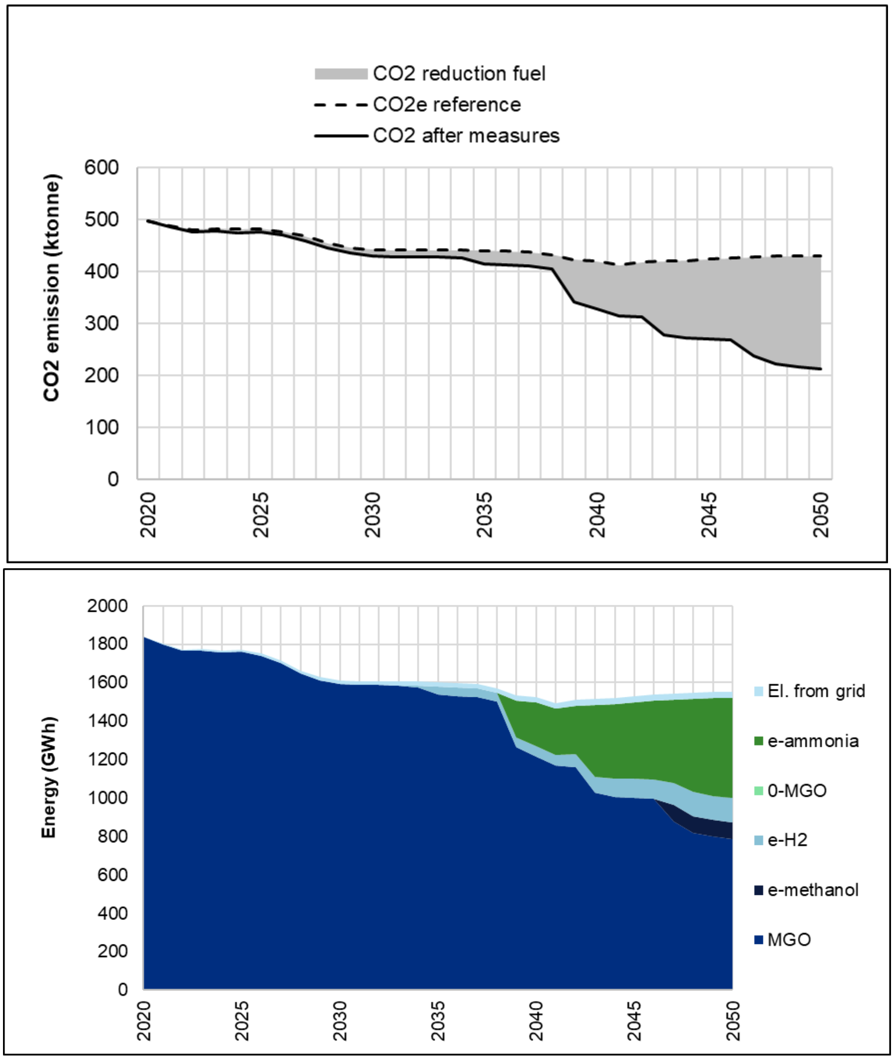

Figure 6-12: Emission trajectory (ktonne CO_2) and energy mix (GWh distributed by energy carriers) in scenario 3, with 50 % investment support, no required carbon-neutral share but with CO_2 tax (legend: *0-MGO* denotes e-MGO or bio-MGO (HVO); *el. from grid* denotes direct use of electricity from grid; *e-H2* denotes compressed e-hydrogen gas)

6.3.4 Scenario 4 – Req. (emission targets)

In scenario 4, there is a requirement to gradually increase the share of carbon-neutral fuels in the energy mix (from 5 % in 2025, to 10 % in 2030 and 100 % in 2050). Each ship needs to follow this requirement and selects the least costly option for the requirement to be met. In the beginning, the major share of carbon-neutral fuel is drop-in fuel (labeled *0-MGO* in the figure; HVO or e-MGO). As more newbuilds enter the fleet and start operating on methanol/ammonia, these electro-fuels gain an increasing share of the energy mix and become dominating around 2040. Methanol is preferred over ammonia due to the lower investment cost. However, a share of drop-in fuel remains in the energy mix. When e-MGO becomes cheaper than HVO after 2040, this becomes the preferred option for *0-MGO*.

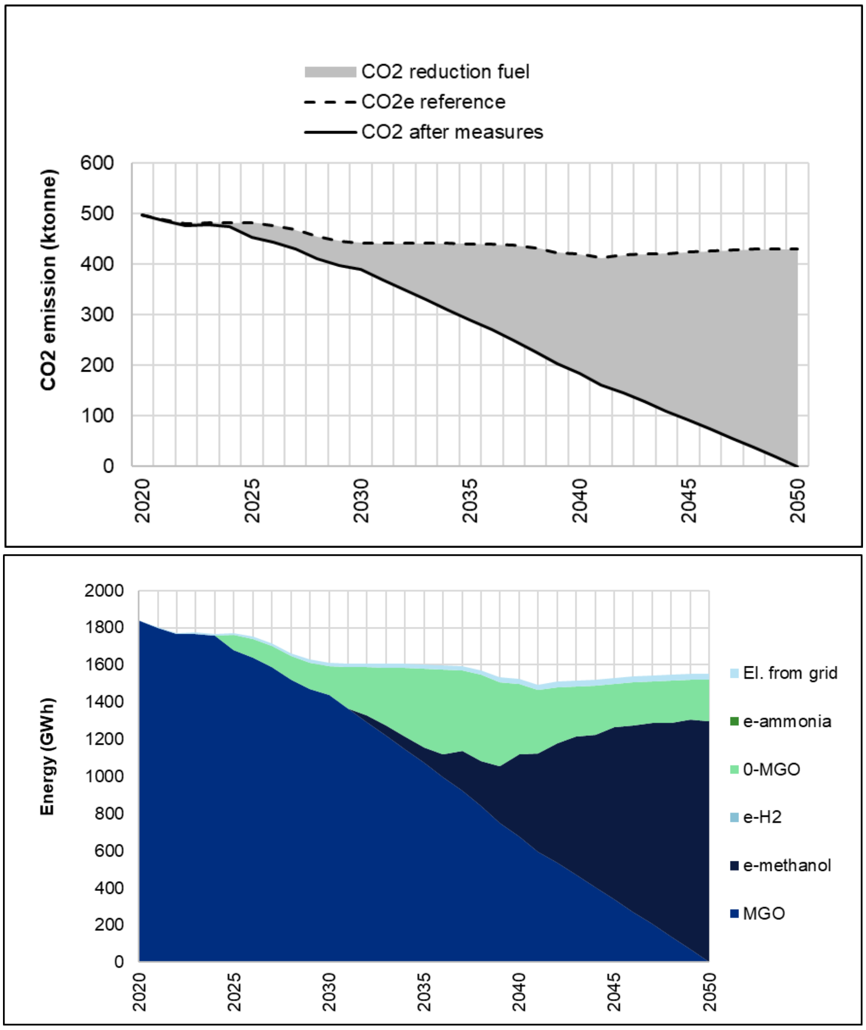

Figure 6-13: Emission trajectory (ktonne CO$_2$) and energy mix (GWh distributed by energy carriers) in scenario 4, with no investment support, no CO$_2$ tax, but with required carbon-neutral share of 10 % in 2030 to 100 % in 2050 (legend: *0-MGO* denotes e-MGO or bio-MGO (HVO); *el. from grid* denotes direct use of electricity from grid; *e-H2* denotes compressed e-hydrogen gas)

6.3.5 Scenario 5 – Req. (emission targets) + tax + subs.

Like in scenario 4, a gradually increased share of carbon-neutral fuels is required in scenario 5. In addition, there is 50 % investment support and CO$_2$ tax in place. The picture is similar to scenario 4, but investment support eases the introduction of both hydrogen and ammonia powered ships, which have a higher investment cost than methanol. Also, MGO is phased out in 2047, as electro-fuels become competitive when an increased CO$_2$ tax is in place.

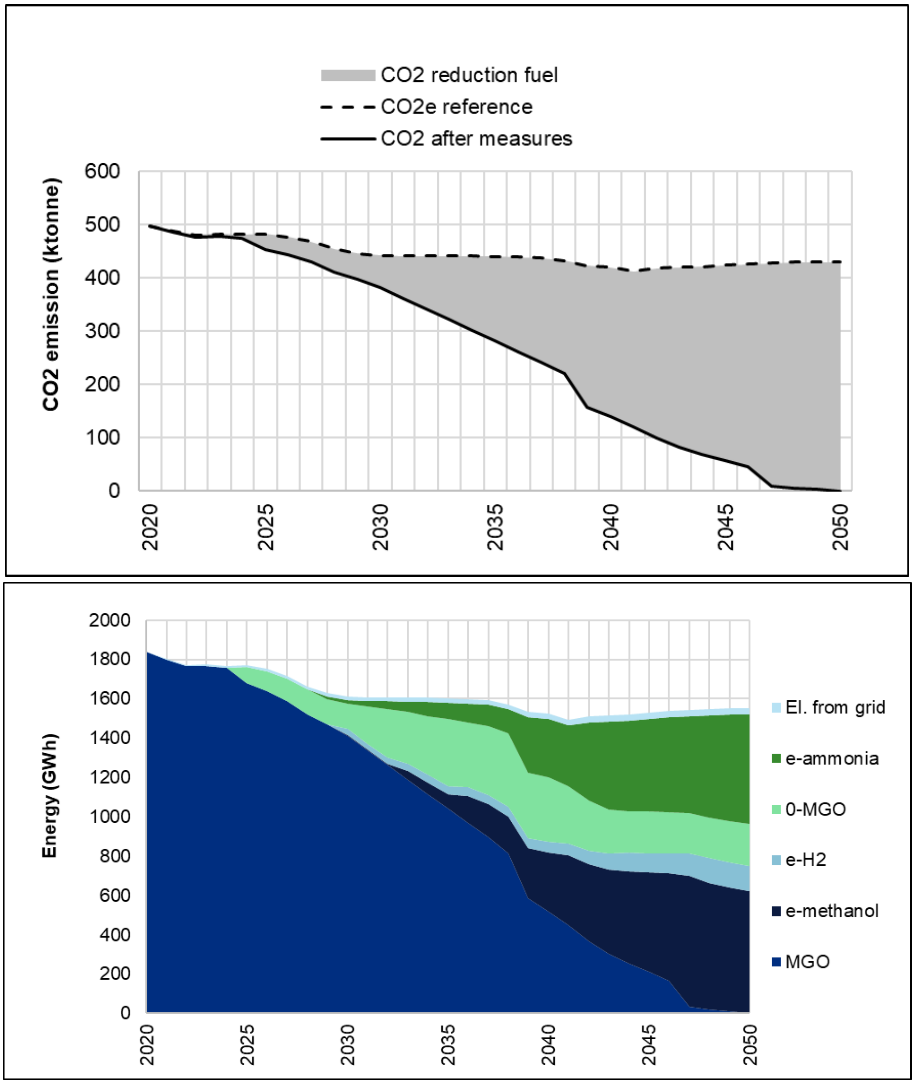

Figure 6-14: Emission trajectory (ktonne CO_2) and energy mix (GWh distributed by energy carriers) in scenario 5, with 50 % investment support, CO_2 tax, and required carbon-neutral share of 10 % in 2030 to 100 % in 2050 (legend: *0-MGO* denotes e-MGO or bio-MGO (HVO); *el. from grid* denotes direct use of electricity from grid; *e-H2* denotes compressed e-hydrogen gas)

6.3.6 Summary of results

In general, there is limited emission reductions and use of alternative fuels before 2030 in the modelled scenarios. Some key figures from the scenarios are given in Table 6-2, for the years 2040 and 2050. Although alternative fuel technologies are assumed to be commercially available from around 2025, it takes time until significant uptake is seen in the fleet. Due to the long lifetime of ships, fleet renewal takes time. The lead time from planning of a complex newbuilding project, via design and building, until the vessel is in operation takes several years. In addition, it takes time for the alternative fuels to become competitive with MGO, also with an increased CO_2 tax.

In the scenarios without an explicit requirement to increase the share of carbon-neutral fuels in the energy mix (scenario 1, 2 and 3), only the scenarios with an increased CO_2 tax in place result in significant uptake of carbon-neutral fuels (scenario 1 and 3). However, onboard investment subsidies are crucial for accelerating the uptake of alternative fuels: In scenario 3, investment subsidies give a substantial contribution to the introduction of electro-fuels before 2040, as opposed to scenario 1 without investment subsidies. This indicates that even a relatively high CO_2 tax level will not cause a significant uptake of carbon-neutral fuels in the short term, as technologies need to be commercialized, and introduced into the fleet over time. It should be noted that decarbonization by 2050 is not obtained in scenarios 1, 2 and 3. It may further be a simplification in this analysis that biofuel is not included in the energy mix in these scenarios. As previously mentioned, there are some minor amounts of biodiesel in use in Iceland today, although this is not necessarily drop-in biodiesel as included in this analysis.

In scenarios 4 and 5 there is a required share of carbon-neutral fuels for all ships, set to fulfill official emission targets. This gives a considerable volume of biodiesel in the short term before electro-fuels start to dominate, reducing the need for biodiesel. If the required share of carbon-neutral fuels would be higher than 10 % in 2030, this would mainly lead to the introduction of more biodiesel, as electro-fuels are introduced primarily after 2030. Again, the introduction of investment subsidies accelerates the uptake and gives more electro-fuels in the energy mix (scenario 5).

In pace with the commercialization of on-board technologies for ammonia, hydrogen and methanol, the production of fuels needs to be scaled up, and fuel distribution and bunkering infrastructure established. An estimate of the amount of electricity needed to produce electricity-based fuels in the different scenarios is given in Table 6-2.[21]

Table 6-2: Summary of results from the decarbonization scenarios

	Scenario 1 ***Tax***		**Scenario 2** ***Subs.***		**Scenario 3** ***Tax + Subs.***		**Scenario 4** ***Req. (emission targets)***		**Scenario 5** ***Req. (emission targets) + tax + subs.***	
	2040	**2050**	**2040**	**2050**	**2040**	**2050**	**2040**	**2050**	**2040**	**2050**
Total energy consumption (GWh)	1524	1550	1524	1550	1524	1550	1524	1550	1524	1550
Energy consumption electricity-based fuels (GWh)	26	398	26	33	308	763	467	1551	676	1551
Required electricity production (GWh)	29	861	29	36	643	1611	910	3338	1398	3454
Energy consumption biofuel/HVO (GWh)	0	0	0	0	0	0	153	0	133	0
CO_2 emissions reduction compared to reference (%)	4	31	4	5	22	51	56	100	58	100

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[21] Here it is assumed an efficiency of 90 % for electricity from grid (loss in transmission, charging etc.), 58 % for production of compressed e-hydrogen (57 kWh required for production of 1 kg of hydrogen), 44 % for liquid e-ammonia (around 12 MWh is required to produce one tonne of e-ammonia), 50 % for e-methanol (around 11 MWh is required to produce one tonne of e-methanol) and 31 % of e-MGO (38 MWh required per tonne of e-MGO). Efficiencies based on Transport & Environment (2018) and IRENA (2021)

7 UNCERTAINTIES

In this chapter we briefly describe some uncertainties in our analysis:

- **Fuel consumption data**: The AIS based calculations of current fuel consumption are estimates, and do not match the reported fuel consumption of the fleet. However, the analysis is detailed enough to give a representative view of energy demand for most of the fleet, reflecting its diversity in terms of different vessel characteristics, operational pattern, sailing distances, energy costs etc., and thereby to assess the fleet's potential for decarbonization.

- **Fleet development**: It is assumed that the fleet activity – in terms of number of ships and energy need - will remain the same in the decarbonization scenarios as in the baseline. The transition may cause the fleet to grow otherwise than what is assumed here. However, whether the growth will be higher or lower than the assumed baseline, the same mechanisms will apply for decarbonizing the fleet.

- **Access to capital**: In the modelling of technology uptake, we do not evaluate if shipowners will be financially capable of handling the needed investments or the operational cost increase. Access to capital is in general a barrier for the uptake of alternative fuel technologies.

- **Investment horizon**: In the economic evaluation of different fuel and technology options (calculation of net present value; NPV), we assume an investment horizon of 10 years. This implies that the shipowner has a long-term view on future costs when making an investment decision. Even though the lifetime of ships is longer than 10 years, investment horizons can in practice be shorter, depending on the shipowner's willingness to take financial risk. A discount factor of 9 % is used the NPV calculations.

- **Access to fuels**: We do not set a limit on fuel production capacity but assume that the chosen alternative fuel will be available when needed. Thereby, we use our scenarios to estimate the fuel volumes needed in the energy transition of the fleet.

- **Investment cost for alternative fuel technology**: We estimate the investment cost on board the ships based on literature review of cost of different propulsion and tank systems, since there is no cost data from actual projects available. The total investment cost for new technology can be higher, especially in the first projects when the technologies are still at a pilot stage. Also, additional risk analyses are necessary in early projects and add cost, and the cost of integrating new components in the ship designs is difficult to predict.

- **Fuel prices**: The difference between the cost of different fuels is decisive for the outcome of the scenarios, and future fuel prices are uncertain. Therefore, we do here a sensitivity analysis, where we assume a high price estimate on the electro-fuels (cf. chapter 6.1.4), as opposed to the low price estimates used in the results in the previous chapter. Figure 7-1 shows the energy mix in scenario 3 (tax and subsidies) and scenario 5 (tax, subsidies and requirement) with this price assumption. This can be compared to Figure 6-12 and Figure 6-14. In scenario 3, there is now no significant uptake of alternative fuels, as no alternative fuel becomes competitive. In scenario 5, a transition with more biofuel will be needed for a longer period, until electro-fuels become the competitive option for obtaining the required carbon-neutral share. It should be noted that these high prices are probably rather conservative, and that lower electro-fuel prices can be more realistic. Other sensitivity analyses could have been performed, for example by reducing or increasing the price of MGO, but after all it is the relative price difference that will be key to the uptake of alternative fuels. In this respect, a higher electro-fuel price will be equivalent to a lower MGO price.

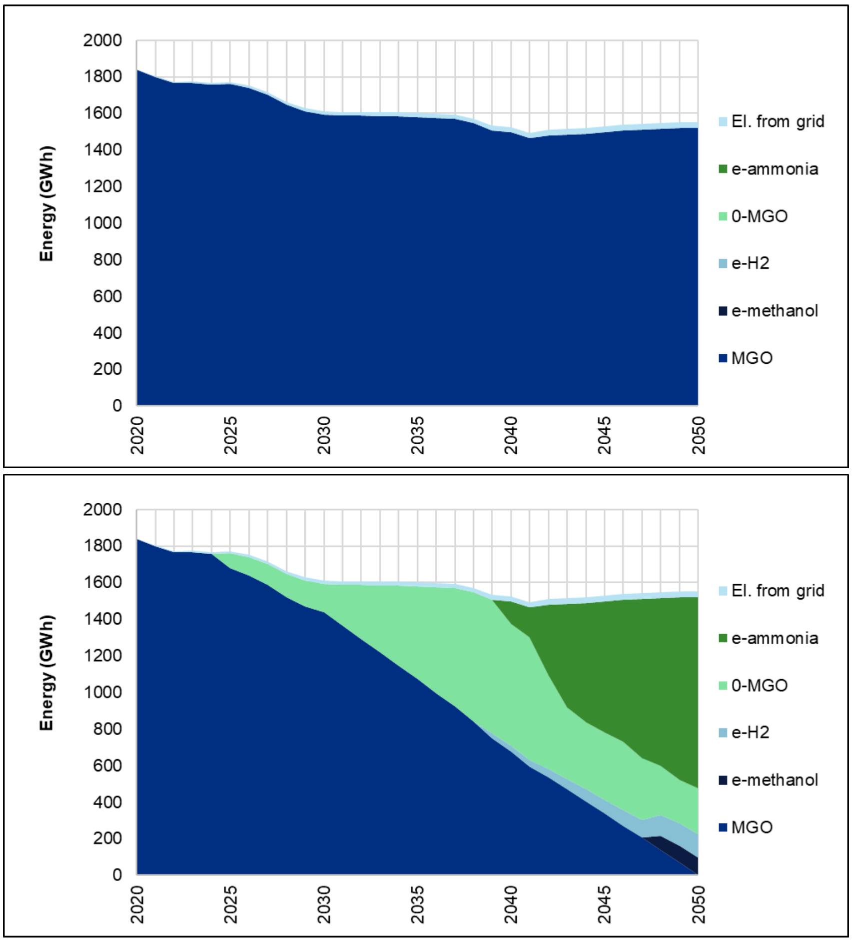

Figure 7-1: Energy mix in scenario 3 (top) and scenario 5 (bottom) with high prices on electro-fuel

8 DISCUSSION

In this study we have chosen an approach where we analyze different decarbonization scenarios, and the outcome is governed by conditions we establish in each scenario. We cannot expect to tell what the future will look like, but illustrate through the scenarios potential trajectories towards 2050. The results provide a foundation for a discussion on possible implications of the scenarios, and actions that need to be taken to realize decarbonization.

A transition to carbon-neutral fuels in the fleet will result in additional costs, both in ship investments and operationally due to increased energy costs. This requires access to additional capital. To ensure sustained profitability in the maritime sector, the additional costs will eventually need to be transferred to the end customers of ship transported goods.

Even with investment subsidies in place, to ensure profitability in the transition it is crucial that the price gap between fossil fuels and alternative fuels is reduced, and eventually that the alternative fuels are the cheapest alternative. Unless the production costs of the alternative fuels become considerably lower than assumed, it is difficult to see other ways of obtaining this than to have a price on CO_2 emissions, for example an increased CO_2 tax as explored in our scenarios. With a gradually increasing CO_2 price, future price levels will need to be accounted for when investment decisions are made. Together with raising the cost of fossil fuel consumption, the production cost of the alternatives – electro-fuels in this study – needs to be reduced. This is driven by technology improvements and may also benefit from investment subsidies for the upscaling of production facilities.

A price on CO_2 emissions will increase operational costs and potentially create vulnerability for actors operating in an internationally competing market, such as the Icelandic fishing fleet. It must be carefully considered how a higher carbon tax might affect the competitiveness of the industry, and a potential tax would probably need to be aligned with tax levels in other states. Delaying the introduction of an increased CO_2 tax could also be an option, as the effect of the CO_2 tax is of significance first and foremost when technologies are available, and the cost of the alternative fuels is low enough. If a CO_2 tax would be imposed, the timing could then be balanced against the timeline of commercialization of technologies. This is a difficult balance. As our scenarios show, the presence of investment subsidies is important to realize uptake of electro-fuels at an early stage. But the future expected fuel costs are also considered in the investment horizon – therefore it is important that a potential CO_2 tax is predictable. On the fuel supply side, predictability is also needed, as contracts with potential consumers will be important to scale up fuel production and infrastructure.

Although pricing of CO_2 can be a sensitive subject, it is important to note that a price on CO_2 emissions for shipping is considered both by the EU/EEC and by the IMO. Although the proposed measures from the EU do not directly affect the Icelandic fleet, it will likely play a role in investment decisions of both national and international actors. The carbon price in the EU has been almost doubled this year and is currently around 60 EUR/tonne.[22] Even if the price would further increase in the coming years, it is uncertain if the EU ETS will be enough to reduce the price gap and introduce carbon-neutral fuels sufficiently to reduce emissions (European Commission, 2020). A measure like the proposed FuelEU Maritime will force the introduction of carbon-neutral fuels and be an incentive to produce sustainable fuels at economies of scale. This is reflected in our scenarios where we require an increasing share of carbon-neutral fuels to obtain decarbonization by 2050.

Our scenarios do not account for biodiesel presently used in the fishing fleet[23], as this volume is not known and assumed to be low. Known projects of biodiesel production in Iceland is limited to smaller volumes.[24] In our analysis there is an uptake of biodiesel only in the scenarios where decarbonization is enforced by a required carbon-neutral share in the energy mix. This is due to the assumed high cost of biodiesel – the price is based on cost of sustainably

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[22] https://ember-climate.org/data/carbon-price-viewer/

[23] http://grebeproject.eu/2018/04/13/bioenergy-is-thriving-in-akureyri/

[24] For example this project aiming at producing 1 million litres per year: https://sorpa.is/um-sorpu/lifdisill

produced hydrotreated vegetable oil (HVO), advanced biofuel. Considering that the international demand for advanced biofuel will grow, the price can be expected to increase, due to it being a limited resource.[25]

Among the considered technologies, only battery-electric operation of ships is commercially mature. However, there is limited potential to cover a significant share of the energy consumption by ships in the Icelandic fleet, as shown in Figure 8-1. Although around 20 % of the energy mix of other vessel types than fishing vessels in our scenarios is found to be battery-electric in 2050, this contributes little to the total energy use, since the energy use of the fishing fleet dominates.

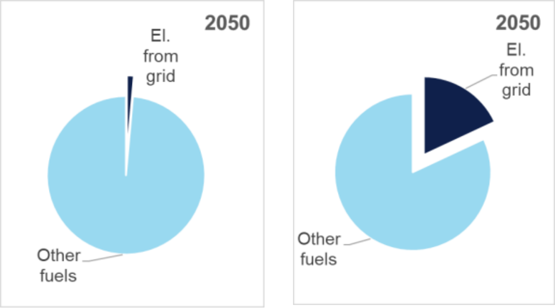

Figure 8-1: Share of the energy mix in scenarios 2050 covered by battery-electric ships for fishing vessels (left) and other vessel types (right)

The major share of carbon-neutral fuels in the energy mix in the scenarios is found to be e-ammonia and e-methanol. It is however uncertain to which degree ammonia fueled fishing vessels will be a preferred option, especially due to the need for careful design to mitigate the toxicity risk. Methanol also has higher energy density – similar to LNG, which is currently the only known alternative fuel used on large trawlers. From a design perspective, methanol-fueled vessels require lower investment costs than ammonia-fueled vessels. The price of e-methanol is however assumed higher than the price of e-ammonia, since we assume the methanol needs to be carbon-neutral and thus based on CO_2 from biomass or direct air capture (DAC). The world's largest DAC plant opened in Iceland in September.[26] Industrial activity can also provide CO_2 as feedstock for recycling – or geothermal CO_2 can be a source to produce e-methanol, like in CRI's George Olah plant in Iceland. Obtaining carbon-neutrality and no net emissions with CO_2-based fuels such as methanol and e-MGO requires careful consideration of CO_2 offsets.

Potential CO_2 sources to produce carbon-based electro-fuels such as e-methanol or e-MGO in Iceland includes heavy industries (aluminum smelters and ferro/silicon plants) and geothermal energy plants. A review of emissions from these sources indicates total annual emissions of around 2350 ktonnes CO_2 from industrial plants and 170 ktonnes from geothermal plants.[27] If the emissions are kept at this level in the coming decades, and capturing these emissions becomes a viable option, this will isolated be sufficient to produce the amounts of carbon-based electro-fuels for maritime use present in our scenarios. For example, in scenario 4 – the scenario with the highest amount of carbon-based electro-fuels – around 300 ktonnes of CO_2 is required to produce e-methanol and e-MGO.[28] However, if carbon-based electro-fuels will also be used in other sectors, for example in the form of e-kerosene for aviation, additional carbon sources might be required. This could be imported CO_2 or CO_2 from DAC.

It could be argued that the energy mix eventually will converge towards one dominating fuel, although it is now too early to determine which fuel that would be. The alternative fuel chosen by the "first movers" within the fishing industry will be of importance to create a demand and production at industrial scale, as well as technology learning that will benefit the

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[25] See description of blend-in of advanced biofuel as climate gas reduction measure in Norway here (in Norwegian): https://www.miljodirektoratet.no/tjenester/klimatiltak/klimatiltak-for-ikke-kvotepliktige-utslipp-mot-2030/sjofart-fiske-og-havbruk/avansert-biodrivstoff-i-avgiftsfri-diesel/

[26] https://www.weforum.org/agenda/2021/09/worlds-biggest-carbon-machine-iceland/

[27] Numbers compiled from the website https://himinnoghaf.is/loftslagsmal/article/skuldbindingar-islands/ (industrial sites) and the National Inventory Report (geothermal plants)

[28] 1.38 tonnes CO_2 is required to produce one tonne of e-methanol (IRENA, 2021), and 3.5 tonnes of CO_2 is assumed required to produce one tonne of e-MGO (based on figures stated by Concawe (2019).

whole sector. With the George Olah e-methanol plant in mind and the fact that methanol engines are relatively close to be commercially available, it may be that e-methanol will be the most relevant option for the fishing fleet. Also, if ammonia will not be accepted as a safe marine fuel, methanol will most likely gain a larger share of the fuel mix.

Whatever becomes the dominating carbon-neutral fuel, ships with alternative fuel technologies will most likely be designed with capabilities to operate also on conventional fuel for many years to come, especially to ensure operability while alternative fuel infrastructure and supply is still insufficient and developing. We emphasize that although a transition to carbon-neutral fuels economically can be obtained with strong policy actions, as shown in our scenarios, there are still several barriers that need to be overcome for this to be realized in practice. This includes access to capital to cover additional costs, overcoming technical and safety related challenges, operational experience with new technology and timely scaling of fuel supply.

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APPENDIX A

Alternative Marine Fuels

A1 GENERAL

The carbon-neutral fuel candidates for shipping, may be divided into three main fuel families; *blue fuels*, *electrofuels*, and *biofuels*. Each fuel family is based on its respective source of primary energy, as shown in the below figure. Blue fuels are not included in this report but included here for completeness.

Biofuels are made from processing of different types of biomass into final fuel products. Electrofuels, meanwhile, are made using renewable electricity from sources such as hydropower, wind or solar. Blue fuels are produced through processing of fossil primary energy sources like natural gas and crude oil with carbon capture and storage, into fuels like blue hydrogen. It is important to note that methanol, hydrogen, and ammonia that are produced from fossil sources without CCS are characterized as 'grey'. This is currently, by far, the most common production-route for these substances. It is worth noting, that electricity also may be applied as an energy carrier directly in battery-electric vessels, with no processing required.

Similar fuel types may originate from different primary energy sources. Take for example methane, which is known as LNG when derived from liquefaction of natural gas. LNG has for practical purposes the same properties as liquefied methane derived from electricity (e-LNG) and biomass (liquefied biogas or bio-LNG). This is shown in Table 1, which contains a non-exhaustive list of many relevant carbon-neutral fuels for shipping. In the following we structure the description of fuels according to the fuel molecule/substance, given the many common characteristics for onboard usage across fuel families.

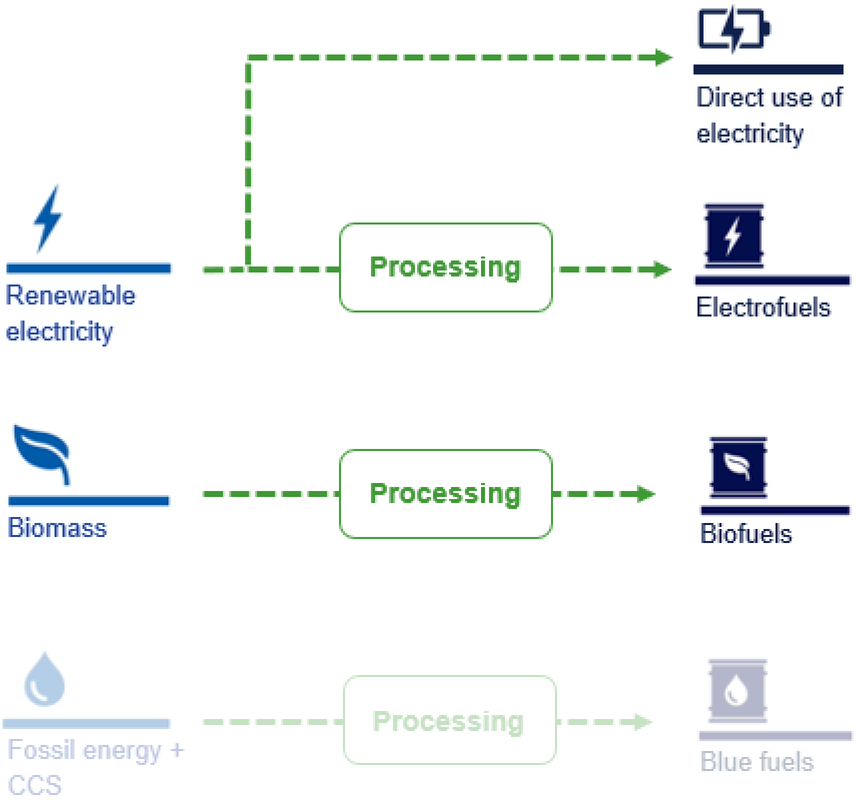

Figure: Illustration of primary energy sources for production of carbon-neutral fuels

The different fuel families can lead to the same chemical product, for example diesel (fossil MGO, bio-MGO/biodiesel or e-MGO) or methane (fossil LNG, bio-LNG/liquefied biogas or e-LNG). For the many electrofuels, it is important to note that *hydrogen* serves as major building block in the production, as illustrated in the below figure. In the sub-chapters below, some of the different fuels are further described.

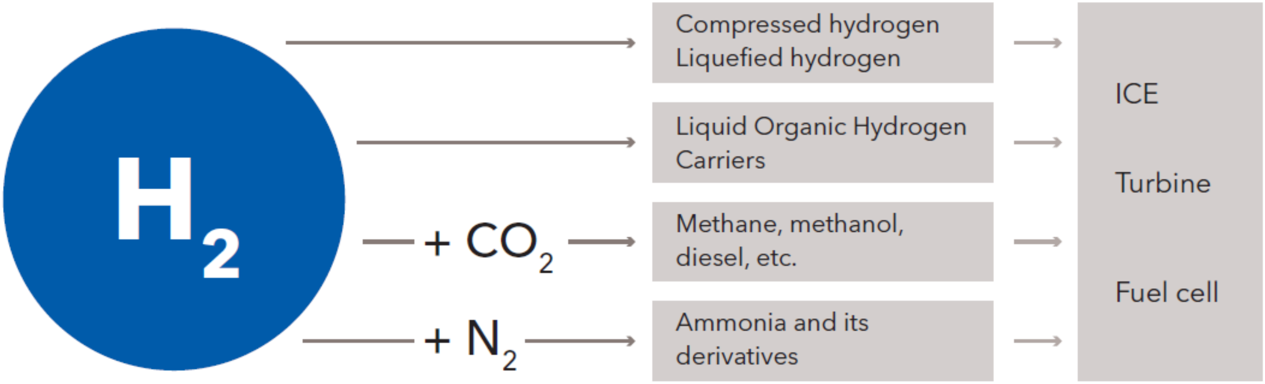

Figure: Illustration of hydrogen as building-block in the production of electrofuels

A2 HYDROGEN

Hydrogen (H2) is a colourless, odourless and non-toxic gas. Hydrogen is an energy carrier and a widely used chemical commodity. Today, 95 per cent of hydrogen is produced from fossil fuels, mainly natural gas without CCS (i.e. 'grey hydrogen'). Alternate carbon-neutral production pathways (below figure) include electrolysis of water using renewable electricity (e-hydrogen), or through reforming of natural gas with CCS (blue hydrogen). Hydrogen production from electrolysis is a well-known and commercially available technology suitable for local production of hydrogen, e.g. in port when an adequate supply of electricity is available.

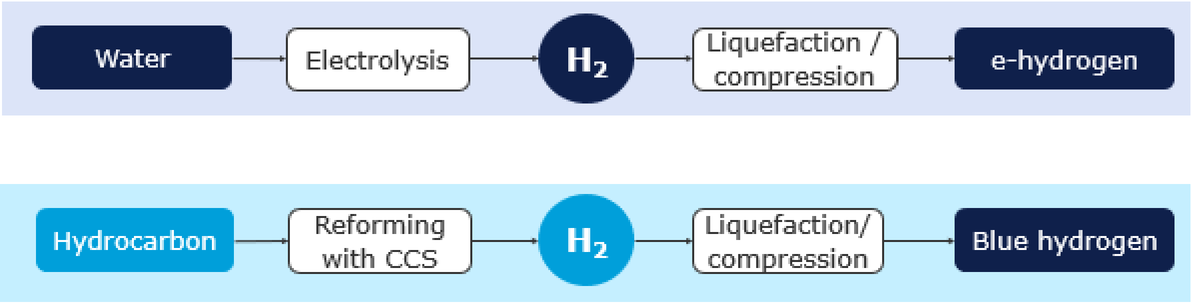

Figure: Production processes for carbon-neutral hydrogen. Also other other storage options exist, such as LOHC (liquid organic hydrogen carrier)

For use on ships, hydrogen can either be stored as a cryogenic liquid (at ~-253°C), or as compressed gas (200 – 700 bar). Other potential hydrogen carriers such as Liquid Organic Hydrogen Carrier (LOHC), which is liquid at room temperature, is also being considered. Hydrogen storage as a liquefied gas achieves a significantly higher energy-density than that of compressed hydrogen. Due to the very low boiling point of hydrogen, super-insulated pressure vessels are used for storage in liquid (cryogenic) form. A drawback with respect to the implementation of hydrogen as a fuel on larger ocean-going ships is its volumetric energy density, which is significantly less than that of LNG and fuel oils. Therefore, a higher space-allocation to storage, or more frequent bunkering, is necessary.

Fuel cells (FC) is considered the key technology for onboard power production using hydrogen, however, other applications are also under consideration, including gas turbines and internal combustion engines in stand-alone operation or in arrangements incorporating fuel cells. Developments of hydrogen-fuelled vessels has so far favoured its use in Proton Membrane Exchange Fuel Cells (PEMFCs), with its application in other fuel cells and in internal combustion engines (ICEs) at a less mature stage. The first major hydrogen-fuelled ferry is set to enter operation in Norway in 2021 with fuel cells (low-temperature PEMFCs).

Hydrogen, when consumed in fuel cells or ICEs, does not produce any CO_2 emissions or other emissions directly, other than H2O. It is important, however, that carbon-neutral production pathways for hydrogen (e.g. reforming of natural gas with CCS) is used to realize low emissions in the value chain.

A3 AMMONIA

Ammonia is a toxic compound consisting of nitrogen and hydrogen, with chemical formula NH_3. Currently, the vast majority of ammonia is produced via reforming of natural gas without CCS, followed by Haber-Bosch synthesis (i.e. 'grey ammonia'). In the future however, other production routes based on renewable electricity (e-ammonia) or natural gas with CCS (blue ammonia) could deliver carbon-neutral ammonia for use as a marine fuel (below figure).

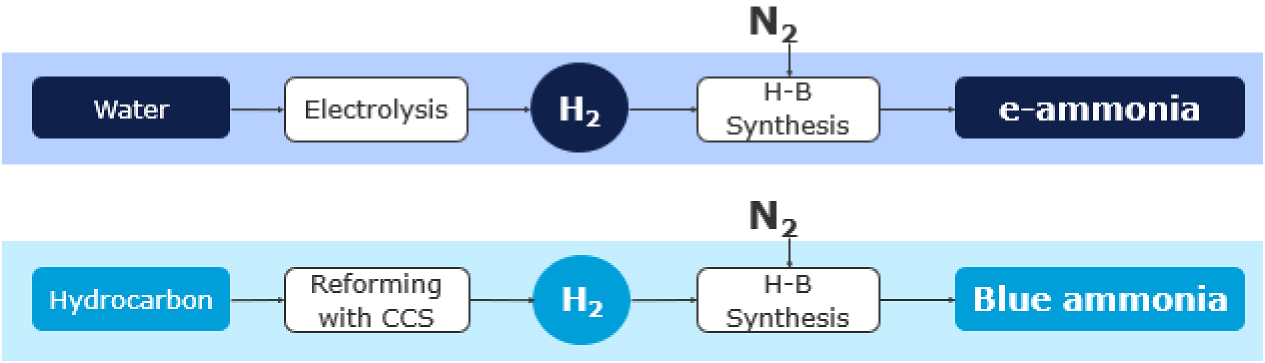

Figure: Production processes for carbon-neutral ammonia (H-B – Haber-Bosch; N2 – nitrogen gas)

Production of ammonia from hydrogen and nitrogen through H-B synthesis is a well-known commercial process. However, production of carbon-neutral ammonia (blue ammonia or e-ammonia) is currently very low. Infrastructure for transport and handling of ammonia exists, due to its wide use in production of fertilizers. However, bunkering infrastructure for ships is currently non-existent and needs to be developed.

Ammonia is stored as a liquid, primarily in three different states: i) fully pressurised (~18 bar, 20°C). ii) semi-pressurised (~5 bar, ~-10°C), or iii) fully refrigerated (1 bar,~-33°C), depending on the quantity stored. For use as fuel on ships, fully pressurised is the most applicable for the general fleet. Liquid ammonia has a significantly lower volumetric energy density compared to conventional fuels like MGO/HFO. Consequently, significantly more space is needed; more than methane but less than other alternative fuels such as liquefied hydrogen.

Ammonia may technically be applied as a fuel in both ICEs and FCs. As far as FCs are concerned, ammonia may be consumed directly in high-temperature fuel cells such as SOFCs, or after being cracked into hydrogen and purified for traces of ammonia for use in low-temperature fuel cells such as PEMFCs.

No ammonia-fuelled propulsion systems are currently available on the market. However, given the similarity of ammonia-fuelled ICEs with current commercially available engine-designs, there is reason to believe that ammonia-fuelled ICEs could be available within the next three to five years. Notably, the engine manufacturer MAN ES is developing a concept for applying ammonia as a fuel in two-stroke dual fuel engines[5]. Research efforts are being made with respect to the application of ammonia in FCs, however, there is still a long time before the technology is expected to be commercially available.

The end-use of ammonia in ICEs or FCs does not cause any emissions of CO_2. Emissions of nitrous oxide, which is a potent greenhouse gas, could however be a challenge. In a value-chain perspective, it is also important that ammonia is produced from production pathways including natural gas reforming with CCS or electrolysis of water with renewable electricity.

A4 METHANOL

With its chemical structure CH_3OH, methanol is the simplest alcohol with the lowest carbon content and highest hydrogen content of any liquid fuel. Today, methanol is a basic building block for hundreds of essential chemical commodities and is also used as a fuel for transport. It is, however, primarily produced from fossil energy sources without CCS, and is therefore characterized as 'grey'. Carbon-neutral methanol may be produced from biomass (bio-methanol) or renewable electricity (e-methanol), as shown in the below figure[29]. In each case, a source of CO_2 is required for methanol synthesis.

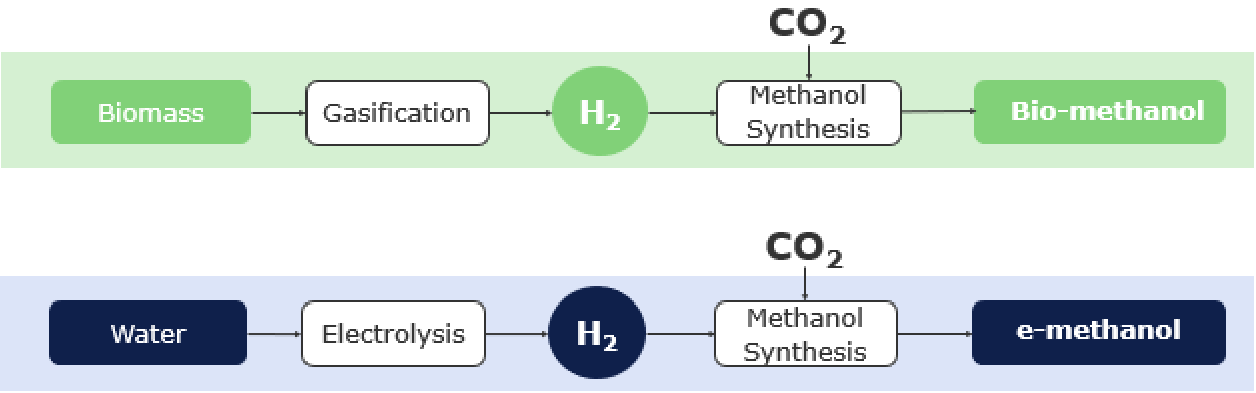

Figure: Production processes for carbon-neutral methanol. Other production pathways also exist[29]

Fossil methanol is one of the top five chemical commodities shipped around the world each year. It is readily available through existing global terminal infrastructure. However, dedicated bunkering infrastructure for ships is currently limited. Distribution to ships can be accomplished either by truck or by bunker vessel. Production of carbon-neutral methanol (bio-methanol or e-methanol) is currently very limited.

Methanol is a liquid between –93 °C and 65 °C at atmospheric pressure, which entails that it is more easily stored on board ships than some other carbon-neutral fuels such as liquefied methane. It may be stored in standard fuel tanks with minor modifications. Its volumetric energy density is, however, significantly lower than conventional marine fuels. Therefore, when compared to a conventional fuel like MGO, approximately twice as much volume is needed to store the same amount of energy on board ships.

There are two main options for using methanol as fuel in conventional ship engines; in a two-stroke diesel-cycle engine or in a four-stroke, lean-burn Otto-cycle engine. Both options have seen real-life operation for extended periods of time on board ships and use pilot fuel oil ignition. Another possibility would be to use methanol in fuel cells, which is in a less mature technical stage.

For the time being, only methanol-fueled two-stroke dual fuel diesel engines, as part of the MAN ME-LGI series, is commercially available on the marine propulsion market. Wärtsilä 4-stroke engines are, however, in operation on board the passenger ferry Stena Germanica, fueled by methanol. Use of methanol as a fuel on major ships has a relatively

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[29] Carbon-neutral methanol may also be produced via reforming of natural gas with CCS, but this is not covered here. In this case, carbon must be extracted from an environmentally friendly source in order to combine with hydrogen in a methanol-synthesis reaction.

short track-record (first ship retrofitted in 2015), and so far, it has largely been restricted to the niche market of methanol tankers.

The GHG reduction potentials for carbon-neutral methanol is largely dependent on the production-pathway. Carbon neutrality is possible assuming that renewable electricity is used for hydrogen production (e-methanol) or sustainable biomass with carbon-neutral footprint is used as a feedstock (bio-methanol).

A5 DIESEL

Carbon-neutral diesel can also be denoted *synthetic diesel*, has two primary production pathways, bio-based or electro-based (below figure). Using biomass, bio-based carbon-neutral diesel may be produced in different ways including hydrotreatment of waste oils and fats (known as hydrotreated vegetable oil) or from Fischer-Tropsch synthesis using hydrogen produced from gasification of biomass (both referred to here as bio-MGO). It may also be produced from renewable electricity (e-MGO). For production pathways involving Fischer-Tropsch synthesis, a source of CO_2 is required. As implied by its name, carbon-neutral diesel is a hydrocarbon with equivalent properties in use to those of fossil conventional diesel.

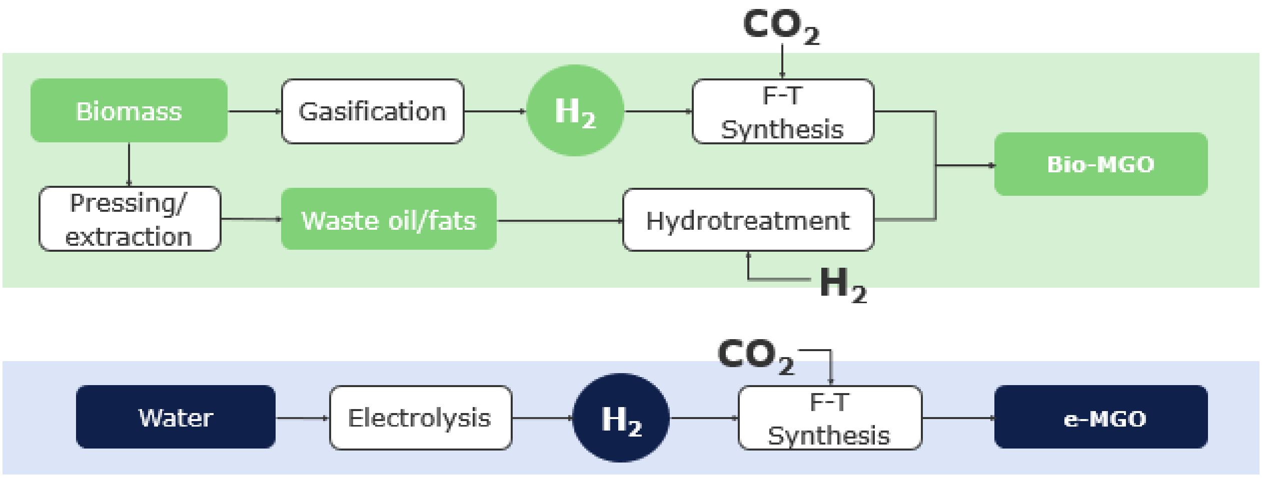

Figure: Production processes for carbon-neutral diesel (F-T – Fischer-Tropsch)

The technical maturity of onboard propulsion and energy storage systems for carbon-neutral diesel is very high, owing to the fact that it is compatible with existing systems designed for use with MGO or HFO. Also, bio-MGO and e-MGO may use existing infrastructure for distribution and bunkering in place for fossil MGO or HFO. Unlike MGO and HFO, the current production of carbon-neutral diesel is very limited. Bio-based diesel, more specifically hydrotreated vegetable oil (HVO), is by far the most common production-pathway for synthetic diesel, and its total production amounted to the equivalent of 5.8 Mtoe in 2018.

The GHG reduction potentials for e-MGO and bio-MGO is largely dependent on the production-pathway. For electro-based synthetic fuels, carbon-neutrality is possible assuming that renewable electricity is used for hydrogen production. For bio-based synthetic diesel, carbon neutrality is possible because biomass is derived from feedstock which absorbs CO_2 from the atmosphere when growing.

A6 BATTERY-ELECTRIC

Electricity from grid can be stored in a battery on board a ship and directly supply energy required for propulsion and auxiliary systems. This is typically solved by plug-in hybrid solutions which also include combustion engines for liquid/gas fuels, to enable flexibility. Compared to using the electricity from grid to produce electro-fuels – which have significant energy losses in the production process - using electricity directly on board the ship is an effective way of utilizing the electric energy (figure below).

Figure: Battery-electrification in principle

The access to enough renewable power from the electricity grid at relevant ports is crucial to realize carbon neutral battery-electrification of ships. Although the access to shore power for the purpose of covering the energy need while in port is steadily increasing, the power capacity is not necessarily sufficient to simultaneously charge large ship batteries for other parts of the ship's operation. A development of higher power capacities at ports in some places can be expected in the near future, for example due to large passenger ships (like the Coastal Route Bergen-Kirkenes along the Norwegian coast) being planned to operate plug-in hybrid. In conjunction with electric motors, electricity from batteries may be used for propulsion onboard ships with very high energy efficiency.

According to DNV's Alternative Fuels Insight platform there are currently almost 200 electrified (fully or partly) in operation or on order globally. Electric driven ships are today mostly restricted to short-sea segments such as ferries, passenger vessels and other ship types that operate in fjords or along the coast in regular trade with frequent port calls. Usually, these also have a redundant fuel tank and conventional propulsion systems onboard. One of the reasons for this is the very low energy density of batteries compared to conventional fuels. How much of the ship's energy consumption that is supplied by electric energy (denoted as *electrification degree*) from the batteries depend on the capacity of the batteries, the available charging power at port and the energy consumption between port calls. Current technology development for batteries leads to higher energy density, but the energy density is still far below that of other fuel alternatives.

Battery-powered vessels, when operating exclusively on electricity from the battery, have zero ship-side emissions of GHGs and local pollutants (e.g. NOx, and SOx). The GHG reduction potential for battery-electric vessels therefore depend on the carbon-footprint of electricity-generation.

APPENDIX B
Calculation of energy use

The DNV method for estimating fuel consumption for ships based on AIS was developed in 2008 (DNV, 2008) and is continuously in use in multiple projects and for example on the Norwegian Coastal Administration web portal havbase.no, showing live emissions of ships in Norwegian waters.

The calculation of energy needs and fuel use for ships is based on AIS data and ship data (installed main and auxiliary engine power, ship type, ship size and service speed). The ship data for each specific vessel is collected from various ship databases, such as IHS Fairplay, Icelandic Ship Register, DNV's own records, and coupled to the AIS data through the vessel's IMO number, MMSI number or ship name. For vessels where ship data such as engine power or service speed is not available, average values from similar ships are used (type and size is available for all ships from the used databases).

From the AIS data, a speed profile is generated for each ship and each voyage. This shows how much of the sailing time the ship is operating at various speed segments. The main engine load factor is an exponential function of the speed, where the engine load is assumed to be 80 % at service speed. The energy need of each speed segment can then be calculated by the time the vessel is at that speed segment times the engine power and the relevant load factor. In addition to main engine consumption for propulsion, generic factors are used for different ship types for auxiliary power at sea and at port.

For fishing vessels, a modification of the model is applied: It is assumed that the vessel is fishing when speed is below 5 knots while at sea and that during fishing, 80 % engine load is assumed[30]. This is considerably higher than the engine load at slow speed transit. This implies that the *energy use per hour* is assumed approximately the same while fishing as when steaming at service speed (to and from fishing field). Such an engine load during fishing is probably too conservative for certain types of fishing gear, while more representative for e.g. trawling, which constitutes most of the total fuel consumption of the fleet.

The figure below shows how estimated fuel consumption is spent at different speeds for fishing vessels (at sea). As the figure shows, around 70 % of the fuel consumption at sea is during fishing, *for the fleet as a whole*. This distribution will differ based on sailing distance. For comparison, Fisheries Iceland (2017) provides data suggesting that for bottom trawlers, 75 % of the fuel consumption is while fishing, while for others, 50 % is while fishing.

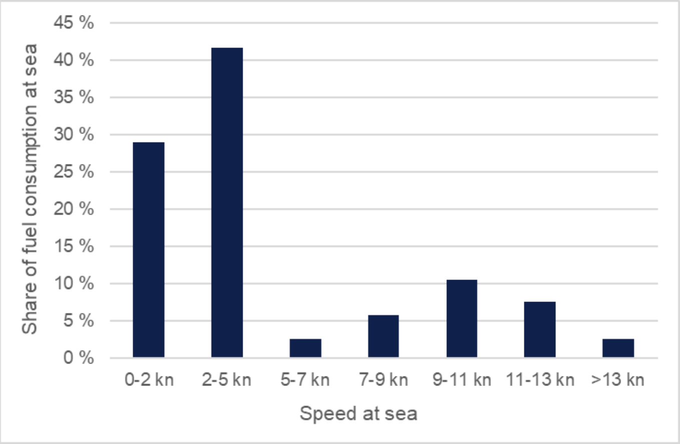

Figure: Share of estimated fuel consumption at sea at different speeds, for fishing vessels

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[30] This was agreed in workshop with industry representatives on May 26 2021

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