PAME

Protection of the Arctic Marine Environment

DNV·GL

Alternative fuels in the Arctic

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Objective: Shipping activities in the Arctic impacts on climate change, health and the environment. Introducing alternative fuels in arctic shipping could significantly reduce emissions and impacts, as well as risk associated with the use and carriage of heavy fuel oil (HFO). On behalf of PAME, DNV GL has in this report assessed alternative fuels and technologies for potential arctic use. The work is funded by "Funds for Arctic Environmental Cooperation" provided by the Norwegian Ministry of Foreign affairs. Co-leads for PAME; Norway and WWF.

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Table of contents

1 EXECUTIVE SUMMARY

Shipping activities in the Arctic impacts on climate change, health and the environment. Introducing alternative fuels in arctic shipping could significantly reduce emissions and impacts, as well as risk associated with the use and carriage of heavy fuel oil (HFO).

Globally, alternative fuels are emerging as a viable option to oil-based fuels. There are currently 135 LNG powered vessels sailing, and a further 135 confirmed newbuilds. Biofuels and methanol are available in certain ports and used in nice applications. Fully electrical ferries are now in use, particularly in the Norwegian domestic ferry sector, with phasing in of more than 60 battery electric ferries over the next few years. Hybrid electric ships are emerging in the short sea segment for offshore and passenger ships/ferries. Hydrogen fuel cell powered ships are planned for first commercial application 2021.

On behalf of PAME, DNV GL has in this report assessed alternative fuels and technologies for potential arctic use. The work is funded by "Funds for Arctic Environmental Cooperation" provided by the Norwegian Ministry of Foreign affairs. Co-leads for PAME; Norway and WWF.

What we did

The objectives of this report are three-fold;

1. Provide an updated inventory of arctic shipping fuel consumption and emissions to air. The inventory is AIS-based and is carried out for 2017, for the IMO Arctic Polar Code area. The emission components covered are CO_2, NOx, SOx, particulate matter (PM) and black carbon (BC). The fuel consumption inventory includes the volume of HFO used in the Arctic (volumes carried not included). This inventory provides a baseline for assessing impacts of alternative fuels.

2. Describe and assess a range of alternative fuels and technologies for potential arctic use. To capture different characteristics and enable a comparison between them, a new method for holistic assessment of fuel and technology options has been developed and applied. The options are evaluated and ranked with respect to environmental performance, costs and scalability.
   The alternative fuels included are; HFO, Diesel/MGO, Low Sulphur Hybrid, Low Sulphur Hybrid (arctic optimized), bio diesel (HVO), bio-gas, LNG, full electric, methanol, hydrogen and ammonia. Each of these fuels assessed was allocated a relevant converter, as well as battery hybridization for fuel- and emission optimized engine operation where applicable. Relevant converters (propulsion systems) for shipping include gas, dual fuels, multi fuel engines, marine fuel cells, battery electric propulsion systems, and gas and steam turbines.

3. Based on assessment in step 2, the most promising fuel for application in the Arctic is identified, and the potential for reductions in emissions to air is quantified, and oil spill reduction potential evaluated. Furthermore, barriers and drivers for uptake are discussed, included measures and policies to overcome the barriers.

What we found

Fuel consumption and emissions to air

The AIS-based modelling shows that a total of 1 870 ships had operations in, or transits through, the IMO Arctic Polar code area in 2017, consuming about 581 Kton[1] of oil equivalents. The key findings from the fuel consumption modelling are:

- Fishing vessels, oil tankers, general cargo vessels and other service vessels together accounts for around 80% of the total fuel consumption in the area.

- The larger ships, above 10 000 gross tonnage, accounts for nearly 50% of the total fuel consumption.

- HFO is the dominating type used with 58% of the totals, followed by distillate fuels with 36% and nuclear ships having approximately 6% of fuel consumed in terms of oil equivalents. LNG as fuel is sparse, representing less than 0.1% of the totals.

- In the four-year period 2014 to 2017 there has been 45% increase in fuel consumption inside the IMO Arctic polar code area.

Ship emissions in the IMO Arctic Polar code area are calculated by multiplying the fuel consumption by emission factors. Table 1-1 present an overview of fuel consumption and emissions by ship types for the area. Key findings from the emission modelling are:

- CO_2 emissions are 1.85 million tonnes, representing about 0.23% of the global ship emissions.

- Emissions of NOx and SOx are 32.5 Kton and 2.3 Kton, respectively.

- Emissions of PM and BC are 20.0 Kton and less than 0.2 Kton, respectively.

Table 1-1   IMO Arctic polar code area, ship fuel consumption and emissions for 2017

Ship type	Fuel [ton]	CO_2 [ton]	NOx [ton]	SOx [ton]	PM [ton]	BC [ton]
Oil tankers	132 300	421 900	9 200	950	6 780	46
Chemical and Product tankers	26 200	83 300	1 400	130	1 310	9
Gas tankers	8 200	26 300	600	60	430	3
Bulk carrier	29 000	92 600	2 100	220	1 490	10
General cargo	87 300	276 700	5 600	450	4 440	30
Container vessels	14 300	45 600	800	20	740	5
Ro Ro vessels	1 000	3 100	100	10	40	0
Reefers	15 000	47 600	500	30	750	5
Passenger	34 300	109 100	1 900	160	1 080	9
Offshore supply vessels	15 300	48 400	700	20	190	3
Other offshore vessels	2 200	7 100	100	5	30	0
Other activities	70 100	222 000	3 100	80	910	13
Fishing vessels	145 900	461 400	6 400	180	1 840	26
Total	**581 100**	**1 845 000**	**32 500**	**2 310**	**20 030**	**160**

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[1] 1 Kton = 1 000 tonne

Assessment of alternative fuels

The many alternative fuels, and their diverse characteristics, make comparisons challenging. To capture the key characteristics and enable a comparison between fuels, a new method for holistic assessment of fuel options has been developed and applied. The approach assesses how well an alternative fuel performs compared with traditional fuels or other alternative fuels. The main performance categories used are **environment**, **economics**, and **scalability**, and each of these are further divided into sub categories (e.g. air emissions, bunker spill), and criteria to be considered (Figure 1-1). For each criterion, the methodology captures two aspects. Firstly, the objective (physical) property of the fuel, such as the GHG emissions. Secondly the subjective importance placed on this property by the evaluator. Weighting factors can be assigned to reflect the different priorities and views of different evaluators, different environments or different stakeholders. The rating assumes the likely future situation in a 5-10-year perspective.
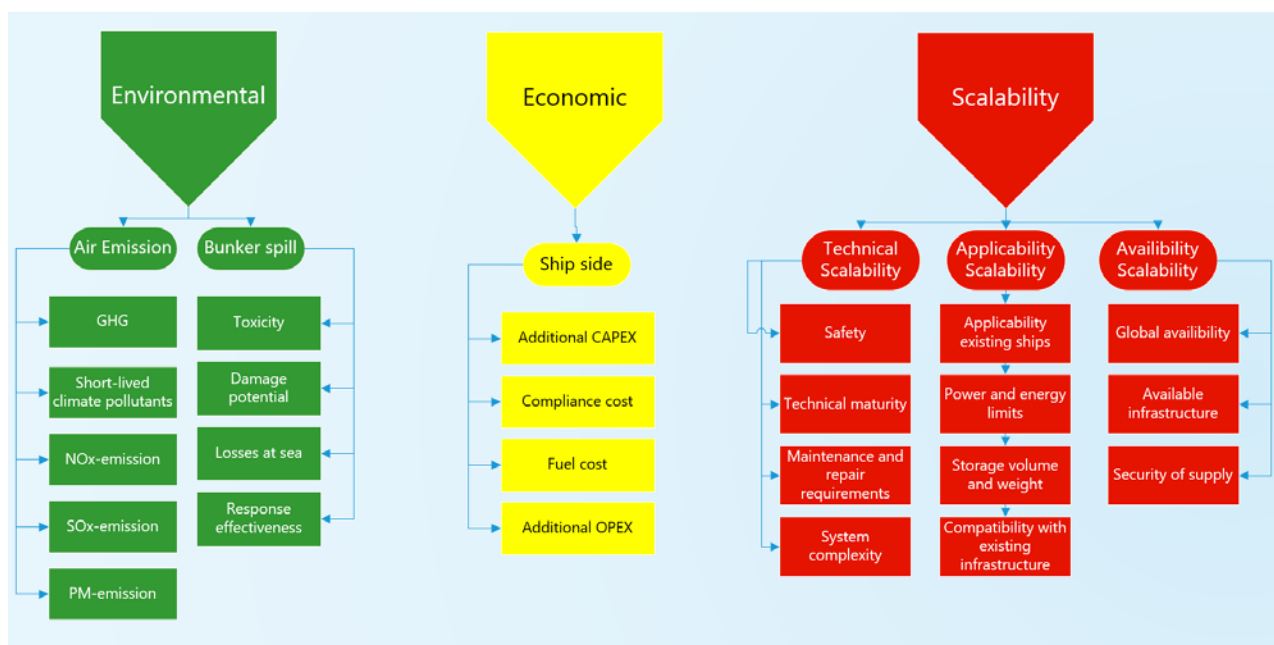
Figure 1-1 – Outline of the ranking criteria for alternative fuels, divided into three main performance categories.

The requirements to alternative fuel for use in short-sea and deep-sea shipping may vary significantly and the ranking results are therefore presented separately for the short-sea and the deep-sea segment (Figure 1-2). The results show that all alternative fuels have better environmental performance compared to the traditional fuels, but generally score worse than the traditional fuels regarding economy and scalability.

Furthermore, the ranking result shows that LNG with a battery-electric hybrid solution receives the highest score for both short- and deep-sea shipping. For short-sea the runners-up were Biogas and Battery-electric propulsion. For deep-sea, the runners-up were biodiesel (HVO) and methanol/FC. applicability and scalability are the factors that mainly differentiate the scores for short-sea and deep-sea shipping.

Even though LNG is not a "zero-emission" solution, the environmental footprint in the Arctic is still favourable due to low emissions of NOx, SOx, PM and BC, and small impacts of accidental spills. It is also scalable to cover both destination/intercontinental traffic as well as regional traffic. The latter is provided an LNG land-infrastructure is developed. Investments in LNG may also pave the way towards use of biogas to further reduction in GHG-emissions. Note that for the smallest vessels in the region, no LNG-engine is currently available in the marked.
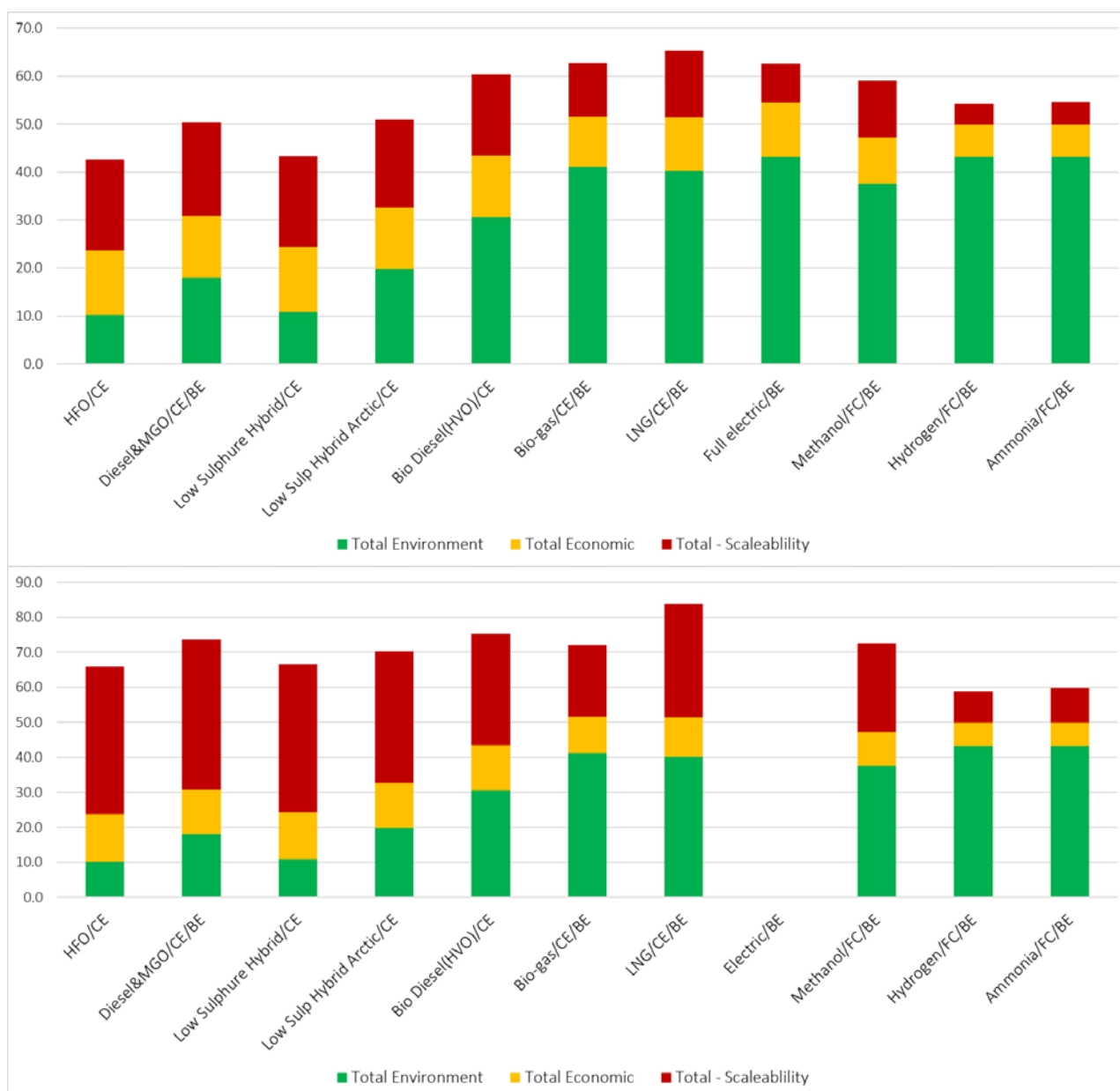
Figure 1-2 – Overall ranking of selected fuels (highest is best), with contributions from the three main performance categories. Short sea shipping (top) and deep-sea shipping (bottom) in the Arctic.

Quantification of potential emission and oil spill risk reduction

In our model, LNG obtain the highest overall score. Thus, a simulation is made assuming the "full" implementation of LNG in the arctic fleet, to quantify the consequent effects on emissions to air. The results show that there is a potential GHG-reduction potential of 12% for the arctic fleet, assuming all vessels above 1000 GT uses LNG. For vessels below 1000 GT sufficiently small LNG engines are not assumed available. The introduction of LNG will reduce the emissions of NOx, PM, SOx and BC by 85%, 95%, 98% and 91% respectively. In addition, use of LNG will eliminate oil spill risk.

In light of the ongoing prosses to ban the use of HFO in the Arctic, it is recognized that on a short term, a more realistic shift will be towards a requirement for distillate fuels. An additional simulation is thus performed assuming the replacement of HFO with MGO in the arctic fleet. The introduction of MGO for all vessels in the Arctic will not reduce the CO_2 and NOx emissions, but it will reduce the emissions of PM, BC and SOx by 67%, 35% and 94% respectively.

Barriers and drivers for uptake of LNG in arctic shipping

All alternative fuels face challenges and barriers. A barrier may be defined as a mechanism that inhibits investment in promising fuel and technologies. In an arctic environment is it expected that these barriers will be "strengthened", due to remoteness and ice-weather conditions. The cost associated with machinery, expected fuel prices, and availability of bunkering infrastructure, will be key barriers. Safety will also be a primary concern and can be translated into monetary terms once a design has been established and the necessary safety measures are identified. The need for infrastructure development, such as bunkering facilities and supply chain, is another hurdle. Uncertainty regarding long-term availability is also a concern. In addition, storage of certain alternative fuels will require more space on board compared with traditional fuels.

There are different barriers introducing LNG battery hybrid for use in the Arctic. The main barriers are indicated in the table below.

Table 1-2 Assessment of barriers related uptake of LNG in the arctic fleet, based on framework reported by DNV GL (2015a)

Main category	Sub category	Barrier level	Comments
Technical	Safety and reliability Technical maturity Infrastructure and availability	Significant	Need for additional safety measures, also during bunkering Mature technology Lack of infrastructure for LNG in the Arctic
Economic	Commercial implications Economic and finical challenges Taxes and incentives	High	High investment cost Suitable for new-buildings Limited demand for "green" ships
Regulatory	Rules by authorities Class rules Incentives and incentives	Low	Established by IMO Established by major classification societies Lack of incentives and drivers
Cultural/ non-technical	Organizational challenges Complexity in applications	Significant	Training of crew Operational and competence intensive

The main drivers leading to the advent of LNG and alternative fuels in the future will be economical motivated as in the past, but environmental and GHG regulations will impact shipping significantly the next decades. While environmental regulations (SOx, NOx and PM) will impact shipping most significantly in the short term, we expect regulation of GHG to be the main challenge in the medium to

long term. It will no longer be possible to assume a "stationary" regulatory and technology landscape for the lifetime of a ship. An important additional driver for arctic will be the potential HFO ban.

It is recommended to initiate studies which further detail the arctic traffic patterns, with special attention to port calls and bunkering. Also, further studies should identify barriers to achieving policy targets. This could provide the basis for a tailored "package" of policy measures to stimulate phasing in alternative fuels which could lead to significantly lowering of the oil spill risk and emissions to air for specific areas or for the region as a whole.

2 INTRODUCTION

Shipping activities in the Arctic impacts on climate change, health and the environment. In the Arctic, particular focus has been on emissions of black carbon (BC) (e.g. Corbett et al., 2010; DNV, 2012; Winther et al., 2014, 2017; Mjelde et al., 2014; AMAP 2015) and the use and transport of Heavy fuel oil (HFO) (e.g. DNV, 2012; Mjelde et al., 2014; ICCT, 2017a, b; 2018; Fritt-Rasmussen et al., 2018), also known as residual oil. This is the preferred bunker fuel for most ocean-going vessels due to price. Geographically resolved ship emission inventories are a fundamental input to evaluate impacts on the environment, human health and climate – and to effectively assess what options are available to mitigate these impacts (e.g. Endresen et al., 2003; Corbett et al., 2008; OECD, 2010). Also, a good understanding of the fuel quantities used, and the geographical distribution of the different oil products transported within the region, is essential for assessing the potential environmental impacts from oil spills. Several arctic studies have been carried out related to developing arctic air emission and HFO inventories, including assessing ways to reducing impact and risks:

- **Risks of using HFO in the Arctic:** AIS-based studies carried out on behalf of PAME (The Protection of the Arctic Marine Environment Working Group under the Arctic Council) and Norwegian authorities, presented in 2011 an inventory of ships carrying heavy fuel oil (HFO) in the Arctic (DNV, 2012). HFO inventory has also been reported by ICCT (2017a, b; 2018a, b). Regarding HFO in the Arctic, a recent review study has reported on the fate and behaviour of HFO spills in cold seawater, including biodegradation, environmental effects and oil spill response (Fritt-Rasmussen et al, 2018). Recommendations to mitigate risks of potential oil spills in arctic has also been reported (e.g. WWF 2018; Ocean Conservancy 2017). Recent studies have also considered economic and environmental tradeoffs of switching from HFO to distillate fuel and liquefied natural gas (LNG), (Delft, 2018; Winther et al., 2017; ICCT, 2017c; ICCT, 2019).

- **Air emissions and its impacts on climate, health and environment:** Modelling studies have produced arctic emission inventories, based on fleet and movement data (e.g. from AMSA in Corbett et al., 2010), as well as on ship observations in the Arctic (e.g. Peters et al., 2011; Dalsøren et al., 2007). AIS-based Arctic emission inventories have been carried out by e.g. Winther et al. (2014; 2017), Mjelde et al. (2014), ICCT (2017a, b), and compared by AMAP (2015) and ICCT (2017a). The impact of these emissions has been studied by e.g. Peters et al. (2011), DNV GL 2012, Dalsøren et al. (2007).

Introducing alternative fuels in arctic shipping could significantly reduce emissions and impacts, as well as risk associated with the use and carriage of heavy fuel oil (HFO). On behalf of PAME and Norwegian authorities, DNV GL has in this report assessed and proposed alternative fuels and technologies for potential arctic use.

The report is structured in three main parts:

1. Firstly, this study provides an updated inventory of arctic shipping fuel consumption and air emissions. The inventory is AIS-based and is carried out for 2017, for the IMO Arctic Polar Code area. The emission components covered are CO_2, NOx, SOx and particulate matters (PM). The fuel consumption inventory includes the volume of HFO used in the Arctic (volumes carried not included). This inventory (section 3) provides a baseline for assessing impacts of alternative fuels.

2. Secondly, the study has described and assessed a range of alternative fuels and technologies for potential arctic use (sections 4 and 5). The alternative fuels included are; hybrid oils, LNG, LPG, biofuel (biodiesel, biogas), methanol, hydrogen, ammonia, battery-electric and hybrids (fuel- and emission optimized engine operation with battery hybridization), synthetic fuels, renewable powering (wind, wave, solar). Alternatives which may play a part further ahead has been described, but not

assessed, i.e. synthetic fuels, renewables powering, and nuclear as fuel. The alternative fuels are associated with the relevant converters (considered the optimal use of the given fuel). This study has evaluated 11 possible fuel/converters combinations.

The alternative fuels included in this study have quite distinctive characteristics in an arctic setting. To capture these characteristics and enable a comparison between them, a new method for holistic assessment of fuel and technology options has been developed and applied. The options are evaluated and ranked with respect to environmental performance (e.g. GHG, spill behaviour and fate), but also costs and scalability. The model may be tailored for any given purpose by changing the weighting of each individual ranking. Using the weighting we distinguish between short-sea and deep-sea shipping.

3. Thirdly, the fuel/converter combinations (based on the ranking method), which are found to have a particular suitability for the Arctic, are then introduced in the Arctic 2017 fleet as a model simulation. The potential for reductions in emissions to air is quantified, and oil spill reduction potential discussed. Furthermore, barriers and drivers for uptake of these fuels are discussed, including measures and policies to overcome the barriers (sections 6 and 7).

3 ARCTIC FUEL CONSUMPTION AND EMISSIONS TO AIR

This section presents the estimated fuel consumption and the emission inventory for ships in the IMO Arctic Polar Code area for the base year 2017. Additionally, the historic developments are presented for the period 2014 to 2017.

3.1 Method and data

The fuel consumption and the emission inventory is produced using DNV GL's model MASTER (Mapping of Ship Tracks, Emissions and Reduction potentials), the use of which has been described previously (e.g. Mjelde et al, 2014; DNV GL, 2014; DNV GL 2018b,c). The model uses global ship-tracking data from the Automatic Identification System (AIS), enriched with ship-specific data from other sources and emission factors.

The AIS data provide a detailed and high-resolution overview of all ship movements, where sailing speeds, operating patterns, sailed distances (nautical miles) and time spent in areas are identifiable for each identified ship (those having the AIS system installed). The AIS transponder is mandatory for almost all ships above 300 gross tons, which automatically transmits a unique ship identity code, a precise position reference and the ship's heading and speed down to seconds' intervals. The AIS system is also used by many smaller vessels (without IMO number). These vessels are not accounted for in the fuel consumption and emissions modelling as there is limited information about their technical data and capabilities.

The information from the AIS system is merged with technical databases for detailed information on the individual ships, such as installed power on main and auxiliary engines, machinery configurations, ship design speed, tonnage, etc. The two data sources together with several supporting data tables form the basis for the AIS-based environmental accounting system for ships. The model is used to calculate engine load profiles, fuel consumption, emissions and operational characteristics for main engines, auxiliary engines and boilers for each individual AIS registered ship position.

The emission components covered are CO_2, NOx, SOx, particulate matters (PM) and black carbon (BC) and the results are aggregated on 13 ship types and 7 size categories. Ship emissions are calculated by multiplying the AIS-based fuel consumption by emission factors (e.g. Mjelde et al., 2014; Winther et al., 2014; 2017; ICCT, 2017a, b).

For this study DNV GL is using our in-house combined AIS dataset which comprises data from several different data sources, Vesseltracker and the Norwegian Coastal Administration (NCA), which are subsequently merged in to a complete global data set with good coverage also towards the north pole. DNV GL processes AIS data continuously, and the combined data used in this study includes 4 full years of AIS ship movement data from January 1st 2014 through to December 31st 2017.

Note that this work does not separate between domestic and international traffic, nor traffic only passing through the area (transit).
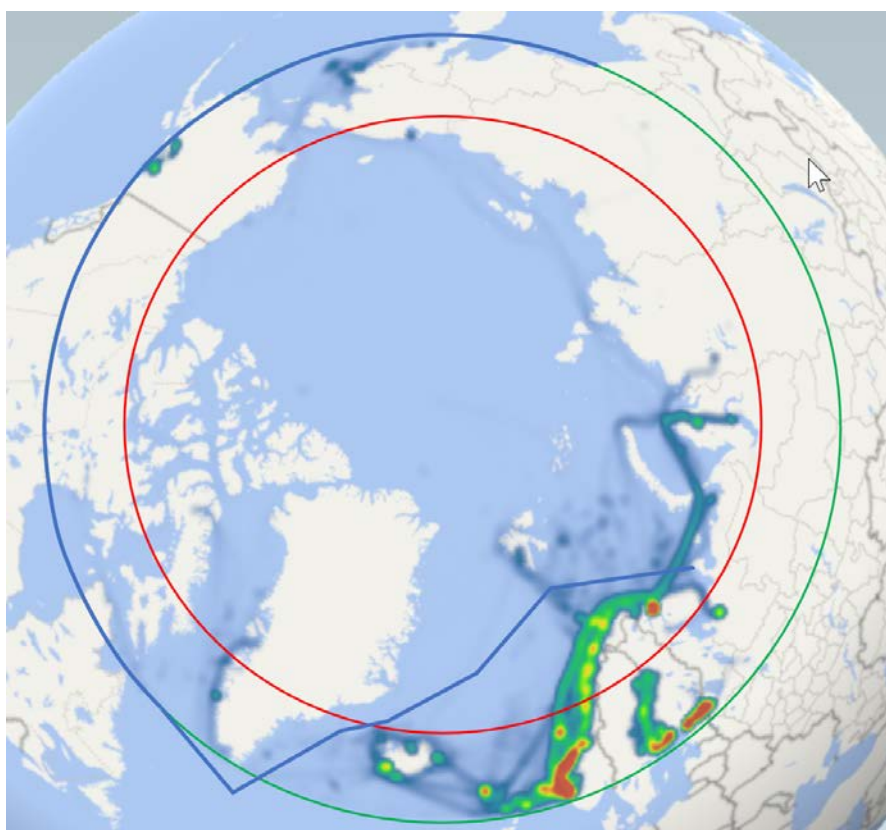
3.2 Arctic delimitation

There are several delimitations defining the Arctic area depending on intent and purpose of use. They are based on different criteria's such as light condition, average temperature, extent of permafrost and ice conditions, etc. Three potential definitions of the maritime Arctic areas have been discussed by the PAME working group (under the Arctic Council), all considered used in this project. These arctic area definitions were:

- **Above 60 degrees:** Even though the waters above 60 degrees potentially have challenging conditions, the area with the absolute dominating traffic is not affected by sea ice normally associated with arctic operation (except for the Baltic traffic).

- **Above the polar circle:** Using traffic north of the Arctic Circle as the delimitation for Arctic, addresses the arctic issues of poor light conditions during winter, but, like for the 60-degree delimitation, the dominating traffic is not affected by sea ice normally associated with arctic operation.

- **The IMO Arctic Polar Code area:** The main purpose with this definition is safe navigation in the Arctic and in regions where sea ice may be expected.

Because most of the maritime activities in the Arctic take place along the southern boundaries and along the Norwegian coast, only small alteration to the Arctic definition have considerable effects on the fleet discussed, traffic volumes and related emissions. Hence, the definition of the area used is of key importance to the statistical material that is produced. Remoteness, ice and light conditions are equally important commonalities also when discussing discharges to sea between the above arctic definitions.

Figure 3-1 shows delimitations of the three above geographical areas together with traffic density. To avoid that the traffic in Norwegian waters totally dominate the results, it was decided by the PAME working group to use the IMO Arctic Polar Code area as the delimiter for the study. This area is also defined with waters affected by ice and darkness during the year as well as remoteness from infrastructure and rescue services.

Figure 3-1 — The geographical area covered by this analysis shown in blue line (IMO Arctic Polar Code area). Alternative arctic delimitations shown in red (the Arctic Circle) and green (60 degrees north). Estimated level of fuel consumption also shown, ranging from low (blue) to red (high)

Figure 3-2 illustrates the magnitude of the differences between the three arctic definitions, where the IMO Arctic Polar Code area only accounts for 16.5% of the total fuel consumed inside the 60-degree circle.
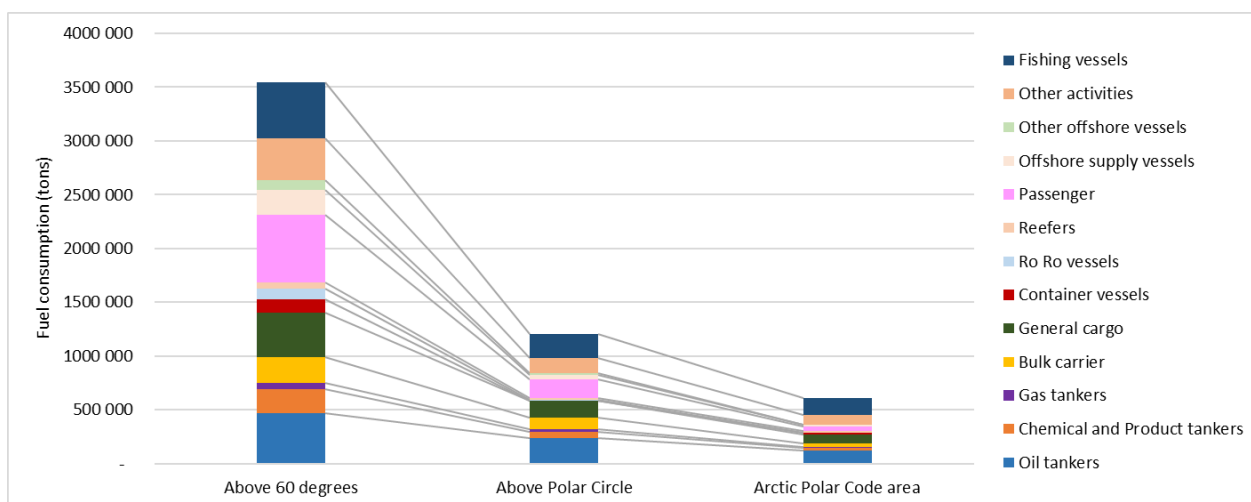
Figure 3-2 — Fuel consumption estimates above 60 degrees, above the Arctic circle and within the Arctic Polar Code area

3.3 Inventory of fuel consumption and emissions for the IMO Arctic Polar Code area for 2017

The AIS-based modelling shows that a total of 1 868 individual ships operates within the IMO Arctic Polar Code area, consuming about 581 million tonnes of oil equivalents (Mtoe) in 2017. Table 3-1 shows the distribution of ships, activity, and fuel consumption on different ship types.

Table 3-1 Number of vessels, activity and fuel consumption in 2017 for the IMO Arctic polar code area

Ship type	# vessels	Sailed distance [NM]	Time in area [hours]	Fuel consumption [ton]
Oil tankers	108	826 200	160 300	132 300
Chemical and Product tankers	66	344 100	73 300	26 200
Gas tankers	6	27 100	4 800	8 200
Bulk carrier	113	263 300	56 900	29 000
General cargo	209	1 143 700	267 600	87 300
Container vessels	11	146 900	21 300	14 300
Ro Ro vessels	8	25 200	8 000	1 000
Reefers	98	177 400	87 200	15 000
Passenger	101	578 200	122 000	34 300
Offshore supply vessels	39	161 400	63 700	15 300
Other offshore vessels	15	41 500	10 600	2 200
Other activities	329	1 382 300	584 800	70 100
Fishing vessels	765	5 305 500	1 524 400	145 900
Total	**1 868**	**10 422 800**	**2 984 900**	**581 100**

The AIS-based modelling offers great potential for performing in-depth studies on specific ship segments. Table 3-2 presents an overview of share of fuel consumed by the 13 ship types and 7 size segments. Fishing vessels, oil tankers, general cargo vessels and other activities together account for around 80 % of the total fuel oil consumption. The larger ships, above 10 000 gross tonnage accounts for nearly 50 % of the total fuel consumption.
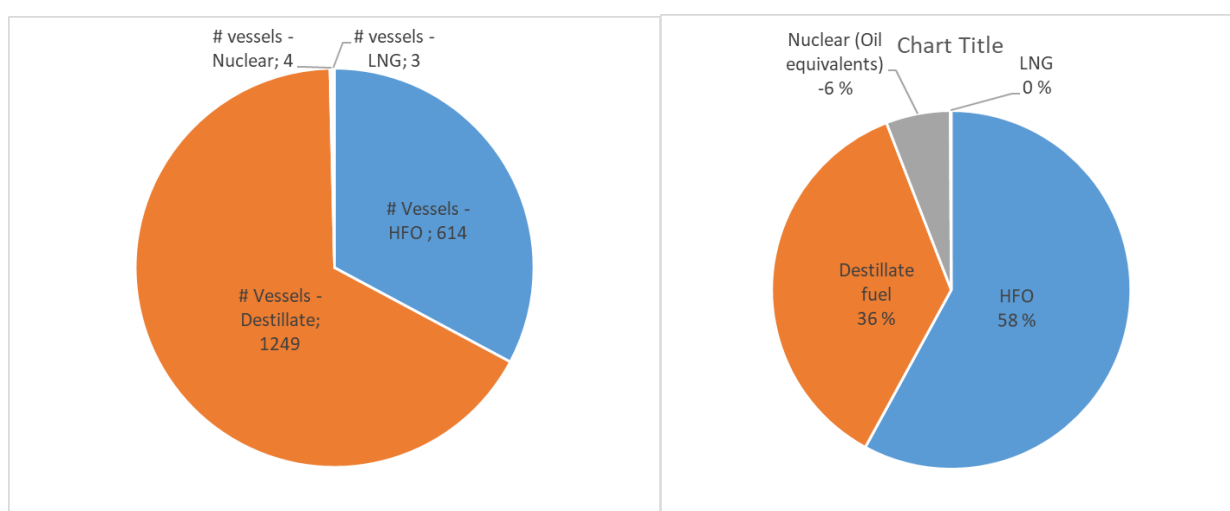
Table 3-2 Share of fuel consumption by ship type and size category in 2017, IMO Arctic polar code area

Ship type	<1000 GT	1000 - 4999 GT	5000 – 9999 GT	10000- 24999 GT	25000- 49999 GT	50000- 99999 GT	≥100000 GT	Totals
Oil tankers		1 %	1 %	3 %	16 %	2 %	1 %	**23 %**
Chemical and Product tankers	0 %	1 %	1 %	2 %	1 %			**5 %**
Gas tankers							1 %	**1 %**
Bulk carrier		0 %		1 %	4 %	0 %	0 %	**5 %**
General cargo	0 %	1 %	4 %	7 %	2 %			**15 %**
Container vessels			1 %	1 %				**2 %**
Ro Ro vessels	0 %			0 %				**0 %**
Reefers	0 %	1 %	1 %	0 %				**3 %**
Passenger	0 %	1 %	1 %	1 %	1 %	1 %	0 %	**6 %**
Offshore supply vessels	0 %	2 %	1 %					**3 %**
Other offshore vessels	0 %	0 %	0 %					**0 %**
Other activities	2 %	3 %	4 %	3 %	0 %			**12 %**
Fishing vessels	5 %	19 %	1 %					**25 %**
Total	**7 %**	**29 %**	**15 %**	**19 %**	**24 %**	**3 %**	**2 %**	**100%**

The fuel used by the ships operating inside the IMO Arctic Polar Code area comprise heavy fuel oils, marine distillates, LNG and ships having nuclear power as the energy source. The distribution of fuel types is based on the study HFO in the Arctic – phase 2 (DNV, 2013), where fuel testing data as well as ship register data for each individual vessel was analysed with respect to fuel quality used. This was mapped to the ship type/ship size matrix and reused for this study.

The Figure 3-3 illustrates that even though the ships using distillate fuel clearly outnumber the ships using HFO which is the dominating fuel type used with 58% of the total consumption followed by distillate fuels 36% and nuclear ships having approximately 6% of fuel consumed in terms of oil equivalents. Note that the calculation of fuel consumption for nuclear powered vessels is uncertain as the emission calculation algorithms are not specifically designed with such fuel in mind. Three LNG fuelled vessels have been identified operating parts of the time inside the IMO Arctic Polar Code area. The amount of fuel consumed for these vessels is sparse, representing less than 0,1% of the totals.

Figure 3-3 – Distribution of fuel types – number of vessels (left) and fuel consumption (right)

Table 3-3 present the estimated emissions by ship types. The estimate of CO_2 emissions is 1.85 million ton, while the emission of NOx, SOx, particulate matters (PM) and black carbon (BC) are 32.5, 2.0, 20.0 and <0.2 Kton respectively.

Table 3-3   IMO Arctic polar code area, ship emissions for 2017

Ship type	CO_2 [ton]	NOx [ton]	PM [ton]	SOx [ton]	BC [ton]
Oil tankers	421 900	9 200	850	6 780	46
Chemical and Product tankers	83 300	1 400	100	1 310	9
Gas tankers	26 300	600	40	430	3
Bulk carrier	92 600	2 100	190	1 490	10
General cargo	276 700	5 600	190	4 440	30
Container vessels	45 600	800	60	740	5
Ro Ro vessels	3 100	100	10	40	0
Reefers	47 600	500	30	750	5
Passenger	109 100	1 900	200	1 080	9
Offshore supply vessels	48 400	700	20	190	3
Other offshore vessels	7 100	100	5	30	0
Other activities	222 000	3 100	120	910	13
Fishing vessels	461 400	6 400	170	1 840	26
Total	**1 845 000**	**32 500**	**1 970**	**20 030**	**160**

3.4 Developments in fuel consumption and emissions: 2014 - 2017

The modelling of annual fuel consumption for the ships operating within the IMO Arctic Polar Code area has been made for the period 2014 to 2017. Figure 3-4 shows the annual developments in fuel consumption split on the 13 ship types. As can be seen from the figure, an overall increase of 45% in fuel consumption is observed over the last four years. Accordingly, the overall number of vessels and shipping activities in the form of operational hours and sailed distance have increased. The number of vessels is up by 7 %, while the operational hours and sailed distance within the IMO Polar Arctic code area increase by 12% and 21% respectively. Note that only vessels with an IMO number is included in the counting. There are also hundreds of unregistered small vessels operating within the region.
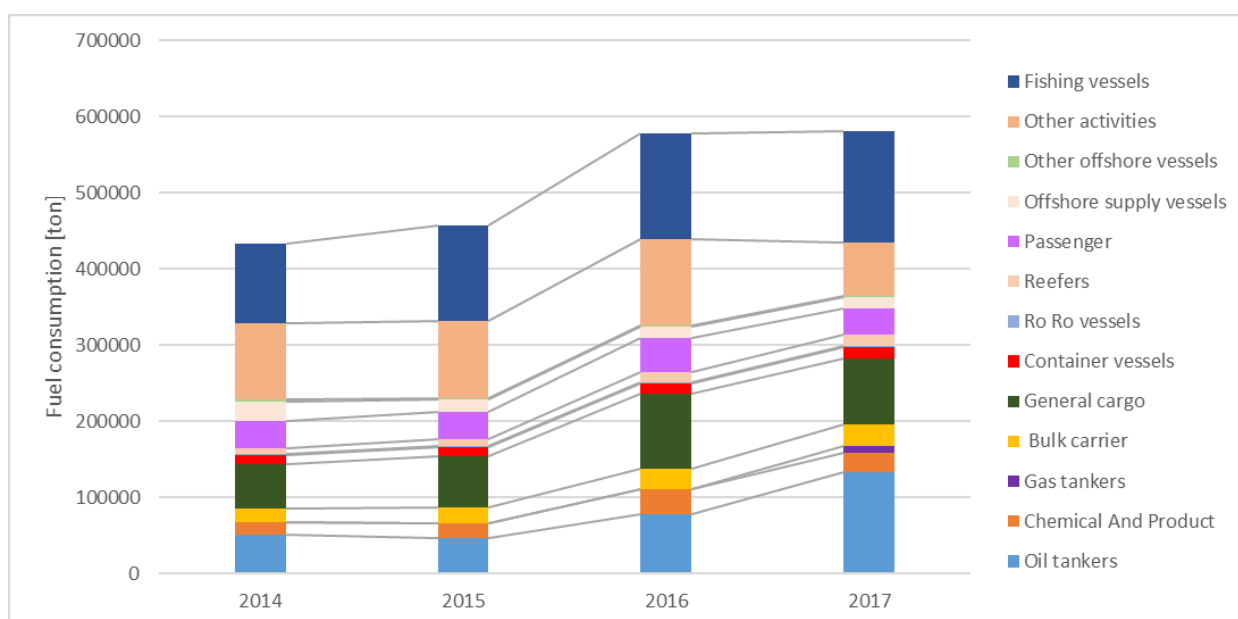
Figure 3-4 – Annual fuel consumption in the Arctic Polar code area for 2014 to 2017

Over the four-year period, there has been a pronounced change in fuel consumption among oil tankers, fishing vessels and general cargo vessels all being on the rise, while offshore supply vessels, other vessels (typically research vessels, tugs, ice breakers etc.) and passenger vessels are declining.

The increase in fuel consumption is related to recent developments in the Russian Arctic. The total cargo volume on the Northern Sea Route (NSR)[2] has increased by 33 percent from around 5 million tons in 2015 to more than 7 million tons in 2016, with 19 full transits from the Atlantic to the Pacific (2016).[3] In 2017, almost 10 million tons of goods were shipped on the NSR.[4] The year-round export of gas from the Yamal peninsula to Asian markets by ice-breaking tankers will increase the traffic along the NSR.[5] The first shipment from Yamal LNG started in December 2017, and by December 2018 the project had offloaded its one hundredth cargo LNG, with cumulative to-date delivery of 7.4 million tons.[6]

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[2] NSR is approximately 40% shorter than via the Suez Canal and Malacca Strait when sailing from Northern Europe to China (or opposite)

[3] http://www.highnorthnews.com/shipping-traffic-on-northern-sea-route-grows-by-30-percent/

[4] https://www.marineinsight.com/shipping-news/9737-million-tons-of-goods-shipped-on-northern-sea-route-in-2017/

[5] http://www.bbc.com/news/science-environment-41037071

[6] http://yamallng.ru/en/press/news/36789/

3.5 Comparison with other similar studies

Arctic emission inventories are reported by several activity-based studies (e.g. Winther et al., 2014; 2017; Mjelde et al., 2014; ICCT 2017a, b), and comparisons have also been made AMAP (2015) and ICCT (2017a). According to AMAP (2015) direct comparisons of the estimates are not necessarily meaningful since there are important differences in the approaches used, such as the area considered as the Arctic and vessel types included. A recent AIS-based study reported that 2,086 ships operated in 2015 within the IMO Arctic area, and they consumed 436 thousand tonnes of fuel and emitted 193 tonnes of BC (ICCT, 2018a). HFO represented 57% of fuel use by weight. Nearly 35% of the ships operating in the IMO Arctic were Russian-flagged (ICCT, 2018b). Comparing the 2015 fuel consumption estimates reported by ICCT (2018a) with estimates presented in this study, we find that our 2015 fuel and emission estimates are 4% higher.

For 2017, our AIS-based modelling for the IMO Arctic area gave 581 thousand tonnes of fuel and 203 tonnes of BC emitted. HFO represented 58% of fuel use by weight. This reflects a significant increase in ship emissions since 2015.

4 FUEL ALTERNATIVES FOR THE ARCTIC FLEET

The use of alternative fuels and technologies in the Arctic may contribute to substantial emissions reductions, and risk reductions related to accidental spills. It is however acknowledged that arctic application introduces additional challenges for new fuel and propulsion technologies due to its remoteness, harsh weather conditions and lack of infrastructure.

Promising alternative fuels for shipping have been reported and assessed by several studies (e.g. IEA 2014; DNV GL 2011a, 2014, 2015a, b, 2017b, 2018a; OECD, 2018) and potential candidates are shown in Figure 4-1. Handling different fuels may require different propulsion systems (energy converters). Alternative propulsion systems for shipping include gas-, dual-, and multifuel-engines, marine fuel-cells, battery-electric propulsion systems, and gas- and steam-turbines. Some converters, such as two-stroke dual-fuel engines have significant fuel flexibility, allowing for use of several fuels such as methanol, ethanol, and LPG, in addition to LNG and HFO/MGO.[7] Promising steam- and gas-turbine concepts, are also being considered. Fully electrical and part-electrical (hybrid) ships are emerging in the short-sea, offshore and passenger segments. Marine fuel cells are emerging, providing a higher efficiency and thereby lower fuel consumption and emissions compared to combustion engines.

For alternative fuels, a distinction should be made between primary energy sources/feedstocks (e.g. oil, biomass, renewable, nuclear) and energy carriers (e.g. fuel oil, gas, hydrogen) for use on board ships (Figure 4-1). Examples of energy carriers for use on board include the following:

- Fuel oil (HFO, vegetable oils) and diesel (e.g. MGO, biodiesel)

- Gases (e.g. LNG, LPG, liquefied biogas (LBG), dimethyl ether (DME), hydrogen (H_2), and ammonia (NH_3)

- Alcohols (e.g. methanol, ethanol)

- Electricity (batteries)

The type of energy carriers (fuels) used by ships will provide a first basis for assessing potential impacts of accidental release to sea (oil spill risk). Only fuel oils represent a major risk of environmentally damaging spills. This is particularly so for HFO and diesel. Gases and alcohols will evaporate with a limited damage potential.

The type of energy carriers (in combination with the converters) also determine exhaust emissions of CO_2, NOx, SOx, PM etc. For example, gaseous fuels often reduces NOx, SOx, and BC emission, impacting local climate forcing and air quality (e.g. Endresen et al, 2003; Corbett et al, 2008; OECD, 2010; Winebrake et al, 2009; Sofive et al, 2018). Promising alternative fuels for arctic use should reduce significantly oil spill risk and reduce or avoid onboard emissions (tank-to-propeller). For alternative fuels in general, it will be important to have a lifecycle perspective that includes emissions arising from production and transport of the fuel (e.g. Bengtsson et al, 2011; DNV GL, 2014, Gilbert et al, 2018), avoiding carbon- and energy-intensive solutions.

This section starts with providing information about the traditional marine fuels, followed by a description of alternative fuels and technology solutions relevant for the current and the future arctic fleet. This builds on work published recently by DNV GL (2017b; 2018a,b), and available literature. The alternative fuels included are; hybrid oils, LNG/LPG, methanol, biofuel (biodiesel, biogas), battery-electric, hydrogen, nuclear, ammonia, synthetic fuel, and renewables. Key characteristics are outlined such as emissions to

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[7] https://marine.mandieselturbo.com/docs/librariesprovider6/technical-papers/the-man-b-amp-w-duel-fuel-engines-starting-a-new-era-in-shipping.pdf?sfvrsn=2

air, oil spill risk (only for liquefied fuels), availability and current uptake. The results from this section are used as input to Section 6 – "Ranking of alternative marine fuels". Additional key aspects are shown in the ranking (Section 6). Appendix B provide information about exhaust gas treatment technologies.
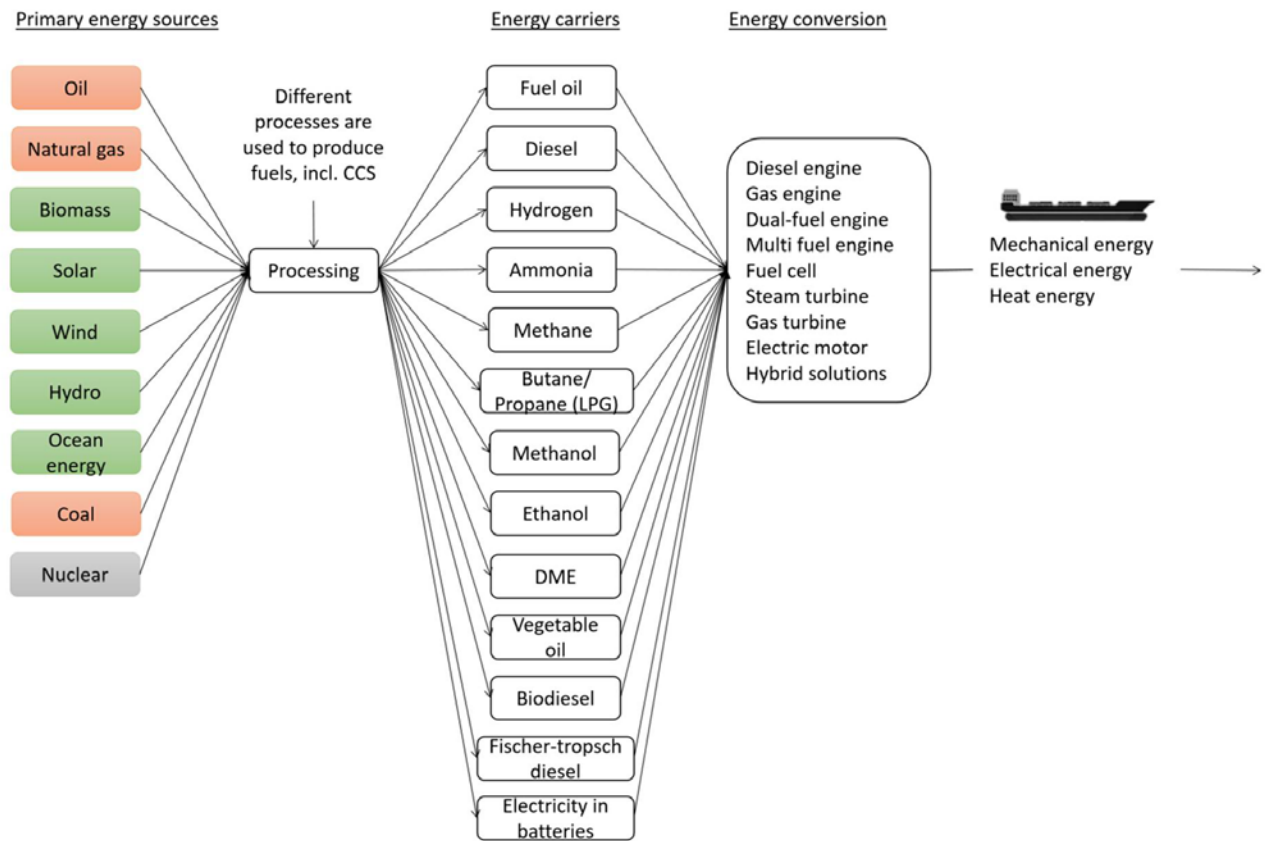
Figure 4-1: Simplified illustration of the chain from primary energy sources to mechanical energy for marine propulsion (inspired by Brynolf, 2014)

4.1 Marine fuels (HFO/MGO)

The arctic fleet is currently using heavy fuel oil (HFO) and marine oil (MGO/MDO) as fuels, with HFO as the dominating fuel type used with 58% of the totals followed by distillate fuels 36% (see Section 3.3).

Heavy Fuel Oil (HFO) is one of several terms used to cover a rather broad range of different marine residual fuels, or blends of residual and distillate fuels (DNV, 2011b). In industry terminology, such fuel may be called by different names, such as heavy fuel oil, heavy diesel oil, residual fuel, bunker, or fuel oil. Different types of HFO are labelled corresponding to the RM (A, B, D, etc) qualities under the ISO 8217 Specification of Marine Fuel.

Distillate fuel - referred to as marine gas oil (MGO) and marine diesel oil (MDO), or just distillates, normally corresponding to qualities within the DM (X, A, Z, B) of ISO 8217. Table 4-1 describe the range of marine fuels and indicates whether it's an HFO or distillate as applied in this report.

Table 4-1 Marine fuel oil terminology (WWF, 2018, their Table 2-1)

Marine Fuel Oil Name	Composition	Type
Bunker C/Fuel oil No. 6	Residual oil	HFO
Intermediate Fuel Oil (IFO) 380	Residual oil (~ 98%) blended with distillate	HFO
Intermediate Fuel Oil (IFO) 180	Residual oil (~88%) blended with distillate	HFO
Low sulphur marine fuel oils	Residual oil blended with distillate (higher ratio of distillate to residual)	HFO derivative
Marine diesel oil (MDO)/ Fuel oil No. 2	Distillate fuel that may have traces of residual oil	Distillate
Marine gas oil (MGO)	100% distillate	Distillate

There are two main qualities or parameters that make the distinction between HFO and distillates useful and appropriate. The first is the behaviour and impact of the fuel when released to water (oil spill risk). The second is the is levels of exhaust emissions when the fuel is combusted, in particular SOx, PM and BC.

Oil spills could have particularly severe impacts on arctic wildlife, the marine environment and could threaten arctic communities' food security and livelihoods (e.g. DNV, 2012, Fritt-Rasmussen et al, 2018, ICCT 2017a,b; 2018a,b). This is due the slow rate of degradation, due to very limited evaporation (typically less than <10%) and limited dispersion into the water column. HFO also emulsifies in water, is extremely viscous and could potentially remain at sea for weeks, having a large damage potential. In ice-covered waters could an oil spill result in oil becoming trapped in ice, causing the oil to persist even longer, and enabling oil to transport even longer distances. HFO is also difficult to handle using conventional recovery measures. Effective response operations are also challenged by lack of infrastructure, remoteness, harsh weather conditions, darkness, and possible ice conditions. WWF (2018) has summarized some of the key considerations for different marine fuels, including spill cleanup limitations (Table 4-2).

Table 4-2 - Oil spill characteristics and properties of different marine fuel types (WWF, 2018, their figure 4.1). The top three fuel types are covered by the term HFO used in this report

FUEL TYPE		CHARACTERISTICS AND PROPERTIES		
Marine Fuel	Composition	Behavior when spilled	Spill Cleanup	Ecological Impacts
Bunker C/ Fuel oil No. 6	Residual oil	May sink or become neutrally buoyant. Forms tar balls and patties. Emulsifies (incorporates water).	Limited technologies for on-water recovery. Most of the cleanup will likely involve remediating shorelines and oiled substrate.	Coats feathers and fur. Persistent and sticky, can have long-term impacts to shoreline, intertidal, and benthic communities.
Intermediate Fuel Oil (IFO) 380	Residual oil (~98%) blended with distillate	May sink or become neutrally buoyant. Emulsifies (incorporates water) and may increase 2-3 times original spill volume.	Fresh product may be recoverable within hours of initial spill, but as oil emulsifies it becomes more difficult to recover with skimmers. Weathered oil will coat surfaces and may be difficult to remove from coarse sediments and substrate.	
Intermediate Fuel Oil (IFO) 180	Residual oil (~88%) blended with distillate			
Low sulphur marine fuel oils	Residual oil blended with distill$ate (higher ratio of distillate to residual)	Initial laboratory and mesoscale testing suggests that it will behave similar to other residual oils, emulsifying and generally acting as a persistent fuel.	Poorly studied. Information from recent pipeline spill in Hawaii suggests that residual blends will pose similar response challenges to other residual fuels.	Poorly studied, likely to be similar to IFO. May have higher initial toxicity than residual fuels because of higher percentage of distillate, which will initially disperse or evaporate.
Marine diesel oil (MDO)/Fuel oil No. 2	Distillate fuel that may have traces of residual oil	High percentage will evaporate or disperse into water column within first few hours of release. Will remain floating but slick will spread in open water.	Can be skimmed from surface if contained to sufficient thickness. As oil spreads and weathers, more difficult to recover.	High initial toxicity to wildlife, particularly in water column, but oil is less persistent in environment. Will still harm fur and feathers when it comes into contact.
Marine gas oil (MGO)	100% distillate			

These aspects (and other) were reviewed in a recent study (Fritt-Rasmussen et al, 2018). The report is based on existing literature and results from laboratory weathering tests of HFO performed by SINTEF. The report addresses the need for large-scale studies and experiments on HFO in ice, and increased knowledge of HFO recovery/removal from the environment.

HFO and distillates also have very different properties when it comes to levels of exhaust emissions when the fuel is combusted, with higher levels of SOx, PM and BC emitted for HFO. BC emissions are of particular interest in the arctic. Atmospheric BC absorb radiation both from incident sunlight and sunlight reflected from snow and ice. In addition, BC deposited on snow or ice reduce surface reflectivity (i.e. albedo), thus accelerating the ice melting process (Flanner et al., 2007; Hansen and Nazarenko, 2004). BC are short-lived, and only stays in the atmosphere for a few days or weeks. Reducing BC emissions from ships would have an immediate impact on shipping's overall global warming effects. According to ICCT (2017e) are BC largely ignored as a climate pollutant from ships ("missing inventory"). ICCT (2017e) indicates that after CO_2, BC contributes the most to the climate impact of shipping.

The IMO is considering a potential ban on HFO in the Arctic, and they agreed in April 2018 to continue the process towards a ban. A recent Delft (2018) study has assessed costs and benefits of a ban on the use and carriage of HFO as fuel by ships. They estimated the ban-related costs for the year 2021 on the arctic fleet level for ships' activities within the IMO Arctic waters, assuming that all ships choose to

comply with the ban by using distillate fuels. The arctic fleet's fuel expenditure for its activities within the IMO Arctic waters would, depending on the bunker fuel prices, increase by 3 to 18% in 2021 due to the HFO ban. In addition, the clean-up costs saved when a ban-compliant fuel was spilled instead of residual bunker fuels was estimated to amount between 5.3 and 70 million USD (HFO spill) for one bunker fuel spill. The socio-economic and environmental damage costs in case of an oil spill will also be reduced following an HFO ban in the region.

It should be mentioned that a HFO ban exists already for certain sensitive areas around Svalbard (Nature Reserve and Nature Reserve). The regulation was introduced in 2007.[8]

4.2 Hybrid fuels

When the Sulphur limit in emission control areas (ECA) fell to 0.10% in 2015, a number of alternatives to MGO appeared in the market[9]. These alternatives were designed to be compliant with the ECA requirement, while costing less than MGO. The introduction of low-Sulphur fuels that were not MGO has led to different names. The term "hybrid fuel" refers to a blended product with specifications similar to HFO, and/or to certain refinery products that have previously not been used as marine fuels. Therefore, they also do not necessarily fit into the traditional specifications for MGO, MDO or HFO oil. These oils may not be fully compatible with ordinary heavy fuel oils and can pose potential technical challenges in operation in connection with the change-over.[10]

Several hybrid fuels combine properties of both distillate and residual marine fuels. According to CIMAC (2015), these new fuels can be divided in to the following categories;

- Ultra-low Sulphur HFO oils; Typically, these fuels have lower viscosity and density, and better ignition and combustion properties compared with conventional residual marine fuels
- Blends of a distillate fuel with small amount of oil (DMB type)
- Heavy distillates; fuels with low metal content but with higher viscosity than conventional DMA

As a result of IMO's decision to implement a 0.5% global Sulphur cap in 2020, consumption of HFO is expected to shift to desulfurized or blended residual fuels, that don't necessarily fit into the traditional distillate/residual tables in the ISO 8217 marine fuel quality standard.

As fuel suppliers seem to have designed their own unique formulation, properties of the new hybrid fuels may vary significantly, which means that each fuel has its own specifics in terms of storing, handling and using the fuel (CIMAC, 2015). The oil properties are also important, if oil is released to sea during an arctic accidental bunker spill. Challenges reported for hybrid fuels relate to risk for solidification at low temperatures, and low oil spill response effectiveness (Sintef, 2017). To reduce their environmental damage potential, proportions may be changed in the future.

Fritt-Rasmussen et al. (2018) state that it is highly important to characterise the new fuel oils on the market, and to gain better documentation of the differences in fate and behaviour in case of a spill at sea and to document the potential / feasibility of the different response options.

Recently Delft (2018) made calculations indicating that clean-up costs that accrue in case of an oil spill are significantly lower if MGO (or ban-compliant fuel) was spilled instead of (low sulphur heavy fuel oil - LSHFO). They estimated the clean-up costs saved to amount to between 3.4 and 45 million USD (LSHFO

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[8] Ban on heavy fuel oil: https://www.sysselmannen.no/en/Shortcuts/Ban-on-heavy-fuel-oil/
[9] http://ibia.net/making-sense-of-low-sulphur-fuel-terminology-ulsfo-rmdm-and-vlsfo-rmdm/
[10] DNV GL (2015b), notice for low-sulphur, "hybrid" fuel operation

spill) for one bunker fuel spill. The socio-economic and environmental damage costs in case of an oil spill will also be reduced.

From a spill risk and response perspective, HFO and hybrid oils seem to have similarities. The IMO is considering a potential ban on HFO in the Arctic, and it is unclear whether hybrid fuels will be captured under the pending Arctic HFO ban (WWF, 2018). These oils could be blended to fall below the HFO density and viscosity thresholds established under MARPOL.

4.3 Liquefied natural gas (LNG)

The main component of LNG is methane (CH_4), the hydrocarbon fuel with the lowest carbon content and therefore with the highest potential to reduce CO_2 emissions (maximum reduction: roughly 26% compared to HFO). LNG has more or less the same composition as natural gas used in households, for power generation and by the industry. Since the boiling point of LNG is approximately −163°C at 1 bar of absolute pressure, LNG must be stored in insulated tanks.

For the Arctic region recent studies have suggested to replace HFO with Liquefied Natural Gas (LNG) (e.g. ICCT, 2017c; WWF, 2017), as oil spill risk will be avoided, and air emissions will be significantly reduced (except for GHG). LNG was introduced as ship fuel (other than for LNG carriers) around 2000. It has mainly been used by small-sized short-sea ships. There have however been recent orders for large vessels selecting LNG as a fuel. As of February 2019, there are 144 LNG powered vessels in operation (excluding LNG Carriers and inland waterways vessels), and 139 confirmed orders for vessels that will be built in the next five years (see Figure 4-2). Large volumes of natural gas are available today and the next decades, but there is still a lack of a global infrastructure and bunkering facilities for shipping. For the foreseeable future, there are no principal limitations to production capacities that could limit the availability of LNG as ship fuel. LNG has a share of approximately 10 % in the overall natural gas market.
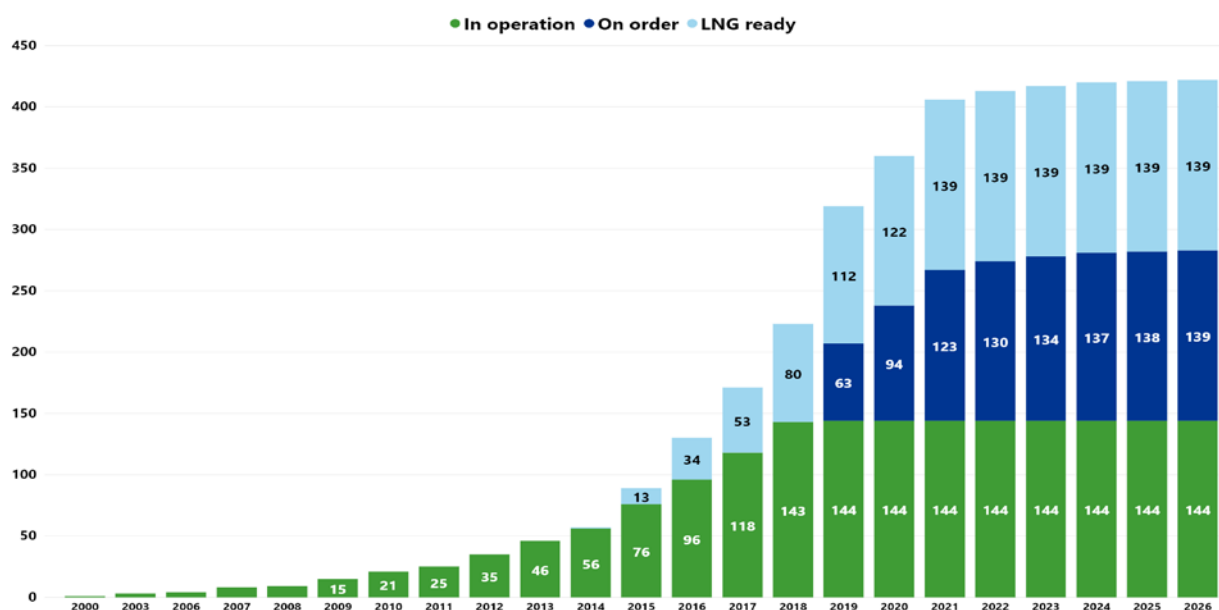

Figure 4-2: LNG ships in operations and on order as of February 2019 (AFI portal[11])

[11] AFI: https://www.dnvgl.com/services/alternative-fuels-insight-128171

LNG is a fossil fuel and its GHG emission reduction potential is estimated at around 0–18% compared to HFO/MDO (e.g. Chryssakis et al., 2013; Bengtsson et al., 2011, 2012; Verbeek et al., 2011; ICCT, 2013; Corbett et al., 2014; Thomson et al., 2016, DNV GL, 2018a), from a lifecycle perspective. The GHG performance of smaller-medium sized (low pressure four-stroke engines) and larger two stroke (high pressure) gas/dual fuel engines are quite different. Recent studies show that for the latter type around a 20% GHG tank-to-propeller reduction may be expected (including a very marginal methane slip) whereas the corresponding number for the four-stroke engines is in the region of 5% (Stenersen and Thonstad, 2017; Lindstad et al., 2018).

LNG significantly reduces or eliminates emissions of sulphur oxide (SOx), particulate matter (PM) and black carbon. The reduction of nitrogen oxide (NOx) emissions depends on engine technology but can be well within the strictest International Maritime Organization (IMO) NOx Tier III requirements in Emission Control Areas (ECAs).

A review of LNG-spills to sea, based on experiments and modeling, shows that LNG could float on water and rapidly vaporize (Luketa-Hanlin 2006). Thus, during an accidently LNG spill to sea, LNG eliminates the environmental risk at sea, but contributes to air emission.

It is expected that strict regulations on NOx and SOx emissions, combined with a more competitive gas price, will drive the uptake of gas as a marine fuel. The extra investment needs to be compensated in operations and will depend on oil and gas prices. Based on recent experience, the new-building cost of LNG-fuelled ships is about 10–30 % higher than for equivalent diesel-fuelled ships (Æsoy et al, 2011; DNV GL, 2015b). Also, LNG fuel tanks are typically twice to three times as the volume of oil tanks with the same energy content (Figure 4-3).

Bio-methane/LBG could be an attractive low carbon alternative to LNG, that could use the existing and upcoming LNG infrastructure (see Section 4.5).
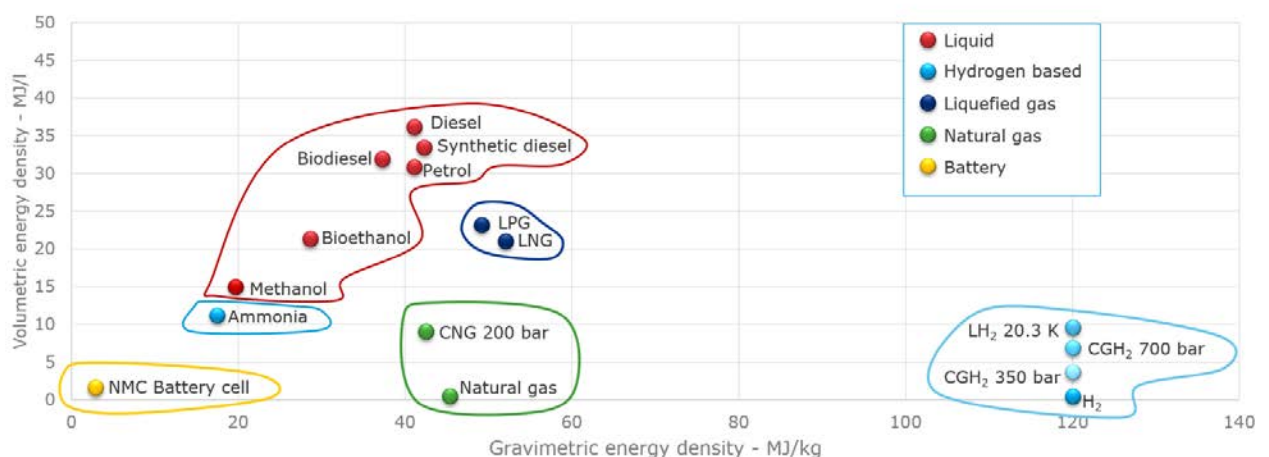
Figure 4-3: Comparison of gravimetric and volumetric energy density for fuels (inspired by Shell, 2017)

4.4 Liquid petroleum gas (LPG)

Any mixture of propane and butane in liquid form can be called LPG. In the US, the term LPG is generally associated with propane. Propane is a gas under ambient conditions, but has a boiling point of -42°C. Consequently, applying moderate pressure allows it to be handled as a liquid at room temperature. At pressures above 8.4 bar at 20°C, propane is a liquid. Butane can take two forms, n-butane and isobutane, with boiling points at -0.5°C and -12°C, respectively. Since both isomers have higher boiling points than propane, they can be liquefied at lower pressures.

Perspective for use of LPG in shipping has recently been reported by DNV GL (2017a). Some findings are:

- LPG combustion results in CO_2 emissions approximately 16% lower than those of HFO or MGO.

- The combination of low production and combustion emissions yields an overall GHG- emission reduction of about 17% compared with HFO or MGO.

- LPG significantly reduces or eliminates SOx and PM emissions. The level of reduction of NOx emissions depends on the engine technology.

The volume of a tank of LPG is typically twice to three times that of an energy equivalent amount of oil-based fuel. The cost of installing LPG systems on board a vessel (e.g. internal combustion engine, fuel tanks, process system) is roughly half that of an LNG system if pressurized type C tanks are used in both cases. This is because there is no need for special materials that are able to handle cryogenic temperatures. Uptake of LPG fuelled ships has started, with two newbuilding orders for Very Large Gas Carriers (VLGC), and four existing LPG Carriers to be converted in 2020.[12,13]

There are two main sources of LPG; as a by-product of oil and gas production or as a by-product of oil refining. It is also possible to produce LPG from renewable sources; for example, as a by-product of renewable diesel production.

According to the World LPG Association, global LPG production in 2015 was 284 million tonnes, or 310 million tonnes of oil equivalent. This is slightly higher than the global demand for marine fuel. Currently, LPG is more expensive than LNG but cheaper than low-sulphur oil.

A large network of LPG import and export terminals is available around the world, but the development of a bunkering infrastructure remains a barrier for the use of the fuel.

4.5 Biofuels

Biofuel is a collective term for a range of energy carriers produced by converting primary biomass or biomass residues into liquid or gaseous fuels. According to Biofuels Aro (2016) biofuels are currently categorised into four generations, depending on the origin and production technology of biofuels:

- The first-generation biofuels are made from crop plants grown on arable land

- The second-generation biofuels are made from feedstock of lignocellulosic, non-food materials like straw or forest residues

- The third-generation biofuels are based on algal biomass

- Photobiological solar fuels and electrofuels are the fourth generation of biofuels

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[12] https://worldmaritimenews.com/archives/259798/bw-lpg-to-retrofit-4-ships-to-lpg-propelled-dual-fuel-engines/
[13] https://www.maritime-executive.com/corporate/first-lpg-powered-dual-fuel-engine-receives-order

Many processes exist for producing conventional (first-generation) and advanced (second and third-generation) biofuels. They involve a variety of feedstocks and conversions, producing a range of energy carriers including diesel, CH_4, and methanol.

Lower GHG contributions are normally attributed to biofuels compared with fossil fuels. CO_2 from the combustion of biological material leads to added CO_2 in the atmosphere in the same way as fossil fuels, but these emissions are countered by the uptake of $CO2$ from the atmosphere as the feedstock for the fuel grows. Bio-CO_2 is therefore considered to be part of the CO_2 that would otherwise have been in circulation through natural cycles, although this depends on the timeframe over which reduction targets and climate impacts are considered. Other aspects of biofuel production are also debated and include land-use and socio-economic issues. Several standards and initiatives address these aspects.

The most promising biofuels for ships are hydrotreated vegetable oil (HVO), fatty acid methyl ester (FAME) and liquefied biogas (LBG), although other options are available. Straight vegetable oil (SVO) can substitute HFO. This is supported with the fact that recently a product tanker successfully completed the first voyage running on carbon-neutral heavy fuel oil-equivalent biofuel.[14]

The use of biofuels is largely motivated by the reduction of greenhouse gases (GHG). The overall GHG emissions from a given biofuel will depend strongly on the type of feedstock used and the production processes (IEA 2011, Ecofys 2012). It is reported GHG reductions between typical 20-90% for different biofuels, based on lifecycle assessments (IEA 2011; 2017a). The highest reduction potential is reported for advanced biofuels. There is debate about the extent to which biofuels lead to GHG reductions and there is a need for systems classifying different biofuels for use in shipping.

For HVO, the NOx emissions may be somewhat reduced (about 10%). The NOx emissions of FAME are higher compared to conventional marine fuel (about 10%), whereas the NOx emission of LBG is similar to LNG, which is about 90% reduction (depending on engine technology). Thus, only LBG satisfies IMO Tier III requirements without additional NOx-abatement technology. In general, both HVO, FAME and LBG have very low SOx emissions. The particulate matter (PM) emissions of biofuels are also lower compared to conventional marine fuels.

Biofuels will in most cases be more expensive[15, 16] than fossil fuels, and particularly for advanced renewable biofuel (e.g. Ecofys 2012, MAN 2016). The market for these fuels is immature and information on prices is very limited. There are also great local and regional variations in price and availability. However, the biofuel market is expected to grow, and there is significant potential for cost reduction. The potential for reducing production costs is expected to be higher for HVO than for FAME (Festel et al., 2014; van Eijck et al., 2014). The reduction will be driven by continuous process improvements, technological development and increased production.

Biofuels can be blended with conventional fuels or used as "drop-in" fuels fully substituting for conventional fossil fuels. A "drop-in" fuel can directly be used in existing installations without major technical modifications. For this reason, bio fuels are well suited to substitute oil-based fuels in the existing fleet. HVO is a high-quality fuel in which the oxygen has been removed using hydrogen, which results in long-term stability. The HVO have characteristics that make it suitable as "drop-in" fuel, substituting fossil fuels. In general, HVO is compatible with existing infrastructure and engine systems, subject to approval by the manufacturer, and modification may sometimes be required. Overall, there is

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[14] https://lloydslist.maritimeintelligence.informa.com/LL1125334/Norden-successfully-runs-product-tanker-on-biofuel

[15] Nets: https://www.neste.com/en/corporate-info/investors/market-data/biodiesel-prices-sme-fame

[16] NP: http://www.np.no/aktuelle-saker/biodrivstoff-i-budsjettforliket-article1031-140.html

limited operational experience with the use of HVO as a fuel in the shipping industry. HVO is currently used on board three ferries[17,18] operating in Norway without reported negative effects.

FAME is not a "drop-in" fuel and blending up to concentrations of 7% is only allowed according to ISO 8217:2017 for DF (Distillate FAME) grade DFA, DFZ and DFB. A number of demonstration projects have tested the technical feasibility of various FAME biodiesel blends in shipping (Ecofys 2012, IRENA 2015). FAME differs from MGO/MDO in terms of fuel stability, cold flow properties, compatibility with materials (e.g. in packs), durability and lubrication properties. Generally, FAME has poor performance at low temperatures, is less stabile when blended, and has short shelf life. It is recognized that the cold flow properties are important during for example winter operations in Arctic, where low temperatures occur. Some tests have experienced increased corrosion and susceptibility to microbial growth. However, the knowledge of possible effects of FAME is limited, as most of the available tests have only considered the use of FAME for a shorter time period.

It is also reported that biodiesel would biodegrade about twice as fast as petroleum diesel (von Wendel, R., 1999). According to CONCAWE (2009), if FAME is released to the environment the following can occur: "*Although FAME is only slightly soluble in water, it will degrade rapidly and fairly extensively in aquatic environments at a rate that is approximately four times faster than that of hydrocarbon-only diesel fuel. Spills and underground leaks of FAME or diesel blends should be treated in the same manner as conventional diesel fuel spills and leaks, including notification of the proper authorities. The FAME supplier's SDS should also be reviewed for recommendations on clean-up procedures for spills*".

LBG can be used as fuel for ships that already use LNG and it is likely that no engine, tank and pipeline upgrading is required. There is no expected change in reliability when replacing LBG for LNG. It is also possible to blend LBG in LNG. For LBG, the life cycle GHG emission is significantly reduce, provided CH4 emission are handled (e.g. Gilbert eta la, 2018; Maritime Knowledge Centre, TNO & TU Delft, 2017). LBG is currently significantly more expensive than LNG.

Third-generation, algae-based biofuels are still at the research and development stage but were tested in 2011 on the container ship Maersk Kalmar (de Nijs, 2018). The US navy has also conducted some testing.

Global production data indicate that 32 million tonnes per year (Mt/yr) of biodiesel and 170 Mt/yr of SVO are produced (Maritime Knowledge Centre, TNO & TU Delft, 2017). Widespread use of biofuel in shipping will depend on production cost, incentives for use, future GHG regulations, and availability of sufficient volumes. Sustainable biofuels are one of few options available for deep-sea shipping that could significantly reduce t GHG emissions.

4.6 Methanol

With the chemical structure CH_3OH, methanol is the simplest alcohol, with the lowest carbon content and highest hydrogen content of any liquid fuel. Methanol is a basic building block for hundreds of essential chemical commodities and is also used as a transportation fuel. It can be produced from several different feedstock resources, like natural gas or coal, or from renewable resources, such as biomass, CO_2, and hydrogen. Methanol[19,20] are available in certain ports, e.g. in Sweden.

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[17] Ruter: https://ruter.no/om-ruter/miljo/gassdrevne-passasjerferger/

[18] TU: http://www.tu.no/artikler/de-blir-verdens-tre-forste-ferger-pa-kun-biodrivstoff/275609

[19] Stena Germanica bunkering in Gothenburg is the only example of methanol bunkering to a ship being carried out presently, http://www.bunkerindex.com/news/article.php?article_id=18047

[20] Seven 50,000 dead weight tonne vessels are built with the first-of-its kind MAN B&W ME-LGI 2-stroke dual fuel engine that can run on methanol, fuel oil, marine diesel oil, or gas oil. https://www.methanex.com/about-methanol/methanol-marine-fuel#sthash.oW84bYPp.dpuf

Methanol is a liquid from 176–338 Kelvin (-93°C to +65°C) at atmospheric pressure. Using methanol in an internal combustion engine reduces CO_2 emissions by approximately 10% compared with HFO or distillate fuel. When considering the complete lifecycle, including production of the fuel from natural gas, the total CO_2 emissions are equivalent to, or slightly higher than (in the order of 5%), the corresponding emissions of oil-based fuels. Currently there are 12 ships in operation and on order powered by methanol, with Sweden waters as the main operating area[21].

The lifecycle emissions of methanol from renewable sources (biomass) are significantly lower than from production from natural gas. Using methanol virtually eliminates SOx emissions and subsequently meets the IMO sulphur emission cap. It is also expected that PM emissions will be significantly lower. The reduction in NOx emissions depends on the technology used.

Methanol if spilled to sea is biodegradable, it dissolves in water, and dilutes to non-toxic levels. The environmental effects of methanol spill are expected to be much lower than those from an equivalent oil spill (Methanex, 2017).

Methanol fuel tanks are typically twice the volume of oil tanks with the same energy content.

The global methanol demand was approximately 80 million tonnes in 2016, twice the 2006 amount. The production capacity is more than 110 million tonnes. From 2010 to 2013, methanol prices per unit of energy content were between European HFO and MGO prices. Currently, methanol is more expensive than distillate marine fuels.

4.7 Hydrogen

Hydrogen is an energy carrier which allows for zero-emission ships if used in marine fuel cells. If the gas is produced from renewable energy sources, or from natural gas with CCS, zero-emission value chains can be created. Even though its lifecycle emissions may be zero, it is important to note that producing H_2 for use as a fuel requires considerable energy. Consequently, even if the energy efficiency of H_2 converted to electrical energy in fuel cells may be high (see below), the lifecycle energy efficiency is significantly lower due to the energy loss in H_2 production.

Fuel cells were previously used mainly for special purposes, such as in outer space and submarines. The technology has matured and is in commercial use in applications such as forklifts, standby generators/uninterruptible power supply, and combined heat and power systems. Fuel cells have advanced to near commercial use for cars, buses, trucks, and rail applications. They provide higher efficiencies and thereby reduce fuel consumption and emissions. Depending on fuel-cell type, electrical efficiency of 50–60% is expected, which is slightly higher than marine diesel generators (DNV GL, 2017d). With heat recovery, the efficiency can increase to 80%. Noise and vibrations are insignificant, and fuel cells are also expected to require less maintenance than conventional combustion engines and turbines.

The cell converts the chemical energy of the fuel to electrical power through electrochemical reactions. For simplicity, the energy conversion is similar to that of batteries, but with continuous fuel and air supplies. Different fuel-cell types are available, and their names reflect the materials used in the electrolyte membrane. The properties of the membrane affect the permissible operating temperature, the nature of electrochemical reactions, and fuel requirements. DNV GL (2017d) evaluated seven fuel-cell technologies and concluded that the solid-oxide fuel cell, the proton-exchange membrane (PEM) fuel cell, and the high-temperature PEM, are the most promising for marine use. Depending on fuel-cell type,

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[21] DNV GL AFI portal, https://afi.dnvgl.com/

they can also be powered by carbon fuels such as natural gas, an option that, in particular, reduces NOx, SOx, and PM emissions. Driven by the expected improvement in performance and efficiency, fuel cells for ships have become a subject of development and largescale testing during the last decade, although their application in shipping is still in its infancy. Several demonstration projects have been conducted, some of which are described in DNVGL (2017d). Fuel cells are currently an expensive option compared with traditional power, due to significantly higher investment and operational costs; for example, high fuel price, fuel storage costs, and a need for stack replacement.

The cost of H_2 produced by electrolysis is closely related to the price of electricity. When produced by steam methane reforming, the cost is closely related to the price of gas, as well to the scale of the production plant. Currently, H_2 produced by natural gas reforming, and as a by-product from industrial processes, is typically expected to be cheaper than H_2 from electrolysis. If using natural gas, the resulting carbon must be captured using CCS for the resultant H_2 to be considered a zero-emission fuel. The fuel distribution chain is another significant cost element. Production and distribution costs vary greatly with local conditions. Indicated production cost range today from USD 3.5–8.3 per/kg for production by electrolysis, and from less than USD 2/kg (e.g. https://idealhy.eu) up to more than USD 6.5/kg for production from natural gas/biogas. Cost estimates typically include production, compression, storage and transport, and can include CCS, but typically not costs for liquefaction in the case of storage and transport of hydrogen as a cryogenic liquid. The price of electrolysers is expected to fall in the near future, reducing the CAPEX and consequently the production cost of hydrogen. Similarly, the growth in intermittent renewable energy supply is expected to be a source of cheaper hydrogen. In the foreseeable future, the typical fuel cost of H_2 is expected to remain higher than the cost of the fossil alternatives.

Hydrogen can be used most efficiently in fuel cells, but it is also possible to use it in adapted combustion engines. Some initiatives are considering blending H_2 with other fuels to improve combustion and emission properties as well as potentially reducing the GHG emissions.

There are challenges to find volume-efficient ways to store hydrogen. Most commonly, it is stored either as a compressed gaseous hydrogen (CGH). Storage and bunkering of H_2 for use on ships will require specially-designed storage tanks and bunkering systems. There is currently limited experience with marine storage and use of H_2, but storage technologies are available from land-based applications.

Development of a bunkering infrastructure is needed in parallel with the development of H_2 as a ship fuel. Hydrogen and fuel cell-specific requirements are lacking and are currently not covered by the IGF Code. According to Part A of this Code, an Alternative Design approach must be carried out to demonstrate an equivalent level of safety. Norway has an ongoing development where DNV GL is supporting the national road authorities in putting in service a new ferry running on hydrogen in 2021[22]. It is expected that national regulations will be developed to secure safe and effective introduction of hydrogen. In addition, one hydrogen-powered ferry will be built in Scotland and one in California.[23]

More than 50 Mt/yr of H_2 are produced globally, but it is lack of a global infrastructure and bunkering facilities; roughly equal to the energy content of 150 Mt of ship fuel. Nearly all H_2 is produced from natural gas. But as it can also be produced by electrolysis of water, there are no major limitations to production capacity, except the energy source, that could restrict the amount of H_2 available to the shipping industry.

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[22] Breaking new ground in hydrogen ferry project:
https://www.sjofartsdir.no/en/news/news-from-the-nma/breaking-new-ground-in-hydrogen-ferry-project/
[23] https://lloydslist.maritimeintelligence.informa.com/LL1123165/US-to-develop-first-hydrogenpowered-ferry

4.8 Ammonia

Several studies have pointed to Ammonia as a potential fuel for shipping (Maritime Knowledge Centre, TNO & TU delft, 2017; OECD, 2018). Safety and regulatory challenges and space/weight considerations related to storing large quantities of H_2 on ships have generated interest in exploring alternative H_2-based energy carriers. Ammonia (NH_3), sometimes called 'the other hydrogen', is carbon-free and liquefies at a higher temperature than H_2 (-33°C versus -253°C). Ammonia is over 50% more energy-dense per unit of volume than liquid H_2 (Maritime Knowledge Centre, TNO & TU Delft, 2017). Storage and distribution can therefore be easier than for hydrogen. A recent study claims that it can be less costly to use NH_3 for long-term storage of liquid H_2 (0.5 USD/kg for H_2 in NH_3 versus 15 USD/kg for H2 stored as liquid H_2, when estimated for half-year storage), (IEA, 2017b). This indicates that there might be significant cost savings associated with storing H_2 as ammonia, including in ship applications. Costs and processing to make the H_2 available for use in fuel cells must be considered. On the other hand, ammonia is highly toxic with potential adverse health effects.

In addition to H_2 fuel cells, there are several fuel cells designed to use ammonia directly (Maritime Knowledge Centre, TNO & TU Delft 2017). It is reported that the first utilization of liquid anhydrous ammonia as a fuel for motor-buses took place in the 1940s, and that the bus fleet logged thousands of kilometers with no difficulties.[24] Combustion of ammonia is reported to have enhanced power output compared to traditional fuels and H_2 (Maritime Knowledge Centre, TNO & TU Delft, 2017). In 2007, a vehicle drove across America, from Detroit to San Francisco, powered by a mix of NH3 and gasoline.[25]

Ammonia's has disadvantages as a fuel in combustion engines, such as very high auto-ignition temperature, low flame speed, high heat of vaporization, narrow flammability limits, and toxicity (Brohi, 2014; Kong, 2012). To overcome disadvantages as a fuel, Ammonia can be mixed with other fuels. Kong (2012) also report that ammonia is corrosive to copper, copper alloys, nickel and plastics and these materials have to be avoided in an ammonia fueled engines.

As for other energy carriers, the GHG emissions from production of ammonia depends on the production path. Most of the ammonia produced today is using the energy intensive Haber–Bosch process, and natural gas as starting point (Brohi, 2014; Päivi T. et al, 2018). The price of ammonia depends therefore on the natural gas price. Most NH_3 plants today are large, and produce from 300 000 t NH_3/year upwards, and the production costs decrease significantly with scale. IEA (2017b) states that a plant producing NH_3 from natural gas will have an average emission of 1.6 t CO_2/t NH_3 produced. NH_3 can also be produced from naphtha, heavy fuel oil and coal, but this will generate larger CO_2 emissions per energy unit.

Ammonia can be produced from renewable sources, utilizing electrolysis. Production via electrolysis is reported to have been made previously by 10 plants where the electricity was obtained from hydropower. The ageing plants have suffered from price of electricity consumed and the cost for the process equipment, and only three plants may still be in operation (Brohi, 2014). An alternative promising path in an early development stages is ammonia produced from wind energy or solar power. A carbon-free production method would enable a carbon-free fuel since the tank-to-propeller phase does not emit any carbon.

More than 170 Mt/yr of NH_3 are produced globally, most of it from natural gas. According to Päivi et al (2018) are currently the major use of the produced ammonia for synthesis of fertilizers or found in home cleaning solutions. Ammonium is aslo used in the Selective catalytic reduction (SCR) systems to reduce

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[24] https://www.agmrc.org/renewable-energy/renewable-energy/ammonia-as-a-transportation-fuel/

[25] https://nh3fuelassociation.org/introduction/

nitrogen oxide (NOx) emissions from industrial plants. Ammonia's advantages as a storage technology may make it an option for transporting large amounts of energy over long distances from remote renewable sources. Ammonia has also an existing infrastructure for transport and handling, since it is used in large quantities as fertilizer in the farming industry. However, the development of a bunkering infrastructure remains a barrier for the use of the fuel. Ammonia is expected to be a future fuel for shipping, provided development of carbon-free production, establishment of necessary infrastructure, and maturing promising on-board converters.

4.9 Electricity

On a *full-electric* ship, all the power, for both propulsion and auxiliaries, comes from batteries which are charged from an on-shore connection to the electric grid while at berth. A *plug-in hybrid* ship, like a plug-in hybrid car (PHEV), can charge its batteries using shore power and has a conventional engine in addition. The ship can operate on batteries alone on specific parts of the route, e.g. when manoeuvring in port, during stand-by operations. A *conventional hybrid* ship uses batteries to increase its engine performance and does not use shore power to charge its batteries. Today more than 320 hybrid/plug-in ships are in operation or in order (Figure 4-4). Limited shore-based infrastructure is available today for charging, but progress is made in certain regions[26,27] (e.g. Ecofys, 2015).

Electrification of ships will reduce the tank-to-propeller emissions according to the degree of electrical energy used. The reduction will clearly be up to 100% when all ship operations are powered by electricity. To obtain true zero emission, the electricity must itself be produced by a zero-emission technology; for example, from renewable energy sources, nuclear, or by using CCS.

The amount of electrical energy which can be transferred from shore to ship depends on several factors, including on-shore electric grid capabilities; battery-charging facilities; and time spent alongside. Together with the installed battery capacity on board the ship, these define the potential of electric operations. The short-sea shipping segment currently has the highest potential for electric operations. Within this segment, ships on short routes, with regular schedules and long contracts, have the greatest potential of all. Ships operating on routes with frequent port calls may also utilize more on-shore electricity. Deep-sea shipping looks unlikely to exhibit much electrification any time soon, but such vessels can already install batteries for energy optimization during cruising, or as a low-emission solution when operating in sensitive areas or near harbours.

The first full-electric car ferry, MF Ampère, has been in service between Lavik and Oppedal on the west coast of Norway since 2015.[28] The next all-electric car ferry started operating between Pargas and Nagu in Finland in 2017. [29] About 50 car ferries, hybrid-electric solutions with a very high share (90–100%) of electrification, are currently contracted for future ferry contracts in Norway, and several more are anticipated. The technological solutions are, with few exceptions, hybrid-electric with diesel/gas engines as backup. This provides flexibility for future use on other routes/trades with different premises for electrification. The back-up provision covers, for example, charging system down-time and yard visits. The Norwegian car ferries typically operate at fjord crossings over distances up to 10 kilometres and consume 200–1,000 kilowatt hours (kWh) of energy per trip. The ferries are mainly charged on each

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[26] First for Shore Power in India: http://www.maritime-executive.com/editorials/first-for-shore-power-in-india

[27] Shore power, Norway: http://www.tu.no/artikler/havner-vil-fa-hurtigruten-over-pa-landstrom/193818
http://www.mynewsdesk.com/no/enova-sf/pressreleases/140-millioner-til-landstroem-1689508

[28] Teknisk ukeblad: http://www.tu.no/artikler/denne-fergen-er-revolusjonerende-men-passasjerene-merker-det-knapt/222522

[29] Teknisk ukeblad: http://www.tu.no/artikler/eksporterer-batteriteknologi-til-finland/278058

docking. Two of HH Ferries' four ferries operating between Helsingborg, Sweden, and Helsingör, Denmark, have been converted to all-electric ships[30]. This combined installation of 8,320 kWh battery capacity will more than halve total GHG emissions for the ferry link. The innovative hybrid-electric sightseeing ship, Vision of the Fjords, which can carry 400 passengers, was introduced by the Norwegian marine transportation company The Fjords in 2016. [31] An all-electric passenger ship, Future of the Fjords, was delivered to the same operator in April 2018. [32]

Installing battery systems (incl. replacement after typically 8-10 years) on board is significantly costlier, compared to traditional diesel engines. In addition, infrastructure investments on land is required to provide electricity. The electricity production from hydropower is reported to be price competitive (e.g. Hansson et al, 2016; DNV GL, 2015a) with MGO. However, considering the uncertainty about future electric prices and the large geographical variations (IEA, 2015), it is expected to be challenging to pay back the investments (through only the price difference).
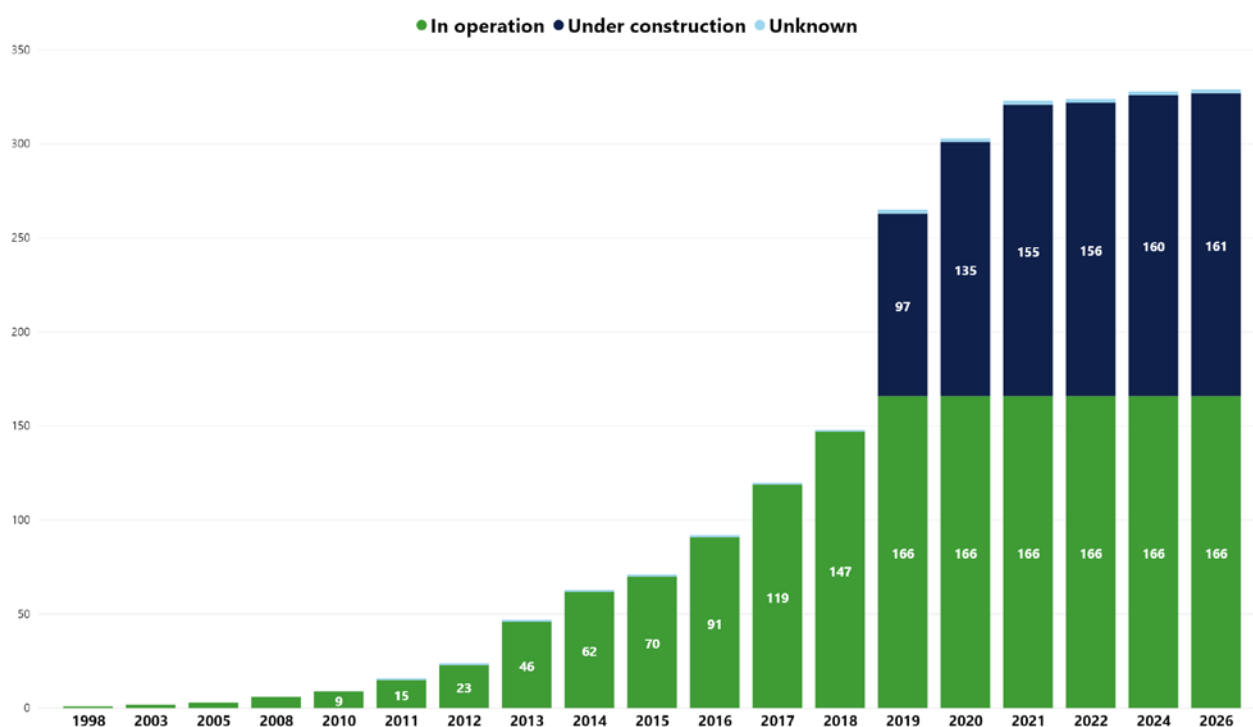

Figure 4-4: Ships with batteries in operations and in order per February 2019 (AFI portal[33])

4.10 Electrofuels

Electrofuels is an umbrella term for carbon-based fuels such as diesel, methane, and methanol, which are produced from CO_2 and water using electricity as the source of energy (Taljegård et al., 2015; Hansson et al, 2016; Brynolf et al, 2018). Electrofuels are also known as e-fuels, power-to-gas/liquids/fuels, or synthetic fuels. The CO_2 can be captured from various industrial processes, the air,

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[30] https://new.abb.com/marine/references/hh-ferries

[31] https://www.tu.no/artikler/ingen-har-noensinne-bygget-et-slikt-skip/358454

[32] https://www.skipsrevyen.no/helelektriske-future-of-the-fjords-klar-i-april-2018/

[33] AFI: https://www.dnvgl.com/services/alternative-fuels-insight-128171

or seawater. This is referred to as carbon recycling, as carbon can be taken from industrial exhaust gases or even from ambient air. Electrofuels are carbon-neutral, if produced using nuclear power, renewables, or with CCS. Studies have assessed the potential role of electrofuels as marine fuel and reported that it is not unlikely that they will be able to compete with other fuel options in the shipping sector in the near term (Hansson et al, 2016). They also report that H_2 is more cost-effective than e-methanol in the shipping sector, under the chosen assumptions.

Electrofuels is an emerging fuel, with several demonstration scale facilities of electrofuels in Europe. The first commercial electrofuel plant was built on Iceland in 2012, with a capacity to produce more than 5 million liters e-methanol per year. Iceland produces e-methanol by using geothermal energy and CO_2 from the same source (CRI, 2016). It is reported that Audi has invested in a 6 MW electrofuel plant in Germany.

A comprehensive review of the production costs of electrofuels is reported by Brynolf et al (2018). They are costlier than fossil fuels and biofuels, and the competitiveness depends mainly on the capital cost of the electrolyser, the electricity price, and the capacity factor. Other cost aspects reported to be less important are CO_2-capture costs, and cost of water. Brynolf et al (2018) do not compare costs for H2 and electrofuels as this would require additional information related to the costs for propulsion and storage systems. They expect that cost is higher for H_2-fuelled fuel cells (need fuel storage systems) than for the (drop-in) electrofuel options used in combustion engines.

4.11 Nuclear propulsion

The International Atomic Energy Agency (IAEA) defines nuclear materials as uranium, plutonium, and thorium. Onboard ships, nuclear power plants fuelled by these materials produce electricity which is used for propulsion. Nuclear power is currently a controversial technology that can be used for propulsion on very large ships, or on vessels that need to be self-supporting for longer periods of time. The Russian ice-breaker fleet operating on the Northern Sea Route is an example of fully marine adapted nuclear power. Several nuclear-powered navy vessels operate today. Three experimental nuclear-powered merchant ships have been built and operated, so far without commercial success; Savannah (US); Otto Hahn (West Germany); and, Mutsu (Japan) (Schøyen & Steger-Jensen, 2017). These ships were independently developed and operated in the 1960s and 1970s for technology demonstration and learning. A fourth ship, Sevmorput (Soviet Union/Russia, 1988–to date), was built and operated, a pioneer in respect of its logistics, functions and propulsion system.

Limited resources of nuclear material mean that is not considered a truly sustainable energy alternative. However, it has an obvious advantage in that nuclear generation does not emit GHGs, except for emissions related to handling of the nuclear materials. While studies have shown that nuclear powered ships can be a cost-effective option to reduce CO2 from shipping (Eide et al., 2013), the extent of its future use will depend on technology developments and social acceptance. Given the public opposition to nuclear power in most countries, and the fears related to potential consequences from accidents and misuse, it seems very unlikely that nuclear propulsion will be adopted in shipping within the next 10–20 years. This is supported by a recent study reporting that it is unlikely that further merchant nuclear-fuelled ships for ocean cargo transport will be built, unless their lifecycle costs and corresponding infrastructure are improved relative to conventionally powered ships (Schøyen & Steger-Jensen, 2017). They also point out that there may be potential for nuclear ships, including non-military, only in nations where there is some strong political reason for investing in nuclear ship propulsion. To avoid the possibility of unwanted use of nuclear material, nuclear-powered ships would need to run on low-enriched nuclear material.

Electricity produced from nuclear power plants on land can also be used for shore powering, for charging batteries of electric ships, or for providing energy for producing other fuels, such as biofuels, electrofuels, NH_3, or hydrogen.

4.12 Wind, solar and wave

Various actual sail arrangements (e.g. sail, kite, fixed wing, Flettner rotors) have been tested out on merchant vessels over the years. Large scale experiments were carried out using fixed wing sails during the oil crises in the late 1970s and early 1980s, and the reported fuel saving was 30% under optimal wind conditions (e.g. bulk/log carrier Usuki Pioneer), (UNCTAD[34]; DNV, 1984). Promising wind concepts have also recently been reviewed[35]. A new Delft study estimated significant saving potentials for wind powering and found that the larges tank and bulk ships had the largest potential. An overall CO_2 reduction for the world fleet of 3.7% was projected in 2050 (Delft, 2017). Currently three ships (Research, ro-ro, ro-lo vessel) have installed wind rotors and one general cargo ship is under planning (Delft, 2017). It is also reported that rotor sail technology has been retrofitted onboard on a ferry in 2018.[36] Furthermore, an oil tanker of nearly 110,000 tonnes recently arrived in Saudi Arabia on its first

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[34] Low Carbon Shipping Module: http://unctadsftportal.org/wp-content/uploads/2016/08/PRINT-2b-Case-Studies-of-Previous-PacificTrials.pdf
[35] http://www.marineinsight.com/green-shipping/top-7-green-ship-concepts-using-wind-energy/
http://www.nsrsail.eu/wp-content/uploads/2015/12/Wind_powered_shipping-Lloyds-Register.pdf
[36] https://www.mpropulsion.com/news/view,viking-lines-iviking-gracei-and-newbuild-to-use-wind-power_51368.htm

voyage since the installation of two 30-metre rotor sails.[37] In addition, three ships (two multi-purpose, one bulk carrier) are equipped with a towing kite.

Wave-powered ships with foils that convert the vertical motion in waves into propulsive thrust has also been studied and demonstrated (Bøckmann, 2015).[38] Such wavefoils could save fuel (typical 2-15% and up to 40%, deepening on foil span, wave direction, ship speed etc), and reduce the most violent vessel motions. It is also development related to hybrid wave energy and batteries system for ships.[39]

More radical concepts[40] are also reported, claiming large fuel and emission savings. A hybrid electrical ship could contain alternative diesel engine configurations, marine fuel cells, battery packages, solar panels, and retractable wind turbines. Increasing the level of electrification can improve the overall efficiency and enable incorporation of many types of renewable sources. The large number of embedded components will increase the system complexity and require carful design, performance monitoring, and power management.

Figure 4-5: The first deep-sea merchant ship designed and outset for sail-assisted propulsion, a 26 000 dwt bulk/log carrier Usuki Pioneer (DNV, 1984)

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[37] https://www.economist.com/business/2018/10/06/wind-powered-ships-are-making-a-comeback

[38] The history of wave-powered boats, www.wavepropulsion.com/

[39] https://marineenergy.biz/2017/09/18/uksnoy-inks-deal-with-hydrowave-for-green-power-solution/
https://www.marineinsight.com/future-shipping/a-ship-with-energy-harvesting-system-to-generate-power-from-waves/

[40] Vindship: http://www.ladeas.no/

5 RANKING OF ALTERNATIVE FUELS FOR ARCTIC SHIPPING

The many alternative fuels, and their diverse characteristics, make it difficult to clearly identify and weigh the strengths and weaknesses for the different new fuel alternatives and make comparisons. To capture various characteristics of the fuels and enable a comparison between them, a new method for holistic assessment of fuel options has been developed and applied. The proposed method, outlined in Figure 5-1, is inspired by the work of DNV GL (2014, 2015b), Brynolf (2014), Deniz & Zincir (2016), Månsson (2017) and Hansson et al. (2017), as well as the ranking approach proposed by DNV GL (2018a).

The approach assesses how well an alternative fuel performs compared with traditional fuels or other alternative fuels. The main assessment categories are **environment**, **economics**, and **scalability**, and each of these are further divided into sub-categories and criteria to be considered (Figure 5-1).

In the following sections, the methodology and input used is described, followed by the resulting ranking for fuels in the Arctic. The method is suitable for making assessments today, and for forecasting by making assumptions about technology and infrastructure developments. Use of the ranking method is expected to provide additional support to the stakeholders. Different actors will have different priorities and perspectives, which can be reflected by changing the weighting of the criteria. The rating assumes the likely future situation in a 5-10-year perspective.
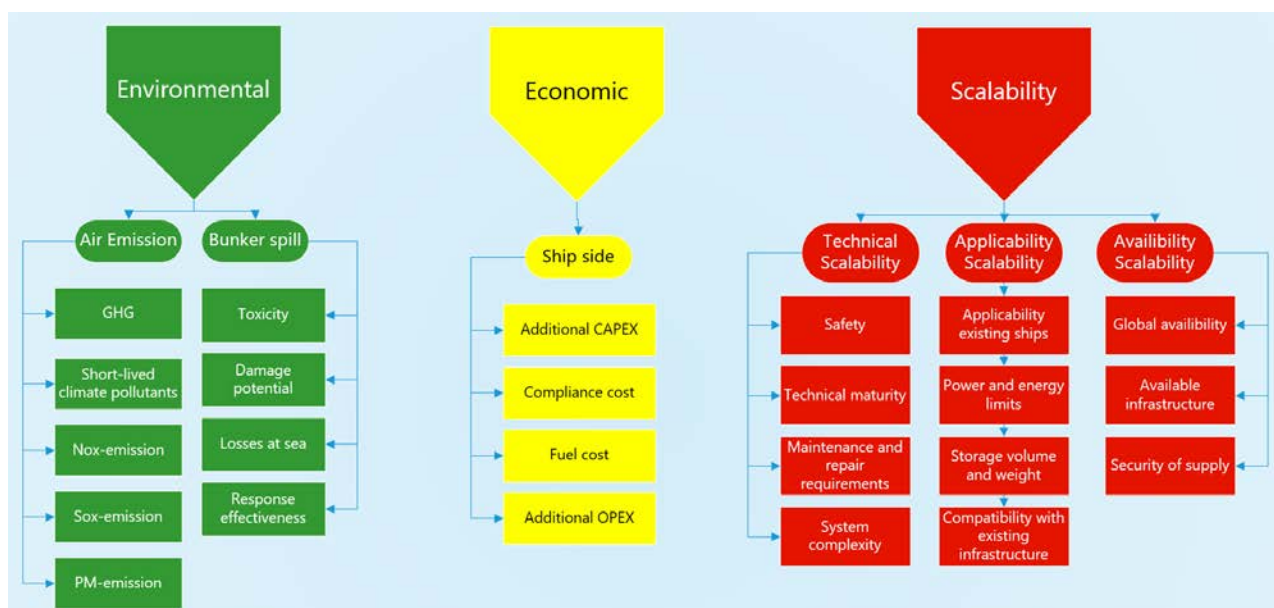
Figure 5-1 – Outline of the ranking methodology for alternative fuels. The overall assessment is divided into three main performance categories. Each are further divided into sub-categories and criteria to be considered

5.1 Ranking methodology

The overall ranking of fuels is a sum of the ranking on three main performance categories (Environmental, Economic and Scalability). Each main performance category consisting of a set of sub categories, which are again split in to the final criteria as illustrated in Figure 5-1 (a full explanation of all criteria is found in Appendix A). Thus, the ranking model has three performance level, i.e. level 0

(overall), level 1 (category), level 2 (sub-category), and level 3 (criteria). The assessment results in this study are presented on level 0, level 1 and level 2.

For each criterion, a *score* and a *weight* are assigned. The *score* reflects the objective (physical) property of the fuel/converter, such as the GHG emissions and oil spill behaviour, on a scale from 1 to 6. The scoring is done relative to optimal or best possible solutions under evaluation. The *weight* reflects the subjective importance placed on this property by the evaluator, on a scale from 1 to 9. Weighting factors are assigned to be able to reflect the different priorities to properly distinguish the useful from the essential. Stakeholders may include national and local authorities, ship owners, cargo owners, ship builders, manufactures and technology providers, classification societies, industry associations, academia, non-governmental organizations, and financial institutions. The final score for a given criterion is the product of the given score and weight (Figure 5-2), from 0 to 54 (6×9) where the highest score is the best.

An average number is next obtained for each sub-category by averaging the respective weighted scores for the criteria. Next, an average number is obtained for each of the three main performance categories (Environmental, Economic and Scalability), by averaging the scores for the belonging sub-categories. Finally, an overall ranking score is obtained for each fuel by summing up the scores for the three main performance categories.

Figure 5-2 — Illustration of the ranking method, combining the scoring and weighting for each criterion. The final ranking is the product of the given <u>scoring</u> and <u>weighting</u>. The scoring is given on a scale from 1 (poor) to 6 (good) as shown, while the weighting factor scale from 1 (irrelevant) to 9 (essential)

5.2 Input to ranking

Several of the fuel characteristics are highly dependent on the ships, and its operation for which the fuel is intended – their size, type, age, etc. - as well as the trading area for these ships. In this report, the objective is to assess fuel for use in the Arctic, and the fleet operating there. To reflect this, the scoring factors are adjusted to reflect particular needs/requirements related to arctic operation. In the DNV GL study HFO in the Arctic from 2013 it was found that regional traffic (mainly fishing vessels & other activities), representing 57% fuel consumption in the Arctic in 2013. Destination traffic plus transit traffic (oil tankers, general cargo, containers & passenger vessels), was found to consume 37% of the total consumption. The priorities and opportunities for the two traffic types are distinctly different and there is a need for rating the different fuel alternatives for each traffic type separately.

A distinction is therefore made between short-sea (regional) and deep-sea (destination) shipping regarding the applicability of, and barriers to, the various fuel alternatives. By using the weighting factors, we may tailor the ranking to different operational conditions while the scores are kept constant. Short-sea shipping includes vessels typically operating in limited geographical areas, on relatively short routes, with frequent port calls. Energy demand, sailing schedules and bunkering patterns for such vessels may be suitable for applying new fuels. On the other hand, for this type of traffic the regional energy infrastructure is critical for the implementation of the fuel. Deep-sea vessels will generally have fewer fuel options compared to the short-sea segment due to the generally lower volumetric energy content for the alternative fuels (Figure 4-3). The segment includes mostly medium sized, ocean-going vessels covering long routes. These vessels require fuel that is globally available as bunkering will be performed globally. For the two separate segments, the applied weighting factors are listed in Table 1A in Appendix A. When tweaking the weighting factors for short-sea adaptation, focus was given to the issues related to applicability. For example, are the power and energy limits of less importance for short-sea shipping than for the deep-sea segment. Likewise, for global availability and infrastructure.

Input to scoring: The criteria developed, are a mix of qualitative and quantitative parameters. Selected criteria are described for each fuel in Section 4. Other criteria are not described in this report but are ranked using expert judgement based on existing literature and studies on the field. For example, this study has used information from DNV GL in-house Alternative Fuel Insight platform (AFI[41]). AFI builds on the LNGi portal, a unique LNG intelligence portal established by DNV GL for supporting and accelerating the uptake of LNG and alternative fuels. In addition to providing regular updates on LNG fuel in the maritime industry, the platform offers a detailed and accurate overview of current ships with batteries, methanol, ethane and LPG. Similar insights on hydrogen/fuel cell applications are currently being developed, as are detailed overviews of methanol terminals worldwide.

Input on weighing: In order to facilitate a best possible process for the weighting of all the criteria, it started with an internal DNV GL process where several authorities on the subject contributed. Following that all ratings were re-evaluated. With these as a basis, a second work shop was held with key personnel from the Norwegian authorities. Finally, the weightings were adjusted prior to a third workshop held with participants from WWF and other NGOs.

Input on fuel/converter alternatives to be investigated: Table 5-1 below lists the fuel alternatives ranked in this study. In total 11 different alternative fuel/converter combinations (fuel paths) are investigated. Note that it is assumed that in the future, all fuel alternatives (with the possible exception of the largest inter-continental vessels) will include some form of electrical hybrid solution. This will allow for a more optimal operation of any type of machinery (less methane slip, less soot and particles as well as overall lower consumption/emission) as well as potentially zero emission in local areas where particular care is required. This assumption is baked in to the scoring.

Note that not all potential fuels are included for ranking in this study. Among these are the following fuels, covered in Section 4: LPG, Electrofuels, and Nuclear, as well as energy from solar and wind.

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[41] https://afi.dnvgl.com/

Table 5-1 – Fuel/Converter alternatives to be investigated for this study

	Fuel type	Converter technology
1	HFO	ICE*
2	Diesel/MGO	ICE/Battery hybrid
3	Low Sulphur Hybrid	ICE
4	Low Sulphur Hybrid (arctic optimized)	ICE
5	Bio Diesel(HVO)	ICE/Battery hybrid
6	Bio-gas	ICE/Battery hybrid
7	LNG	ICE/Battery hybrid
8	Full electric	Battery Electric**
9	Methanol	Fuel Cell/Battery Hybrid
10	Hydrogen	Fuel Cell/Battery Hybrid
11	Ammonia	Fuel Cell/Battery Hybrid

*Internal Combustion Engine, ** With back-up combustion engine installed for redundancy.

5.3 Ranking results

As outlined above, the requirements to alternative fuel for use in short-sea and deep-sea shipping may vary significantly (see weighting factors listed in Table 1A and scores in Table 2A in Appendix A). The ranking results are therefore presented separately below for the short-sea and the deep-sea segment.

5.3.1 Results short-sea shipping in the Arctic

While the deep-sea segment consists of vessels with a predominantly global trading pattern, the short-sea segment is much more varied in size, type and energy requirements. Short sea shipping includes vessels typically operating in limited geographical areas, in relatively short routes, with frequent port calls. Energy demand, sailing schedule and bunkering pattern for such vessels may be suitable for testing new fuels.

Applying the outlined method, the overall ranking result is illustrated in Figure 5-3 below for the short sea segment. Results are also presented in more detail per performance categories in Table 5-2. LNG fuel used with a combustion engine in combination with a battery-electric hybrid solution are ranked highest, followed by bio-gas and battery-electric propulsion.
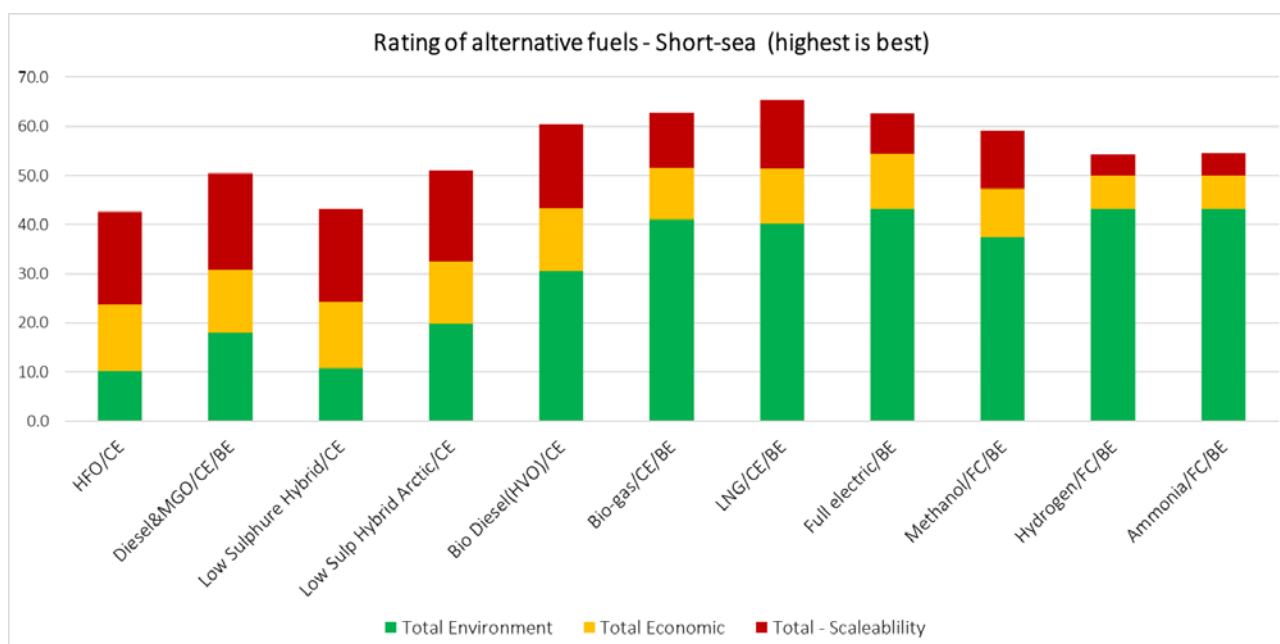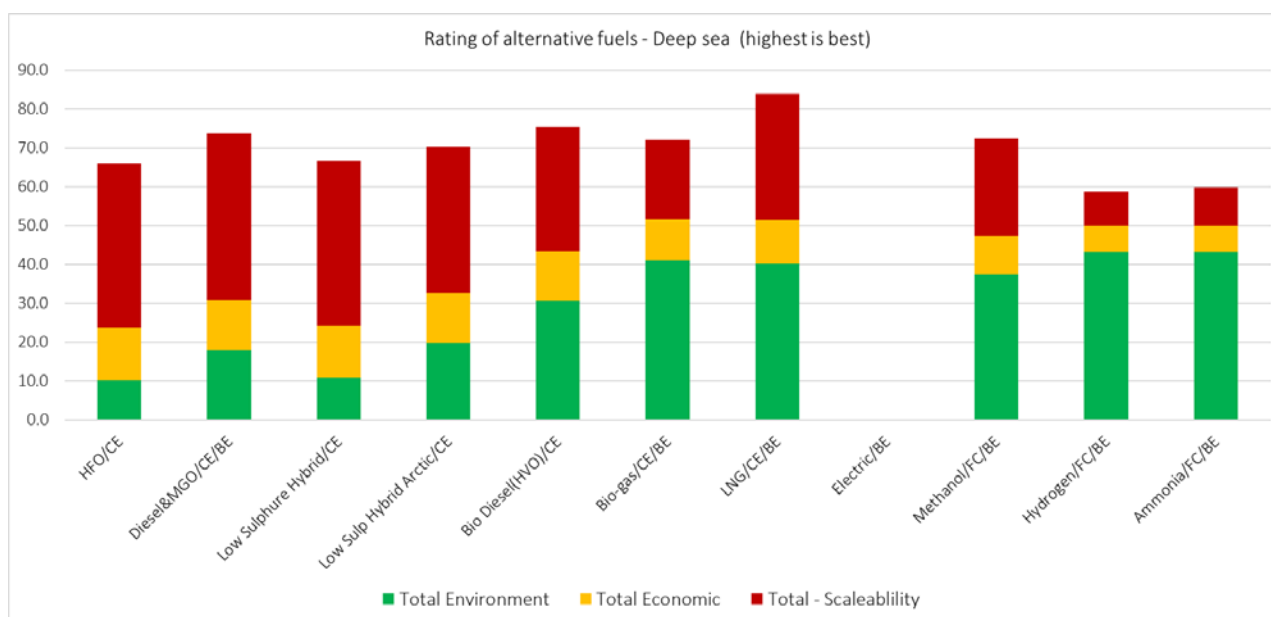
Figure 5-3 — Overall rating of selected fuels, with contributions from the three main performance categories. Short sea shipping in the Arctic

Table 5-2 — Ranking with breakdown on performance categories and sub-categories — Short sea shipping in the Arctic. Colour coding is scaled to each column

Energy source/carrier	Environmental			Economic		Scalability				Sum total
	Air	Bunker	Total Environment	Ship	Total Economic	Technical	Applic-ability	Availi-bility	Total - Scale-ability	
HFO/CE	5.4	15	10.2	13.5	13.5	30.75	14.0	12.0	18.9	42.6
Diesel&MGO/CE/BE	12	24	18.0	12.75	12.8	33	14.0	12.0	19.7	50.4
Low Sulphure Hybrid/CE	9.6	12	10.8	13.5	13.5	30.75	14.0	12.0	18.9	43.2
Low Sulp Hybrid Arctic/CE	9.6	30	19.8	12.75	12.8	30.75	14.0	10.5	18.4	51.0
Bio Diesel(HVO)/CE	22.2	39	30.6	12.75	12.8	31.5	14.0	5.5	17.0	60.4
Bio-gas/CE/BE	28.2	54	41.1	10.5	10.5	23.25	8.3	2.0	11.2	62.8
LNG/CE/BE	26.4	54	40.2	11.25	11.3	23.25	8.3	10.0	13.9	65.3
Full electric/BE	32.4	54	43.2	11.25	11.3	17.25	4.3	3.0	8.2	62.6
Methanol/FC/BE	27	48	37.5	9.75	9.8	21.75	7.7	6.0	11.8	59.1
Hydrogen/FC/BE	32.4	54	43.2	6.75	6.8	6	3.3	3.5	4.3	54.2
Ammonia/FC/BE	32.4	54	43.2	6.75	6.8	6	4.3	3.5	4.6	54.6

5.3.2 Results deep-sea shipping in the Arctic

Applying the outlined method, the overall ranking result is illustrated in Figure 5-4 below for the deep-sea segment. Results are also presented in more detail per performance category in Table 5-3. Applicability and scalability are the factors that differentiate short-sea and deep-sea shipping. Power and energy limits as well as global availability are of course essential for the deep-sea segment. Consequently, we observe that the more traditional fuels perform more favourably within this segment. Still, the LNG/battery-hybrid solution comes out on top also for this segment with a relatively strong performance in all categories apart from GHG-emissions.

Figure 5-4 – Overall ranking of selected fuels, with contributions from the three main performance categories. Deep sea shipping in the Arctic

Table 5-3 – Ranking with breakdown on performance categories and sub-categories – Deep sea shipping in the Arctic. Colour coding is scaled to each column

Energy source/carrier	Environmental			Economic		Scalability				Sum total
	Air	Bunker	Total Environment	Ship	Total Economic	Technical	Applica bility	Availibil ity	Total - Scaleablili ty	
HFO/CE	5.4	15	10.2	13.5	13.5	30.75	42.0	54.0	42.3	66.0
Diesel&MGO/CE/BE	12	24	18.0	12.75	12.8	33	42.0	54.0	43.0	73.8
Low Sulphure Hybrid/CE	9.6	12	10.8	13.5	13.5	30.75	42.0	54.0	42.3	66.6
Low Sulp Hybrid Arctic/CE	9.6	30	19.8	12.75	12.8	30.75	42.0	40.5	37.8	70.3
Bio Diesel(HVO)/CE	22.2	39	30.6	12.75	12.8	31.5	42.0	22.5	32.0	75.4
Bio-gas/CE/BE	28.2	54	41.1	10.5	10.5	23.25	29.0	9.0	20.4	72.0
LNG/CE/BE	26.4	54	40.2	11.25	11.3	23.25	29.0	45.0	32.4	83.9
Electric/BE										
Methanol/FC/BE	27	48	37.5	9.75	9.8	21.75	27.0	27.0	25.3	72.5
Hydrogen/FC/BE	32.4	54	43.2	6.75	6.8	6	7.0	13.5	8.8	58.8
Ammonia/FC/BE	32.4	54	43.2	6.75	6.8	6	10.0	13.5	9.8	59.8

5.3.3 Discussion

The fuel paths ranked with the heights score, all perform well with respect to the environmental performance. In most cases the environmental performance is a "constant", meaning that they are given by the characteristics and properties of the fuel and difficult to improve. The two other main performance categories Scalability and Economy are not "constant" in this respect and could be significantly improved by systematic actions by the various stakeholders (e.g. infrastructure developments, reduced fuel price). Common for these fuels are that they are gaseous fuels, dominated by zero carbon emission fuels. On the other hand, for the fuels with a low environmental score, the performance improvement potentials in most cases is already taken due to a mature and well-

established infrastructure/economy. Common for these fuels are that they are liquefied and dominated by fossil fuels.

Table 5-4 also shows the difference in the ranking between the fuel/converter alternatives for short sea and deep-sea operation. LNG fuel in a battery-electric hybrid configuration obtain the highest overall score, both for short and deep sea. Even though it is not a "zero-emission" solution, the potential environmental footprint in the Arctic is favorable regarding both BC/NOx/SOx emission and potential accidental spills to sea which is considered to be essential in this assessment. LNG does not reduce CO2 emissions sufficiently compared to the established IMO ambitions. Although there are currently no commercially available fuel options for reducing CO2 emissions with ~50% on deep sea ships, there is a long range of known options which may develop into viable options such as biodiesel, biogas, H2, ammonia, synthetically produced diesel/gas/methanol. A dual fuel LNG engine today gives you the widest range of compatible fuels for a vessel; all liquid diesel-like fuels and all liquefied gases such as bio-LNG and synthetically produced methane can be burned in the DF engine without modification. With some modifications other fuels may also be possible to burn in the DF engine.

LNG is followed by bio-gas and full electric in short sea, while bo-diesel and distillate fuel comprise top three for the deep-sea segment. The result reflects that fewer really green options are available for deep sea and energy content and global infrastructure is given a higher relative priority. It should also be noted that even though full electric scores well for short-sea shipping, it is based on the assumption that "renewable electricity" is readily available. Per today, this will not be the case for most ports in the Arctic. Further, the limited energy storage capacity of electric batteries will pose a serious limitation to the applicability if this technology for arctic operation. Both heating and the requirement for redundancy, will drive any implementation towards a form of hybrid solution between battery and a combustion engine, and unless the engine is powered with gaseous fuels, the problem of spills to sea will still be part of the solution.

It is recognized that the results presented depends heavily on the weightings made in this study. Our intention with the exercise has been to have an arctic perspective, resulting in the promotion of fuels avoiding the devastating results of oil spills in ice infested waters and BC and particle emission in particular. The ranking process also clearly illustrate that unless the environmental considerations are heavily weighted, the traditional fuel will score considerably better than the alternative and greener fuels.

Table 5-4 – Ranking for all fuels/converters – Short sea vs. deep sea shipping in the Arctic

#	Short sea	Deep sea
1	LNG/CE/BE	LNG/CE/BE
2	Bio-gas/CE/BE	Bio Diesel (HVO)/CE
3	Full electric/BE	Diesel & MGO/CE/BE
4	Bio Diesel (HVO)/CE	Methanol/FC/BE
5	Methanol/FC/BE	Bio-gas/CE/BE
6	Ammonia/FC/BE	Low Sulp. Hybrid Arctic/CE
7	Hydrogen/FC/BE	Low Sulphur Hybrid/CE
8	Low Sulp. Hybrid Arctic/CE	HFO/CE
9	Diesel & MGO/CE/BE	Ammonia/FC/BE
10	Low Sulphur Hybrid/CE	Hydrogen/FC/BE
11	HFO/CE	Electric/BE

6 ESTIMATE OF THE EMISSION REDUCTION POTENTIAL FOR PROMISING ALTERNATIVE FUELS FOR THE ARCTIC FLEET

Section 5 provides an assessment of suitability for arctic shipping application, for a range of fuels. The assessment is provided separately for short-sea and deep-sea arctic shipping. For both ship segments, the assessment points to LNG as the most promising fuel for arctic use given the priorities in the assessment. This section provides an estimate of the emission reduction potential if LNG is introduced in the arctic fleet, building on results from Section 3, 4 and 5. The modelling assumes full implementation of LNG in the fleet ("what if") apart from the smallest vessel group under 1 000 GT.

In addition, it is an ongoing prosses on banning HFO as fuel in the Arctic. Therefore, this study also comprises an assessment of the potential emission reduction potential by assuming all vessels currently operating on HFO transit to distillate fuels.

6.1 Reduction potentials for full implementation of LNG

As requirements to emissions to air become more stringent, one possible solution for reduced emissions is to use liquified natural gas (LNG) as a fuel for shipping. The LNG fuel scores well on all air emission components, except for green-house gases. Additionally, the physical characteristics for the LNG makes the fuel far less harmful to the marine environment if accidentally released to air or discharged to sea in comparison with residual or distillate fuel. This is further described in Section 4.3.

LNG in combination with an ICE (Internal Combustion Engine) and in a battery-hybrid drive-line is an alternative which is ranked on top for arctic use as presented in Section 5.3.1 and 5.3.2. The energy density allows for powering both deep-sea and short-sea vessels, and there is already LNG production and plans for bunkering possibilities along the Northern Sea Route (see Section 7.2).

In this section we provide an estimate for the emission reduction potential for LNG, if applied to its full technical potential in the arctic fleet. The following assumptions apply;

- We assume that the 2017 traffic picture is representative for future traffic

- We apply LNG to all vessels where it is technically feasible (above 1 000 GT)

- We do not consider economic implications

- We assume availability of LNG bunkering facilities wherever necessary

At the time of writing, no small maritime LNG engines (less than 1 000 kW) are available in the marked. Further, the relatively low volumetric energy density (requiring larger tanks) makes LNG less viable for the smallest vessels. For this LNG case study, this means that the vessels below 1 000 gross tonnage are excluded from uptake of LNG as an alternative fuel. The small vessels below 1 000 gross tonnage will therefore in the case modelling results presented in this section use MGO as fuel and appurtenant emission factors.

There is a difference in applicability, GHG-emission reduction potentials and other emission components between high-pressure 2-stroke LNG-engines and low-pressure 4-stroke LNG engines which has to be accounted for, as discussed in Section 4.3. The latter solution is associated with higher methane slip, resulting in a less advantageous GHG emission profile than for the high-pressure 2-stroke engines. On the other side, the 2-stroke engines will have a higher NO_x emission unless this is compensated for by using Exhaust Gas Recirculation (EGR) or Selective Catalytic Reduction (SCR), (all currently known 2-stroke high pressure engines will have this). The 2-stroke LNG engines available in the marked, are large units and hence only applicable for larger vessels (typically for slow speed engines, e.g. less than 300 RPM). For this LNG case study, this means that only cargo vessels (oil tankers, chemical and product

tankers, gas tankers, bulk carriers, general cargo vessels, ro-ro vessels and reefers) above 5 000 gross ton are allocated to 2-stroke LNG engines while the remaining vessels above 1 000 gross ton are allocated 4-stroke LNG engines.

Table 6-1 shows the emission reduction potentials for the two LNG engine types. The CO_2 emissions are presented as CO_2 equivalents where methane slip is accounted for.

Table 6-1 Reduction factors for different LNG-engines

LNG engine alternative	Reduction CO₂e	Reduction NOx	Reduction PM	Reduction SOx	Reduction BC
4-stroke low-pressure LNG engine	5%[42]	90%	98%	100%	98%
2-stroke high-pressure LNG engine	20%	90%*	98%	100%	98%

* This type of engines will be supplied NOx-reduction measures to ensure emission levels equivalent to low pressure engines. Without measures, a high-pressure LNG-engine will typically only yield a 30% NOx-reduction compared to baseline.

Using the 2017 baseline for fuel consumption and emission for the IMO Arctic polar code area, as presented in Table 3-1 and Table 3-3, the emission reduction potentials for LNG as fuel in the Arctic is calculated. The calculations are made by multiplying the respective reduction factors from Table 6-1 to the 2017 baseline results.

Table 6-2 shows that there is a GHG (CO_2e) reduction potential of 12% for the arctic fleet, assuming all vessels above 1 000 GT uses LNG as fuel. Additionally, the introduction of LNG will reduce the emissions of NOx, PM, SOx and BC by 85%, 95%, 98% and 91% respectively.

Table 6-2 Estimated emission reduction potentials for the arctic fleet, assuming uptake of LNG

Component	Baseline emissions (ton)	LNG case emissions (ton)	Emission reductions (ton)	Emission reductions (%)
CO₂e	1 845 000	1 620 400	224 700	12 %
NOx	32 500	4 900	27 600	85 %
SOx	20 030	400	19 630	98 %
PM	1 970	100	1 870	95 %
BC	160	14	146	91 %

The above presented emission reductions, as result of LNG as fuel for the arctic fleet, are theoretical figures. LNG uptake in the arctic region and for the transit traffic through the arctic waters is closely linked to the development for global shipping. Projections for global LNG uptake is given by studies such as DNV GL (2017b), (2018a) and Fevre (2018). It is recognized that LNG uptake will take time, and necessary regulatory and economic drivers will be needed (see Section 7).

6.2 Risk and emission reduction potentials with distillate fuels

Using residual fuel (HFO) onboard vessels in the Arctic poses a significant risk to the environment, not only because of potential oil spills but also because burning it produces harmful air and climate pollutants, including black carbon (BC). As ship traffic increases in the Arctic, the risk to the arctic environment and its people will also increase.

In this section we provide an estimate for the emission reduction potential of changing all residual fuel use to MGO, as applied to its full technical potential in the arctic fleet. The following assumptions apply;

- We assume that the 2017 traffic picture is representative for future traffic

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[42] https://www.nho.no/siteassets/nox-fondet/rapporter/2018/methane-slip-from-gas-engines-mainreport-1492296.pdf

- We apply MGO to all vessels

- We do not consider economic implications

- We assume availability of MGO bunkering facilities in all relevant ports

As opposed to distillate fuels, residual HFO emulsifies in water and breaks down very slowly, particularly in a cold marine environment. Whereas distillates typically disappear from the water surface after three days, nearly all HFO remains at the surface after 20 days (DNV, 2011b). More recent weathering's studies by Sintef support these results (Sintef, 2017; Fritt-Rasmussen et al., 2018). In the paper "Transitioning away from heavy fuel oil in arctic shipping" (ICCT, 2019) it is concluded that distillate spills are estimated to be 70% less costly than HFO spills when the cleanup, socioeconomic, and environmental costs are considered. HFO spill may move further with currents, waves and the wind and impose a much higher risk of affecting vulnerable areas along the ice edge and shores. When mixed with ice, it is close to impossible to clean HFO spills (WWW, 2017). One should still bear in mind that distillate spills, though not persisting in the environment in the same way as HFO, still poses severe toxic and contamination impacts to the local habitants, and the effect of such a spill may still be devastating to communities and the wild life. This is further described in Section 4.1 and 4.2.

Assuming a full transition to MGO (distillate fuel with 0.1% Sulphur content) in the Arctic will also influence the emissions to air. As seen in Table 6-3, no reduction in CO_2 emission and NOx emissions is expected from a potential fuel transition, but PM, BC and Sulphur emissions will be considerably reduced (e.g. Buffaloe et al., 2014; EMEP/EEA, 2016; ICCT, 2017a,d,e).

Table 6-3 Reduction factors for MGO versus HFO*

	Reduction CO₂e	Reduction NOx	Reduction PM	Reduction SOx*	Reduction BC
Diesel engine	0 %	0 %	84 %	96 %	49 %

Assume MGO with 0.1 % Sulphur and HFO with 2.58 % Sulphur

Table 6-4 Estimated emission reduction for the arctic fleet, assuming all ships using MGO

Component	2017 baseline emissions (ton)	MGO case emissions (ton)	Emission reductions (ton)	Emission reductions (%)
CO₂	1 845 000	1 845 000	-	0 %
NOx	32 500	32 500	-	0 %
SOx	20 030	1 200	18 830	94 %
PM	1 970	600	1 270	66 %
BC	160	100	60	35 %

Table 6-4 shows the magnitude of emission reduction one may expect based on the traffic in the Arctic in 2017 assuming all traffic uses MGO (distillate fuel with 0.1% Sulphur content). From 2020 all ships will have to use fuel with a maximum Sulphur content of 0.5%. It is likely that the fleet that currently uses HFO will convert to either the new hybrid fuels or, should there be no ban of HFO fuel use on ships in the Arctic, continue with HFO in combination with scrubbers. Using a scrubber will reduce SOx emissions, but also remove a fair part of the particle/BC emissions (ICCT, 2017d). If a 2020 scenario is used as reference, the reduction potentials will be lower than shown in Table 6-4, but the environmental benefit from a switch to MGO will still be significant.

7 BARRIERS AND DRIVERS FOR UPTAKE OF LNG IN THE ARCTIC

A barrier may be defined as a mechanism that inhibits investment in promising fuel and technologies. All alternative fuels face challenges and barriers, as reported by recent studies (e.g. DNV GL 2014, 2015a, b, 2017b, 2018a; Brynolf, 2014). In an arctic environment is it expected that these barriers will be "strengthened", due to remoteness, ice and harsh weather conditions.

In the following, barriers to implementation of promising fuel and technologies in general are categorised and discussed, followed by a specific assessment barriers actions to be taken to overcome the barriers. This section ends with discussing the main drivers for use of LNG in the Arctic.

7.1 Categorisation of barriers

According to DNV (2015a), the barriers to uptake of alternative fuels and technologies can be categorised as commercial, regulatory, technical, and non-technical. A recent study addressing barriers for uptake of LNG as marine fuel has divided the barriers into the similar four categories (International Gas Union, 2017). In the following, the four categories of barriers are presented:

- **Technical:** New fuels are adopted by a few pioneers first and it may take more than a decade until large scale deployment, provided that the technology will prove reliable and fulfilling its promises. This is due to reluctance to use new, unproven technologies and due to the lack of adequate infrastructure or support personnel for installing, maintaining and operating the new solution. This is a natural behaviour, very unlikely to change, unless the use of certain technologies is enforced through regulations or if a sudden breakthrough is achieved. Lack of appropriate infrastructure, such as bunkering facilities and supply chains, and uncertainty regarding long-term availability of fuel are additional barriers for the introduction of any new fuel.

- **Economic:** Access to capital and investment horizon may be the single most important barrier for implementation of any new technology. For many shipowners, finding capital to fund proven fuel saving technologies can be a challenge – even for technologies that pay for themselves in a matter of years. When introducing a new fuel, existing ships may have to be retrofitted because of incompatible machinery. This makes changes a long-term investment. For pioneers - owners who take the risk to invest in new technology solutions – unforeseen technical issues often result in significant delays, requiring additional capital. At the same time, bunker costs for certain shipping segments are paid for by the charterer, removing incentives for owners to explore alternative fuels or even fuel efficiency measures. Large companies can usually afford having longer investment horizons than smaller ones, while they also have the advantage of economies of scale, which offer leveraging when negotiating prices.

  Uncertainty in future fuel price of emerging fuels will be a business reality and an important barrier.

- **Regulatory:** Safe introduction of alternative fuel will normally require rule development, also covering bunkering. When rules are not available for maritime use, this will hamper the uptake of new fuels. An Alternative Design approach must then be carried out to demonstrate an equivalent level of safety. A confusing regulatory landscape enforced by different government bodies ranging from international, to national, and subnational levels should be avoided. Shipping is an international industry, and international environmental and safety standards for shipping are developed by the International Maritime Organization (IMO), a United Nations specialized agency. The International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF Code) Code was adopted by the IMO in June 2015 (MSC.391[95]) and went into force on 1 January 2017. It is compulsory for all gaseous and other low-flashpoint-fuel ships and currently (2017) covers natural gas in liquid or compressed form (LNG, CNG).

The ship side of the bunkering operation (from the bunkering flange on the ship side) is covered by the IGF-Code, but not the shore part. Therefore, other standards for safe bunkering of the relevant fuels are needed to support the implementation of bunkering technology for maritime use. For LNG, the ISO/ TS 18683 – "Guidelines for systems and installations for supply of LNG as fuel to ships", issued Jan 2015 – provides useful guidance, as does recommended practices and guidelines published by the major classification societies. The standard ISO 20519 "Ships and marine technology – Specification for bunkering of gas fueled ships" is under preparation for its final publication, but the focus of this standard seems to be limited to LNG.

- **Cultural:** A long-established industry facing shift of fuels and technologies may be resistant to change. The cultural resistance to a less familiar fuel and technology is an important barrier, especially when operating in the Arctic where rescue resources will likely be far between. The lack of, quality of and/or awareness of information regarding the various aspects of new marine fuels could often be a barrier. Improved communication around advantages and benefits, could help reducing this barrier. In addition, the first movers and followers are expected to gradually overcome this barrier.

  When introducing a new technology, there is increased complexity that must be handled by the crew, adding to their existing workload. Many shipping organizations are set up to handle normal day to day operations, and any added complexity will be seen as an unwanted burden. There are large variations between segments: Offshore Supply Vessels and large Cruise vessels are known for being early adopters of new technologies and typically have highly qualified crew. In other segments, there is concern that a lack of qualified crew will be a significant barrier for adopting new technical solutions. This problem can be solved if equipment manufacturers and ship owners cooperate to provide appropriate training. This is a non-technical barrier that has to be dealt with in order to accelerate the uptake of new fuels and technical solutions.

Findings from recent studies considering uptake of emission reduction technologies in shipping indicates the importance of financial and technical barriers, but also managerial practices and legal constraints (e.g. DNV 2012; DNV GL, 2016, 2017c; Acciaro et al 2013; Rehmatulla et al., 2015; Rehmatulla & Smith, 2015).

7.2 Barriers to uptake of LNG and actions to overcome them

The final decision with regard to investing in LNG fuelled ships will vary for different ship types/sizes, operations, and strategic directions of each ship owner. The assessment of the LNG for use in the Arctic is presented in Table 7-1. In all cases, the cost associated with LNG machinery and fuel tanks, as well as the expected fuel prices, will play the dominant role. Access to capital may be one of the most important barriers, as the new-building cost of LNG-fuelled ships is about 10–30 % higher than for equivalent diesel-fuelled ships (see Section 4.3). Lack of appropriate infrastructure, such as bunkering facilities and supply chains, and uncertainty regarding long-term availability of fuel are additional barriers for the introduction of any new fuel. Owners will not start using new fuels if an infrastructure is not available, and energy providers will not finance expensive infrastructure without first securing customers. Breaking this deadlock will require a coordinated, industry-wide effort and the political will to invest in the development of new infrastructure, enforced by different government bodies. In addition to infrastructure, support personnel for installing, maintaining and operating the new solution will be needed.

Table 7-1 Assessment of barriers related uptake of LNG in the arctic fleet, based on framework reported by DNV GL (2015a)

Main category	Sub category	Barrier level	Comments
Technical	Safety and reliability Technical maturity Infrastructure and availability	Significant	Need for additional safety measures, also during bunkering Mature technology Lack of infrastructure for LNG in the Arctic
Economic	Commercial implications Economic and finical challenges Taxes and incentives	High	High investment cost Suitable for new-buildings Limited demand for "green" ships
Regulatory	Rules by authorities Class rules Incentives and incentives	Low	Established by IMO Established by major classification societies Lack of incentives and drivers
Cultural/ non-technical	Organizational challenges Complexity in applications	Significant	Training of crew Operational and competence intensive

There are actions aimed to mitigate or remove barriers to the widespread use of LNG as fuel. Governments and the industry can take actions on different levels. The overall key recommendations from this study for arctic operations are:

- Building up availability and infrastructure for LNG

- Develop national and regional home-markets in the Arctic as to create local demand for LNG

- Tailor a package of policy measures to stimulate phasing in of LNG-fueled vessels

A recent research project at the Fram Centre[43] (CASE, 2014) categorised the arctic ship traffic into 3 traffic types; Transit (transport Atlantic-Pacific without visiting arctic ports), destination (resource export, goods import, tourism), and internal (internal transport, offshore operations, fishing). For each traffic type detailed data on ship types, destinations, cargo volumes, fuel consumption, emission factors etc. was used to calculate emissions to air. The arctic internal traffic accounted for 57% of the total fuel consumption in the area, while destination and transit represented 37% and 6% respectively. It should be recognized that traffic in the Arctic area has large seasonal variations.

It can be assumed that the arctic traffic modes are not changed significantly, hence the internal and destination traffic are still most relevant when discussing alternative fuels in the Arctic.

Figure 7-1 shows that the transit shipping has a small share of the total arctic traffic and is not likely using the Arctic region as an energy hub.

Figure 7-1 shows the geographical traffic distribution for arctic internal and destination traffic. This gives an overview of key areas where development of LNG infrastructure could be focused. The high traffic areas are found in the Barents Sea, Kara Sea, west coast of Greenland, Bering Sea and Gulf of Alaska. LNG ship bunkering infrastructure could initially focus on these areas and should be seen in relation to arctic LNG development plans in general, as shortly described below, and reflected in Figure 7-2.

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[43] Located in Tromsø, Norway
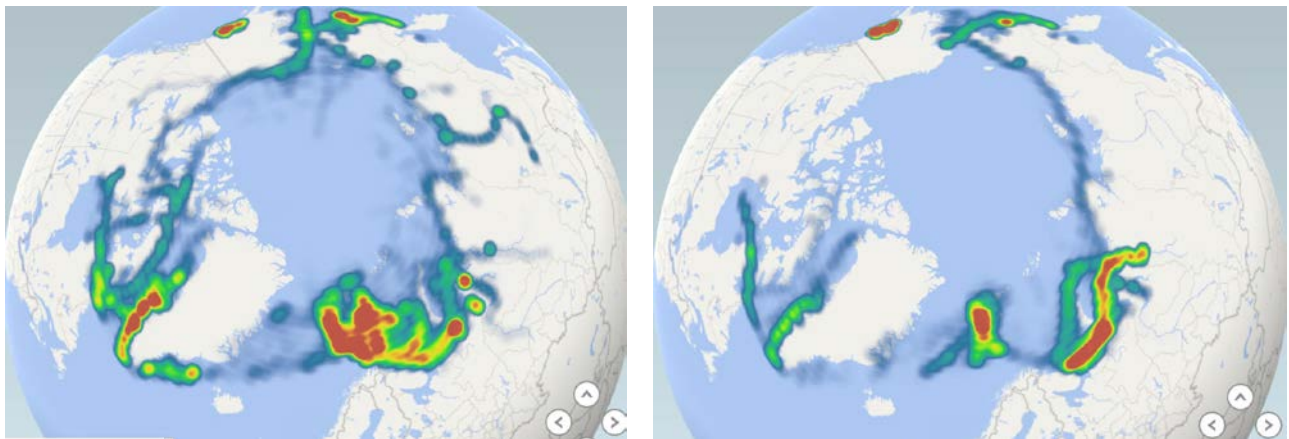
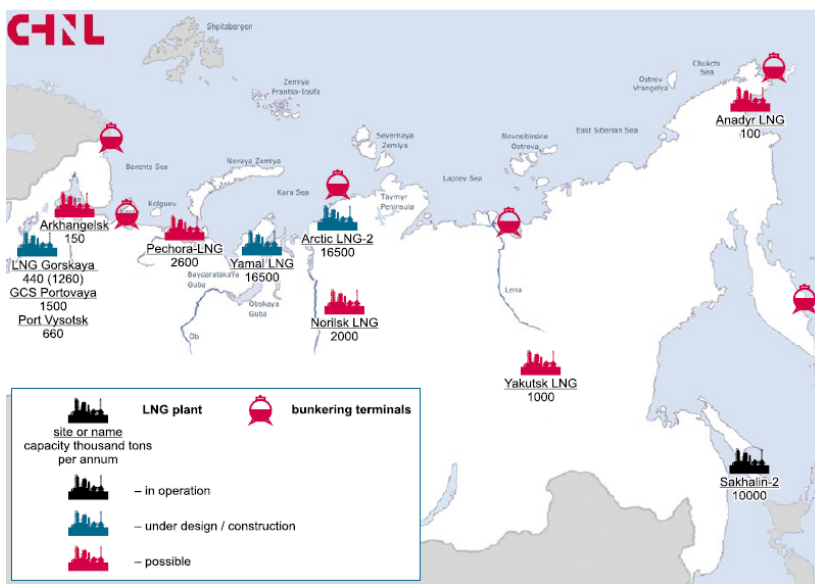**Figure 7-1 Arctic internal traffic (left) and destination traffic (right) (CASE, 2014)**

LNG may be an attractive marine fuel for the Arctic if the price of LNG continues to be much less than that of distillate and residual fuel, and as LNG bunkering infrastructure becomes increasingly available. For the later, WFF (2017) indicate promising prospects for using LNG for bunkering in the arctic regions of Russia. This is supported by the following statement in august 2018[44]"...*Russian President Vladimir Putin has spoken out in support of a proposal by Finnish President Sauli Niinistö to use LNG as bunker fuel in the Arctic...*".

LNG does not reduce CO_2 emissions sufficiently compared to the established IMO ambitions. This is a fact and it is therefore interesting to investigate what this means in terms of future fuel lock-in/flexibility. There are currently no commercially available fuel options for reducing CO_2 emissions with ~50% on deep sea ships, and such solutions will likely not be available in the short future. There is a long range of known options which may develop such as biodiesel, biogas, H2, ammonia, synthetically produced diesel/gas/methanol etc, but knowledge on their future availability and price level is still limited. Investing in LNG (Dual Fuel) today gives the widest range of compatible fuels; all liquid diesel-like fuels and all liquefied gases such as bio-LNG and synthetically produced methane can be burned in the DF engine without modification. With some modifications other fuels may also be possible to burn in the DF engine.

For the Arctic region recent studies have suggested that LNG could be an attractive fuel for ships (LNG) (e.g. WWF, 2017; ICCT, 2017c). According to WWF (2017) this is based on the ongoing development of LNG production and expected bunkering terminals in the Arctic regions of Russia (e.g. along the Norther sea route) (Figure 7-2). A large LNG production facility is also located in North of Norway (Melkøya).

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[44] https://www.maritime-executive.com/article/putin-voices-support-for-lng-as-fuel-in-arctic

Figure 7-2- Map of possible LNG production plants along the NSR (WWF, 2017, their figure 14)

Sakhalin and Yamal in Russia are large LNG production facilities. The oil companies participating in these projects, are actively working not only on LNG production and export, but also on its use in shipping (WWF, 2017). This could make LNG available for bunkering along the transport corridor between Europe and Asia. The first vessels using LNG in the Russian Arctic will be the LNG carriers of the Yamal LNG project. Also, the first LNG-powered icebreaker "Polaris" has become an example of technological solutions that promote environmental development of the Arctic region.[45]

In addition to use LNG by ships, WWF (2017) suggest use LNG for land vehicles in the Arctic, and to supply gas to coastal settlements and local communities, plants and industrial customers, like is already happening in the Kaliningrad. Both terrestrial and maritime infrastructure in the Polar Code Arctic region is extremely limited, making transportation in the Arctic difficult (Ocean Conservancy, 2017). There are few large and modern ports in the Polar Code Arctic, with other smaller ports not necessarily able to provide a full range of maritime services or meet modern standards. This could hamper the potential uptake of LNG.

It is recommended to initiate studies which further detail the arctic traffic patterns, with special attention to port calls and bunkering. Also, further studies should identify barriers in way of achieving the policy targets, in order to tailor a package of policy measures to stimulate phasing in of fuels which could lead to significantly lowering of the oil spill risk, as well as providing sustainable emission levels in specific areas or for the region.

7.3 The main drivers for shifts to alternative fuels

The introduction of LNG as alternative energy source in the arctic fleet will take place at a very slow pace initially as technologies necessary infrastructure becomes available. In addition, introduction of LNG will take place first in regions where the fuel supply will be secure in the long-term. To understand the future transitions, it is important to understand that major changes in the shipping industry in the past have been slow and, to a large extent, economically motivated. This section highlights some of the major

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[45] https://www.motorship.com/news101/industry-news/team-finland-hones-its-edge

historical shift and future drivers related to fuel types and main engines, building on work published by DNV GL (e.g. OECD 2010, DNV GL 2017b, c, 2018a) and Brynolf (2014).

There have been a few transitions, over the history as seen in Figure 7-3. The merchant world fleet gradually shifted from sail to a full engine powered fleet from about 1870 to 1940. Steamships burning coal dominated up to 1920, and since then coal has gradually been replaced by marine oils, due to the shift to diesel engines and oil-fired steam boilers. The transition from coal to oil fuel as the preferred maritime fuel occurred in the period 1914-1935. It took about 20 years before internal combustion (diesel) engines reached a 20% share of the fleet. This contrasts with the 6 years required for oil to get a 20% share of the fuel market (Fletcher, 1997). The shift to modern marine diesel engines has been a slow process taking more than 100 years. In 1961 there were still over 10 000 steam engine powered ships and 3 536 steam turbine powered ships in operation (36% by number), (LR, 1961). This indicates that switching fuels on existing hardware, can be achieved more swiftly than the implementation of new hardware (main engines). Also, the switch to motor ships occurred first within the smaller segments in the fleet.
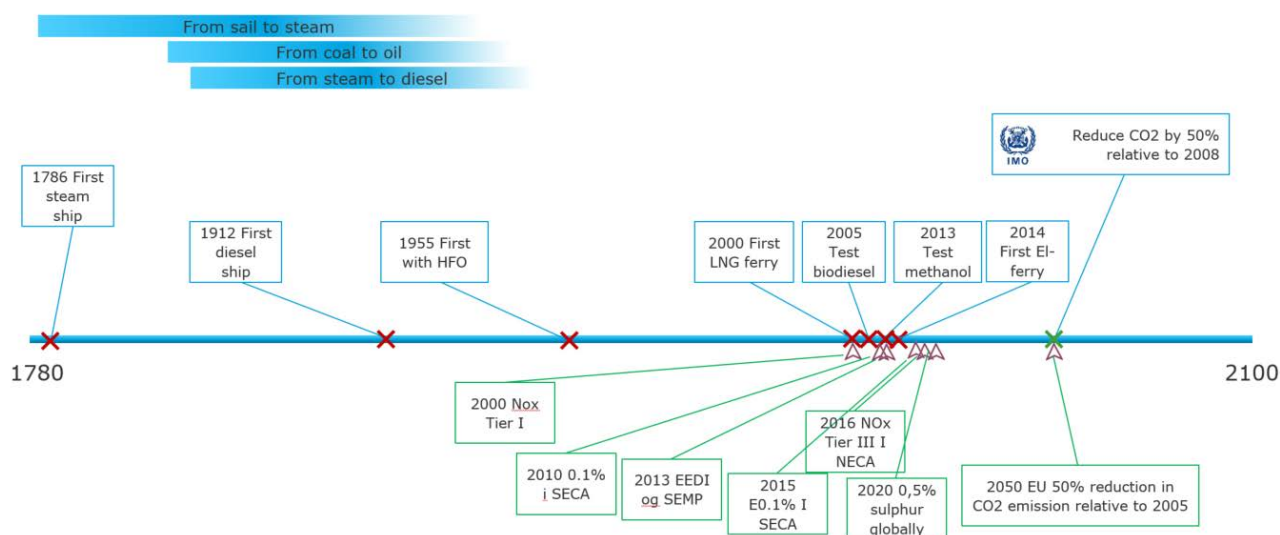
Figure 7-3 - Overview of major transitions and environmental regulations (Brynolf, 2014)

The main drivers leading to the advent of alternative fuels in the future will be economical motivated as in the past, but environmental and GHG regulations will impact shipping significantly the next decades. While environmental regulations (SOx, NOx and PM) will impact shipping most significantly in the short term, we expect regulation of GHG to be the main challenge in the medium to long term. It will no longer be possible to assume a "stationary" regulatory and technology landscape for the lifetime of a ship. An important additional driver for the Arctic will be the potential HFO ban.
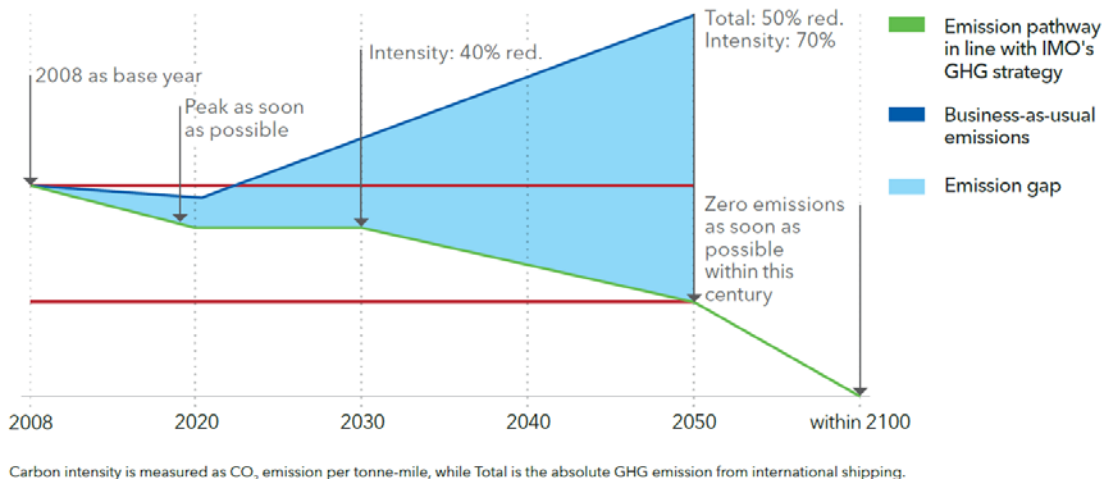
In April 2018, the IMO adopted a strategy to achieve major emission reductions in shipping. Figure 7-4 shows a "business as usual" scenario for GHG emission from the world fleet towards 2050 (blue line) – and the emission pathway needed to fulfill the strategy. Taking 2008 as a baseline year, the strategy aims to reduce total GHG emissions from shipping by at least 50% by 2050. Also, the strategy aims to reduce the average carbon intensity (CO_2 per tonne-mile) by at least 40% by 2030 while aiming for 70% in 2050. The IMO's ultimate vision is to phase out GHG emissions as soon as possible within this century. This will require introduction of alternative low carbon fuels in shipping.

It is plausible to assume that the price of oil — and other fuels - will significantly influence future trends of shipping as we have seen in the past. In addition to fuel prices, a strict future CO_2 regime will drive introduction of low emission technology and fuels. A ship is normally designed and optimized for a given fuel, or two types of fuels (e.g. operating inside and outside ECA). It will normally operate over its lifetime, say 20-30 years, on the chosen fuel and propulsion system. As fuel cost often represents around 50-60% of the total operating cost, the key question is then what fuels and technologies will make the ship competitive and profitable on short and long term (20-30 years)? Also, will the ship be attractive on the second hand marked, and will it be able to operate in different geographical regions, including the Arctic, having access to necessary bunkering infrastructure?

To help navigate this future, and manage the uncertainty, DNV GL has developed the Carbon Robustness framework to assist ship-owners in "future proofing" their vessels to secure long-term competitiveness and profitability. The framework test competitiveness for individual designs under different scenarios. For more details, consider DNV GL (2018a).

Figure 7-4 - Illustration of the IMO GHG strategy. In April 2018, the IMO adopted a strategy to achieve major emission reductions in shipping (DNV GL, 2018a)

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APPENDIX A
Fuel selection data

Fuel selection criteria – with explanations, environmental performance – air emission

Table 1A under encompass all the selection criteria providing the basis for this assessment. For each criterion, also the weighting factors used for the short and deep-sea scenarios are also displayed illustrating the difference between the priorities. Note that a time frame of 5 to 10 years provides the basis for the assessment.

Table 1A – Weighting factors used for short- and deep-sea in the Arctic

Air emission			Weighting factor Short-Sea	Weighting factor Deep-Sea
	C1	**GHG**: Incorporates long-lived climate forcing, i.e. CO2, N2O etc.	3	3
	C2	**Short-lived climate pollutants**: Incorporates gases and particles that contribute to warming and that have a lifetime of a few days to approximately 10 years. This includes black carbon (BC), tropospheric ozone (O3) and its precursors CO, nmVOC and NOx, methane (CH4), and some hydrofluorocarbons (HFCs).	9	9
	C3	**NOx-emission**: Incorporates air pollution and nitrate deposition from NOx emissions. NOx-emission closely linked to the combustion temperature and engine efficiency, causing health problems, eutrophication, and acidification of vulnerable ecosystems (environmental impacts). NOx emissions will also affect pollution levels, especially through enhanced surface ozone formation. Ozone is also an important greenhouse gas.	3	3
	C4	**SOx-emission**: Incorporates air pollution and sulphate deposition from Sox, causing health problems, acidification in vulnerable ecosystems (environmental impacts). Through chemical reactions in the air, SO2 into fine sulphate particles. Tiny airborne particles are linked to health problems and premature deaths. The amount of SOx in the exhaust gas from an engine is directly proportional with the sulphur level in the fuel burned.	3	3
	C5	**PM-emission**: PM missions that cause harm to human health, with focus on the small sized particles (<2,5 nm). The formation of particulate matters (PM) are closely linked to fuel type and quality, the sulphur content and the operational load of the engine.	3	3
Accidental bunker spill				
	C6	**Toxicity effects of water-soluble components (water column)**: Toxicity effects of the WAF (Water accommodated fraction). Components that have some solubility in water will migrate from the oil phase to the water phase. Knowledge of the toxicity of an oil (or alternative fuels) is of importance for the evaluation of response operations, and estimations of the negative effects on the environment resulting from an acute spill situation (Sintef, 2017).	9	9

	C7	**Environmental damage potential (surface, water column, shore line)**: The environmental damage potential is reflected by the spreading, transport and fate of a spill (for reaching/overlaying valuable marine resources). It is recognized that the damage potential depends on factor such as type of fuel, weathering, spill volumes, location (resources, distance to shore/ice edge), spill season, response effectiveness (ice condition), etc.	9	9
	C8	**Response effectiveness:** Effectives of removal of oil (or alternative fuels) at sea by response options (mass budget). Incorporates potential response limitations (i.e. for mechanical, dispersion, burning) due to oil (or alternative fuels) properties/weathering under arctic conditions (e.g. ice conditions, low temperature, remoteness).	9	9
Economic				
Ship Economy				
	C9	**Investment cost for the ship (additional)**: Cost above baseline to use the given fuel, i.e. engine and fuel system cost or investment cost new vessel/retrofit.	3	3
	C10	**Compliance cost - cost of modification**: Given the fuel type there could be an additional cost relating to equipment needed to stay in compliance (e.g. scrubbers for Sox compliance; SCR for NOx compliance).	3	3
	C11	**Fuel cost**: Projected fuel cost.	3	3
	C12	**Operational cost for the ship (crew, maintenance etc)**: Captures potential: higher maintenance cost, fuel consumption penalty, boil off, less efficiency, Commercial implications/losses, e.g. reduced cargo capacity, including also reduced range between bunkering, and potential increased waiting time in port, Savings of port charges (e.g. ESI, CSI), Other indirect costs, such as safety related (approval, insurance) cost training, etc.	3	3
Scalability				
Technical – Scalability				
	C15	**Safety - Need for new/additional safety measure to obtain equivalent safety (compared to existing solutions today)?** For fuels associated with high risk, it may be challenging to reach an equivalent safety level within the constraints of traditional ship design. Relevant safety aspects included are buoyancy, auto-ignition point, flammability range, and toxicity (e.g. Zincir, 2018; Månsson 2017). The level of risk reduction needed to reach equivalence may lie in measures that significantly alter the ship design, such as tank location with regards to likely zones for collision and grounding, or hazardous zones due to ventilation opening (DNV GL 2014).	9	9
	C16	**Technical maturity**: Technical maturity level for the fuel and converter technology, i.e. R&D stage - testing on land, large scale demonstration - widely used (international rules and regulations about the fuel are in force by IMO, and class societies).	3	3
	C17	**Energy efficiency** – including converter – What is the system efficiency one can	3	3

		expect given the fuel/converter of choice.		
	C18	**System complexity** - Does the fuel choice introduce requirements for extra system complexity in order to maintain acceptable safety and flexibility of operation.	3	3
Applicability – Scalability				
	C19	**Adaptability, existing ships** – Is the fuel/converter technology easy to adapt to existing ships operating in the region?	3	3
	C20	**Power and energy limits** - Has the fuel/converter practical application limitations wrt. power and energy limits?	**3**	**9**
	C21	**Compatibility with existing infrastructure** – Does the fuel require a dedicated infrastructure or is it possible to continue using existing?	**1**	**9**
Availibility – Scalability				
	C22	**Availability of fuel** - Refer to today's availability of the fuel, future production plans and long-term availability (global reserve).	**1**	**9**
	C24	**Reliable and sustainable supply of fuel** - Reliable and sustainable production chain, affected by factors such as limited raw-material (few suppliers), limited land, nor limited assimilation capacity of emissions (Månsson 2017), vulnerable value chain.	**3**	**9**

As seen Table A1 above, only when considering availability and scalability the weighting factors are different. This is due to the fact that environmental issues are equally important for the deep-sea segment as for short-sea. The same applies to economy whereas for applicability and availability, this will be considered differently for the two ship segments. Generally, it will be easier/possible to upgrade/renew the infrastructure within a region than world-wide.

Table A2 – Individual scores for all fuel/converter alternatives and criteria (1 = least favourable, 6 = best option).

	HFO/CE	Diesel&MGO/ CE/BE	Low Sulphure Hybrid/CE	Low Sulp Hybrid Arctic/CE	Bio Diesel(HVO)/C E	Bio-gas/CE/BE	LNG/CE/BE	Full electric/BE	Methanol/FC/ BE	Hydrogen/FC/ BE	Ammonia/FC/ BE
Emission to air											
GHG	1	1	1	1	4	5	4	6	3	6	6
Short-lived climate pollutants	1	3	2	2	4	5	5	6	6	6	6
NOx emission	1	1	1	1	2	5	5	6	6	6	6
SOx emission	1	4	4	4	6	6	6	6	6	6	6
PM emission	1	3	2	2	5	6	6	6	6	6	6
Accidental bunker spills											
Toxicity effects of water soluble components (water column)	1	3	1	4	4	6	6	6	4	6	6
Environmental damage potential (surface, water column, shore line)	2	4	1	4	4	6	6	6	6	6	6
Response effectiveness (if requeired)	2	1	2	2	5	6	6	6	6	6	6
Economic											
Investment cost for the ship (additional cost)	6	6	6	6	6	2	2	1	2	1	1
Compliance cost - cost of modification	1	3	3	3	3	6	5	6	6	6	6
Fuel cost	6	3	4	3	3	2	4	3	2	1	1
Operational cost for the ship (crew, maintenance etc)	5	5	5	5	5	4	4	5	3	1	1
Technical scaleability											
Safety	5	6	5	5	6	3	3	2	6	1	1
Technical maturity	6	6	6	6	5	5	5	2	2	1	1
Energy efficiency - including converter	3	3	3	3	3	4	4	6	2	1	1
System complexity and maintainibility	5	5	5	5	6	3	3	5	3	1	1
Applicability scaleability											
Adaptability - existing ships	6	6	6	6	6	2	2	3	3	1	1
Power and energy limits	6	6	6	6	6	5	5	1	3	2	3
Compatibility to existing infrastructure	6	6	6	6	6	4	4	1	5	1	1
Availibility scaleability											
Global availability of fuel	6	6	6	3	2	1	5	3	3	1	1
Available infrastructure	6	6	6	6	6	1	4	1	4	1	1
Reliable and sustainable supply of fuel	6	6	6	6	3	1	5	1	3	2	2

Poor-1 Good-6

APPENDIX B

Exhaust after-treatment

To reduce emissions from marine engines, the measures can either be initiated before start of the combustion process, during the combustion or after as treatment of the exhaust gas. The most ideal reduction method depends on which component that is to be controlled.

For instance, SO_X can easily be controlled before the combustion process by removal of sulphur in the fuel, while NO_X can be controlled during the combustion process. After treatment is also an option for both components. Some of the reduction methods can have negative or positive effects on other exhaust gas components. The measures using combustion modifications or after-treatment to reduce the emissions in general comes with a fuel penalty.

The amount of CO_2 and SO_X in the exhaust gas from an engine is directly proportional with the carbon and sulphur level in the fuel burned. Reduction of CO_2 and SO_X emissions can be achieved by an engine efficiency increase, or through a change to alternative fuels with lower carbon and sulphur contents (e.g. LNG). A short outline on relevant reduction measures are given below, and for more details consider e.g. DNV GL (2015c), Danish Environmental Protection Agency (2012), and Leinonen (2016). The below section builds on DNV GL (2018c).

SOx reduction measures

Exhaust gas scrubbers is a well-known and a commonly used method for reducing the SOx emissions from a ship. Worldwide, there are 2471 scrubbers in operation and operation at the end of 2018 (AFI portal). Bulk ships have the highest uptake of scrubbers. By 2020, different projections report between 3,200 to 4,400 scrubbers in service.[46]

In a scrubber, the exhaust gas from main- and auxiliary engines and boilers are cleaned by using sea water or chemically treated fresh water as a scrubbing agent. Additionally, there exist other scrubber technologies applying dry substances such as limestone. By using the exhaust gas scrubber technology, the ship can continue using high sulphur fuels, which is well-known and typically comes at an attractive price. In sulphur regulated areas, scrubbers are an attractive solution avoiding use of costly low sulphur heavy fuels or distillates.

Wet scrubbers are divided between open loop and closed loop systems or as a hybrid system which allows for running in closed loop mode for a given time. In an open loop system sulphur is released to the sea in the scrubber waste water. There are local regulations prohibiting discharges of waste water from scrubbers (open loop systems). The use of scrubbers comes typically with a fuel penalty of up to 2%, costs for chemicals and extra maintenance.

NOx reduction measures

Several methods which separately or combined reduce the NO_X emission from marine engines are available (DNV GL, 2015c). The methods are mostly based on changing the combustion temperature or by performing after treatment of the exhaust gas. Selective catalytic reduction (SCR) is the most commonly used method for removal of NO_X in the exhaust gas. The SCR method use a catalyst and a reductant, typically urea or NH_3 (ammonia), to chemically reduce NOx to nitrogen gas (N_2) and water vapour (H_2O).

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[46] https://www.bunkerspot.com/global/43344-global-2020-scrubbing-will-the-lowest-cost-route-to-compliance-says-consultant

The total number of SCR installations in the world fleet prior 2013 was 519 (Makoveyenko, 2015). Over half of the ships with SCR installations are cargo ships. Data from the NOx fund[47] shows that ships operating in Norwegian waters dominates, accounting for more than 30% of the SCR installations worldwide. Applying this relationship and recent NOx fund data (2014-2017), the SCR installations today is estimated to be around 670.[48]

Another emerging NOx reduction measure is exhaust gas re-circulation (EGR), which can reduce the NOx emission significantly. EGR involves circulating a controllable proportion of the engine's exhaust back into the intake air, which reduce the formation of NOx in the combustion process. The EGR system reduces available oxygen in the cylinder and it is observed the production of particulates may increase.

Addition of water to the combustion process will also reduce the formation of NO_x in the combustion process. There are several ways of adding water to the combustion process, like fuel-water emulsions, humid air systems or direct water injections.

LNG as alternative fuel reduce the NOx emissions significantly.

PM reduction measures

The formation of particulate matters (PM) are closely linked to fuel type and quality, the sulphur content and the operational load of the engine (ICCT, 2017a). Technical measures which reduces particulate emissions are few. However, it is known that the alternative fuels, like LNG and low sulphur fuels, reduce the PM emissions significantly.

For road engines, a series of filter solutions have been developed, providing more than 90% reduction in PM emissions. These filters may also be tuned to reduce around 90% of CO and Hydrocarbon (HC) emission from diesel engines. For maritime engines, such filters have not proven to be practicable due to the large amount of ash emission from the fuel and lubrication oil, and the consequent clogging of the filters. However, the development is on-going and tests have indicated reduction potentials in the region of 60-90% (Jacobs, 2014) [49]. This is counterbalanced by a small penalty on energy consumption due to increased back-pressure from the filters. There are also other challenges reported such as space requirements and cleaning/maintenance needs (Danish Environmental Protection Agency 2012; Leinonen, 2016). An overview of use of diesel filters in the maritime sector has recently been reported.[50] Measures initiated primarily to reduce SOx typically also reduce PM emissions.

It should be noted that recent studies have reported issues related to the particle distribution, where smaller particle distribution is a concern (e.g. Zetterdahl 2016; Zhou et al 2017).

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[47] The NOx Fund gives support to NOx reducing measures: https://www.nho.no/Prosjekter-og-programmer/NOx-fondet/The-NOx-fund/

[48] The NOx Fund gives support to NOx reducing measures: https://www.nho.no/Prosjekter-og-programmer/NOx-fondet/The-NOx-fund/

[49] https://en.nabu.de/imperia/md/content/nabude/verkehr/1602-info_heincke_measurements_en.pdf

[50] http://www.theicct.org/sites/default/files/12-Diesel%20Particulate%20Filters%20for%20PM%20Control%20from%20Marine%20Engines%20-%20Mike%20Geller%2C%20MECA.pdf

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