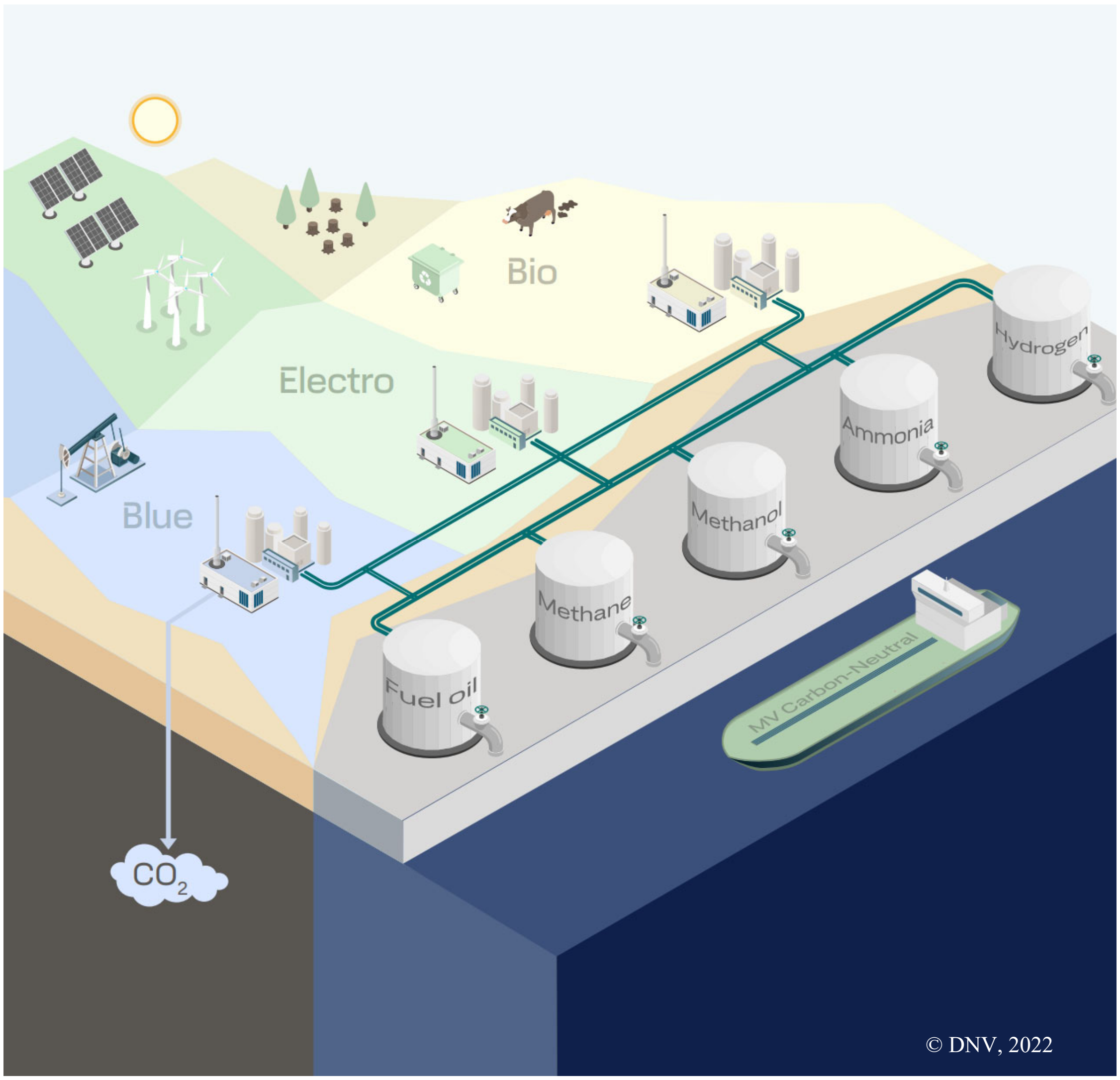
Nordic Roadmap

Future Fuels for Shipping



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Foreword

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

To support this overall aim, Chalmers and IVL Swedish Environmental Research Institute is responsible for life cycle assessment of potential zero-carbon fuels in the Nordic context and has prepared this report. DNV has contributed with AIS data for average ship types and by reviewing the report, MAN Energy Solutions and MENON have contributed by reviewing the report.

Nordic Roadmap Publication No.1-C/1.1/2023 is a second version with updated result figures and tables.

28 April 2023

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Life Cycle Assessment of Marine Fuels in the Nordic Region – Task 1C (version 1.1)

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

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Gothenburg, Sweden, April 2023

Life Cycle Assessment of Marine Fuels in the Nordic Region
ROADMAP FOR THE INTRODUCTION OF SUSTAINABLE ZERO-CARBON FUELS IN THE NORDIC REGION

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Executive summary

To solve the climate challenge requires a transition to the use of fuels associated with zero or very low greenhouse gas (GHG) emissions throughout their life cycle, in all sectors. The Nordic countries are at the forefront of this transition. DNV with partners Menon, Chalmers, IVL Swedish Environmental Research Institute, MAN Energy Solutions, and Litehauz has been assigned by The Norwegian Ministry of Climate and Environment on behalf of the Nordic Council of Ministers the Nordic roadmap for introduction of sustainable zero-carbon fuels in shipping project [1]. The project has an overall aim "to reduce key barriers to implementation and establish a common roadmap for the whole Nordic region and logistics ecosystem towards zero emission shipping".

There are several marine fuels and propulsion systems that can be used in Nordic shipping in 2030 including methanol, hydrogen, and ammonia (which are in focus in the overall project). The fuels and relevant propulsion systems are associated with different maturity levels and their applicability for different ship types varies. What is then the potential for different marine fuels (in various propulsion systems) to reach low or zero GHG emissions in a life cycle perspective? And how do they perform in terms of other environmental impacts (are there any potential trade-offs)? The aim of this report is to assess the impact on the climate and the environment of selected potential zero-carbon fuels for marine use, using prospective life cycle assessment (LCA). The assessed fuels include hydrogen, ammonia, and methanol, as well as methane, electricity in batteries, marine gas oil and liquefied natural gas for comparison. The focus is on GHG emissions and climate impact, but acidification and particulate matter formation potential are also reported. In addition, a screening of several other environmental impact categories is included, to indicate possible impact on environmental sustainability.

As propulsion options, the study include internal combustion engines (2- and 4-strokes), fuel cell technologies (proton-exchange membrane fuel cells and solid oxide fuel cells) and a battery-electric option. The engines considered in this study are in different stages of development, from a diesel engine that has been on the market for decades to hydrogen and ammonia engines that need to be tested for marine application. The included fuel and propulsion options assessed are described in Table A. LCAs are also made for some average ship's representative for Nordic shipping within the ship categories Ro-Pax, chemical tanker and general cargo. The technical system boundaries include fuel production and its infrastructure, transport of the fuel to site of use, the use of the fuel onboard and, in case of the average ship LCAs, the construction of the propulsion system. The ship hull, deck, propeller, accommodation areas and other technical systems are not included in the assessment.

The LCAs of average ships show how the operational pattern of ships can influence their environmental performance, but it does not replace the need for detailed ship specific LCAs where the ship design is an integrated part. Such detailed ship specific LCAs must be performed as separate studies as they, to some extent, will have different goal and scope, and should use specific data that differ depending on for example geographical scope, timeline, and ship design.

The LCAs in this report mainly focus on ship operation in the near future, around 2030, but with an outlook to 2050. It is based on information collected from experts in the consortia, from suppliers and from literature and databases representing the estimated potential performance in 2030 (and the potential changes of selected key factors by 2050). However, which should be stressed, as several of the studied fuel and powertrain options are in the development phase, their actual climate and environmental performance in 2030 (and even more in 2050) are uncertain which is due to the lack of knowledge around e.g., emissions of GHGs and air pollutants. This knowledge will improve further as

[1] https://futurefuelsnordic.com/partners-and-contributors/

the fuel and propulsion options are further developed, tested, and monitored. Thus, LCAs need to be updated when new data is available, but the ones presented here represent the future potential situation.

There are a range of earlier LCA studies of marine fuels. However, very few of them include all the fuel and propulsion pathways included in this study, nor do they present the climate impact in such a way that it can easily be compared with other studies.

As expected, a comparative assessment of other LCA studies (performed as part of this report) indicates that, for hydrogen and ammonia, grey pathways have higher impacts than blue, which in turn have higher impacts than green pathways. However, it is not possible to make more firm conclusions on the quantitative comparison based on earlier studies. This clearly highlights the need for a LCA comparing several marine fuel fuels and propulsion pathways in a similar way (as done in this study) to be able to compare the climate impacts.

In addition, there are some methodological choices that may influence the results, i.e., if and to what extent the environmental impact of the production of the propulsion system and infrastructure for producing the fuels are included, and which electricity mix is assumed (an estimated future Nordic electric mix is used in this study). Globally, there is work ongoing to develop and agree on a life cycle methodology for calculating GHG emissions associated with marine fuels. The reason is that there is a need for a common basis for regulations and policies that are under development, for example within the International Maritime Organization (IMO) and in the EU. However, not all details have been settled yet. The approach used in this report is compared to the approach discussed in the IMO.

In short, the IMO guidelines being developed mainly focus on GHG emissions and a GWP100 perspective whereas this study also considers a range of other environmental impact categories and also a GWP20 perspective (only GWP100 is however presented in this summary). The draft IMO guidelines (document ISWG-GHG 11/2/3) only consider the fuel life cycle (with unclear system boundaries in terms of infrastructure for producing the fuels) and not the impacts from producing the propulsion system, which is included in the average ship specific LCAs in our study to give a more comprehensive picture. The approach for handling the carbon source for the production of electrofuels (in this study e-methanol and e-methane) also seems to differ somewhat between the draft guidelines and this study. However, it is at present unclear how that impacts the results.

Table A Overview of the combined fuel production pathways and ship propulsion options included for each energy carrier in the assessment. Thus, the different fuel production pathways are combined with the relevant possible propulsion options considered. In total 32 options are investigated in this report.

	Fossil fuel production pathways without carbon capture	**Blue fuel production pathways**	**Green fuel production pathways**		**Main propulsion options considered[a]**							**Total # of combinations considered**
		Steam reforming of natural gas with carbon capture and storage (NGccs-)	Biomass (bio-)	Nordic electricity mix (e-)	2-stroke engines (2S ICE)	2-stroke dual-fuel engines (2S-DF ICE)	4-stroke engines (4S ICE)	4-stroke dual-fuel engines (4S-DF ICE)	Proton-exchange membrane fuel cells (PEMFC)	Solid oxide fuel cells (SOFC)	Battery electric (Elec BE)	
Ammonia (NH_3)[c]		Yes		Yes		Yes		Yes		Yes		6
Compressed hydrogen (CH_2)[c]		Yes		Yes		Yes		Yes	Yes			6
Liquid hydrogen (LH_2)[c]		Yes		Yes		Yes		Yes	Yes			6
Methanol (MeOH)[c]			Yes	Yes		Yes		Yes		Yes		6
Liquid methane gas (LMG)[c]			[b]	Yes		Yes		Yes		Yes		3
Electricity				Yes							Yes	1
Liquid natural gas (LNG)	As reference					Yes		Yes				2
Marine gas oil (MGO)	As reference				Yes		Yes					2

[a]SOFC and PEM fuel cell (FC) propulsion systems also includes batteries to manage load changes.

[b]Biomass-based pathways are only considered for the relevant fuels in focus in the Nordic roadmap project (mainly assessing ammonia, hydrogen, and methanol), and thus not for LMG. For assessments of renewable methane from anaerobic digestion and biomass gasification see for example Jivén et al. [1].

[c]Hydrotreated vegetable oil (HVO) is assumed to be used as pilot fuel for the alternative to use only potential zero-carbon in the operational phase.

Estimates of life cycle climate impact of 32 different fuel and propulsion system options in a 2030 perspective in terms of global warming potential, based on the LCAs in this report, are shown in Figure A. The figure illustrates the total climate impact in a well-to-wake perspective (from acquisition of raw material to onboard use of fuel for transport) and the contribution from different phases (the construction of the propulsion system is not included here). Compared to the traditional fuels used in shipping, as marine gas oil and liquefied natural gas, all options could reduce GHG emissions by 2030 (Figure A). The green fuel production pathways (from biomass or Nordic electricity mix) are associated with lower GHG emissions compared to the corresponding blue fuel production pathways (from natural gas with carbon capture and storage). There is a better performance in terms of climate impact of the fuel cells compared to the 2-stroke ICE pathways, which in turn performs better than the corresponding 4-stroke engine pathway, which is due to differences in efficiency of the propulsion options. Fuel cells and engines are under development and their performance may change more than assumed in this report.

In the 2030 perspective, the biomass-based methanol options and the battery electric options show the lowest climate impact followed by the different green hydrogen options and green ammonia in fuel cells. Also, the rest of the green options, with the exception of electro-methane in 4-stroke engines, show lower climate impact than the blue pathways. For ammonia and hydrogen pathways fuel production contributes, as expected, to the dominating share of the climate impact. The negative climate impact from the production phase of the green fuels that contain carbon comes from that carbon is captured as part of the carbon cycle. Methane-based fuels are associated with leakages of methane (CH_4) during production, distribution and use in marine engines; this contributes significantly to the climate impact and can hopefully be reduced further in the future if relevant regulations are in place.

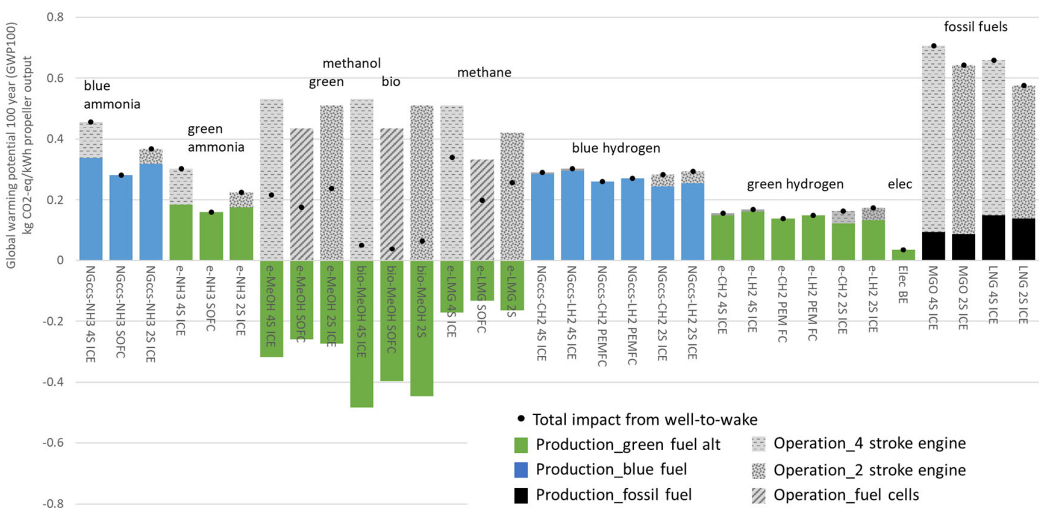

Figure A Estimates of life cycle climate impact in a 100 year time perspective for 32 potential zero-carbon marine fuels in 2030 compared to 4 fossil fuel alternatives illustrating the contribution from two different phases (fuel production including transport and distribution, and ship operation). ***The black points show the total climate impact from well-to-wake****. See Table A (and appendix A) for description of the propulsion system options. NGccs - steam reforming of natural gas with carbon capture and storage, NH3 - ammonia, 4S – 4-stroke engine, 2S – 2-stroke engine, ICE – internal combustion engine, SOFC - solid oxide fuel cell, e-NH3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass based methanol, e-LMG – electro-methane, CH2 – compressed hydrogen, LH2 – liquefied hydrogen, PEMFC – Proton-exchange membrane fuel cell, Elec-BE – Battery Electric, MGO – marine gas oil, LNG – liquefied natural gas.*

Ammonia-based propulsion systems have challenges with emissions of nitrous oxides (N_2O) when used in marine engines (in this study estimated to correspond to about 60-85% of the operation related emissions of GHGs, as GWP100, of the studied ammonia ICE pathways based on what is considered relevant for the 2030 case). However, the N_2O emission from marine ammonia engines when they are used onboard ships is still largely unknown and engine manufacturers will work on reducing these emissions. It should be noted that the emission levels assumed in this report are lower than preliminary test engine data and, thus, we assume that further emission reduction will be in place in 2030 and 2050 in the present analysis. The use of ammonia in fuel cells is still an unmature pathway and it is difficult to know the future performance.

The climate impact of the assessed pathways may be reduced by (i) an increased share of renewable energy in the assumed electricity mix (in particular the green fuel production pathways), (ii) solid-oxide electrolysers used for hydrogen production instead of alkaline electrolysers, (iii) reduced impact from production of materials, (iv) renewable urea instead of natural gas-based urea (v) lower assumed emissions of N_2O and CH_4 for the ammonia and methane cases. The potential impact of such changes is illustrated in the 2050 outlook presented in Figure B, where the impact of reducing N_2O and CH_4 emissions is indicated separately (the short black line under the relevant dots). The results indicate that it might be possible to considerably reduce the GHG emissions from all the green fuel pathways assessed in the mid to long term. It is possible to reduce fuel related emissions of CH_4 and N_2O but with a cost. For fuels such as ammonia and methane to become a low or zero carbon fuel with low climate impact, policies that regulate several GHGs including CH_4 and N_2O are needed. The required reduction in GHG emissions linked to these fuels will likely not materialize without such policies and regulations.

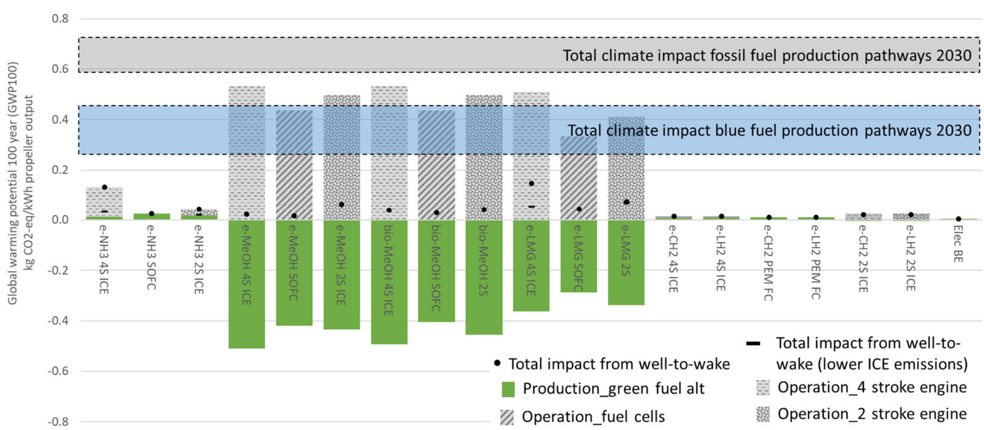

*Figure B Estimates of life cycle climate impact in a 100-year time perspective for potential zero-carbon marine fuels in 2050, illustrating the contribution from different phases (fuel production, ship operation and manufacturing of propulsion system). **The black points show the total climate impact and the short black line the total climate impact in case of lower emissions of methane and nitrous oxides in ICE from ammonia and methane.** NH3 - ammonia, 4S – 4-stroke engine, 2S – 2-stroke engine, ICE – internal combustion engine, SOFC - solid oxide fuel cell, e-NH3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass based methanol, e-LMG – electro-methane, CH2 – compressed hydrogen, LH2 – liquefied hydrogen, PEMFC – Proton-exchange membrane fuel cell, Elec-BE – Battery Electric. For full description of the assessed pathways see Table A and Appendix A.*

The climate impact of also including the production of the propulsion system and a vessel's use of energy in port is illustrated in the ship specific LCAs made for six average vessels, using operational patterns extracted from AIS data (from Task 2A in this project that includes an AIS analysis of the Nordic ship traffic and energy use), see Figure C. Some fuel-propulsion combinations (e.g., battery electric, compressed hydrogen, or liquid hydrogen in internal combustion engines) are not feasible for all assessed average ships. The difference in results between different ship types depends mainly on different use of auxiliary engines and different operational patterns. With the feasibility criteria applied in this report the propulsion system is not contributing largely to the overall environmental impact; this could however possibly be the case in the future if ships with significantly larger batteries are introduced.

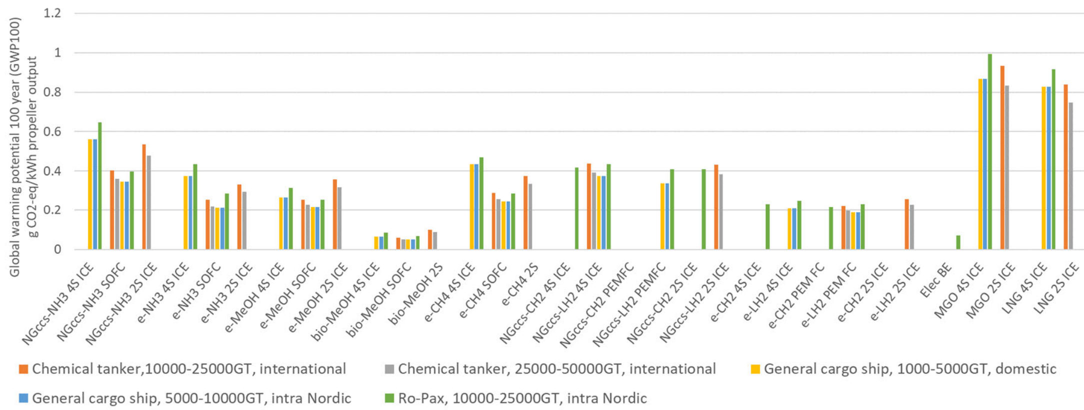

Figure C Overview of global warming potential (in kg CO_2-eq.) in a 100-year time perspective for the investigated potential zero-carbon fuels in Nordic shipping in 2030 for 1 kWh propeller output. The global warming potential includes fuel/energy carrier production including distribution and transport, use of shore-power in port, operation onboard the ship, manufacturing and replacement of the ship propulsion system. NGccs - steam reforming of natural gas with carbon capture and storage, NH3 - ammonia, 4S – 4-stroke engine, 2S – 2-stroke engine, ICE – internal combustion engine, SOFC - solid oxide fuel cell, e-NH3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass based methanol, e-LMG – electro-methane, CH2 – compressed hydrogen, LH2 – liquefied hydrogen, PEMFC – Proton-exchange membrane fuel cell, Elec-BE – Battery Electric, MGO – marine gas oil, LNG – liquefied natural gas. For full description of the assessed pathways see Table A and Appendix A.

To summarize, it is possible to substantially reduce the GHG emission/climate impact by introducing the assessed fuel-propulsion options by 2030. It does not seem possible to reach completely zero carbon marine fuels by 2030 in a LCA perspective with the chosen approach and system boundaries. The electro-methane used in 4-stroke engines and natural gas-based ammonia in 4-stroke engines pathways need to reduce the emissions of CH_4 and N_2O even further than what is assumed in the 2030 perspective in order to reduce the climate impact substantially. It is possible to provide very low climate impact for most of the assessed pathways when/if the society transform to a low GHG society (around 2050) as it means that also steel, cement and electricity production will reach zero or close to zero carbon emissions.

There is a potential to decarbonize the shipping industry through changing fuels both in the short and long term. A change of fuel from conventional marine gas oil (MGO) is indicated to reduce some of the other environmental impacts (including acidification and particulate matter formation). However, the opposite is also possible for some impacts and fuels (including, e.g., eutrophication, human toxicity, and resource use). The results of the screening of other environmental impacts are illustrated in Figure D, which illustrates the relative impact of the assessed fuel pathways on the studied environmental impact categories compared to MGO (orange and red represent higher impact while green represent lower impact and yellow represent same or similar impact). There is an indication that some of the studied options could have significantly higher impact on eutrophication (mainly in freshwater), human toxicity, resource use, land use, and ionising radiation, compared with MGO.

Thus, with a fuel switch there is a risk for other sustainability challenges to arise that need to be considered. The potential impact on other environmental impacts of changing fuels needs to be assessed in more detail to understand to what extent the effects are problematic. This to ensure the introduction of sustainable low-carbon marine fuels. A way to reduce the risks is to consider a broad set of sustainability criteria when selecting fuels, when producing fuels and when forming policy and regulations, and not solely focus on the climate impact (nor, as already indicated, only CO_2 emissions). Further studies of the climate impact of ammonia and hydrogen pathways are also needed as knowledge about their performance in marine operations increase. Finally, the implementation of policies that besides CO_2 regulate CH_4 and N_2O emissions are called for.

	NGccs-NH3 4S ICE	NGccs-NH3 SOFC	NGccs-NH3 2S ICE	e-NH3 4S ICE	e-NH3 SOFC	e-NH3 2S ICE	e-MeOH 4S ICE	e-MeOH SOFC	e-MeOH 2S ICE	bio-MeOH 4S ICE	bio-MeOH SOFC	bio-MeOH 2S	e-CH4 4S ICE	e-CH4 SOFC	e-CH4 2S	NGccs-CH2 4S ICE	NGccs-LH2 4S ICE	NGccs-CH2 PEMFC	NGccs-LH2 PEMFC	NGccs-CH2 2S ICE	NGccs-LH2 2S ICE	e-CH2 4S ICE	e-LH2 4S ICE	e-CH2 PEM FC	e-LH2 PEM FC	e-CH2 2S ICE	e-LH2 2S ICE	Elec BE
Acidification	0.8	0.2	0.9	0.7	0.2	0.8	0.7	0.2	0.8	0.6	0.1	0.7	0.8	0.2	0.9	0.7	0.7	0.2	0.2	0.8	0.8	0.6	0.6	0.1	0.1	0.8	0.8	0.1
Ecotoxicity, freshwater	0.9	0.7	1	1.9	1.5	1.9	2	1.7	1.9	0.2	0.2	0.3	2.2	1.7	2.2	0.5	0.6	0.4	0.5	0.5	0.6	1.2	1.3	1.1	1.2	1.3	1.3	0.2
Ecotoxicity, freshwater - inorganics	0.3	0.2	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.1	0.1	0.1	0.3	0.2	0.3	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0
Ecotoxicity, freshwater - metals	1.5	1.2	1.6	3.2	2.5	3.3	3.4	2.8	3.2	0.4	0.3	0.4	3.6	2.9	3.7	0.8	0.9	0.7	0.8	0.8	0.9	2.1	2.2	1.9	2	2.2	2.3	0.3
Ecotoxicity, freshwater - organics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eutrophication, freshwater	4.5	3.6	5.6	5.8	4.6	7.2	3.4	2.8	4	1.2	1	1.7	4.4	3.6	5.6	1.4	1.5	1.3	1.4	1.9	2.1	2.4	2.6	2.2	2.3	3.1	3.3	1.1
Eutrophication, marine	1.1	0.2	1.1	1.1	0.2	1.1	1.1	0.2	1	1	0.1	1	1.1	0.2	1.1	1	1.1	0.2	0.2	1	1	1	1	0.1	0.2	1	1	0
Eutrophication, terrestrial	1.1	0.2	1.1	1.1	0.2	1.1	1.1	0.3	1.1	1	0.1	1	1.1	0.3	1.1	1	1	0.2	0.2	1	1	1	1	0.1	0.2	1	1	0
Human toxicity, cancer	3.7	2.9	4.1	4.6	3.6	5.2	3.1	2.5	3.1	2.3	1.8	2.5	5.9	4.7	6.4	1.5	1.7	1.3	1.5	1.7	1.9	2.2	2.4	2	2.2	2.5	2.7	0.6
Human toxicity, cancer - metals	4.3	3.4	4.8	5.1	4	5.7	2.9	2.4	3.1	2.7	2.3	3.1	5.3	4.3	5.9	1.6	1.8	1.4	1.6	1.8	2.1	2.2	2.4	2	2.2	2.5	2.8	0.7
Human toxicity, non-cancer	2	1.6	2.2	3.6	2.8	3.9	2.9	2.4	2.9	0.8	0.6	0.8	3.2	2.5	3.4	0.8	0.9	0.7	0.8	0.9	1	2.1	2.2	1.8	2	2.2	2.4	0.7
Human toxicity, non-cancer - inorganics	0.8	0.6	0.8	1.7	1.3	1.8	1.8	1.5	1.7	0.2	0.2	0.2	2.3	1.9	2.4	0.5	0.6	0.5	0.5	0.5	0.6	1.3	1.4	1.2	1.2	1.3	1.4	1.1
Human toxicity, non-cancer - metals	2.6	2	2.8	4.5	3.5	4.9	3.3	2.8	3.4	0.9	0.8	1.1	3.6	2.9	3.9	0.9	1.1	0.8	1	1	1.2	2.4	2.6	2.2	2.4	2.6	2.8	0.6
Human toxicity, non-cancer - organics	3	2	4.6	2.1	1.3	3.1	1.3	0.4	0.9	1.4	0.5	1.2	1.3	0.4	1	1.2	1.2	1	1	2	2	0.4	0.5	0.3	0.3	0.7	0.7	0.2
Ionising radiation	1	0.8	1.1	9.7	7.6	9.9	10.9	9.1	10	0.6	0.5	0.6	10.9	8.8	10.8	0.9	1.4	0.8	1.3	0.9	1.4	8	8.6	7.2	7.8	7.9	8.5	3.2
Land use	1	0.8	1	7.1	5.6	7.2	7.8	6.5	7.2	1.3	1.1	1.3	7.8	6.3	7.8	0.7	1.1	0.6	1	0.7	1.1	5.7	6.1	5.2	5.5	5.7	6.1	0.1
Ozone depletion	0.7	0.6	0.7	0	0	0	0	0	0	0	0	0	0	0	0.1	0.6	0.6	0.5	0.5	0.6	0.6	0	0	0	0	0	0	0
Particulate matter	0.5	0.1	0.5	0.7	0.3	0.7	0.7	0.4	0.7	0.3	0.1	0.5	0.7	0.4	0.8	0.3	0.3	0.1	0.1	0.4	0.5	0.5	0.5	0.2	0.3	0.6	0.6	0.1
Photochemical ozone formation	1.1	0.2	1.1	1	0.1	1	1.1	0.2	1	1	0.1	0.9	1.1	0.2	1	0.9	0.9	0.2	0.2	1	1	0.8	0.8	0.1	0.1	0.9	0.9	0
Resource use, fossils	1.4	1.1	1.4	0.9	0.7	1	1	0.9	1	0.1	0.1	0.1	1	0.8	1.1	1.1	1.2	1	1.1	1.2	1.2	0.8	0.8	0.7	0.7	0.8	0.8	0.3
Resource use, minerals and metals	17	13.4	29.3	13.7	10.8	23.6	1.4	1.2	2.9	5.3	4.4	9.5	1.4	1.2	3.1	3.7	3.8	3.4	3.4	6.8	6.9	0.9	0.9	0.8	0.8	2.1	2.2	0.3
IPCC 2021 GWP 100	0.6	0.4	0.6	0.4	0.2	0.4	0.3	0.2	0.4	0.1	0.1	0.1	0.5	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.2	0.2	0.2	0.2	0.3	0.3	0
IPCC 2021 GWP 20	1	0.7	0.9	0.4	0.2	0.4	0.3	0.3	0.4	0.1	0.1	0.1	0.8	0.3	0.5	0.7	0.7	0.6	0.6	0.7	0.8	0.2	0.2	0.2	0.2	0.3	0.3	0.1

Figure D The relative impact of the assessed fuel options on the studied environmental impact categories compared to MGO in 4-stroke engines (MGO 4S) for all 4-stroke and fuel cell options and compared to MGO in 2-stroke engines (MGO 2S) for all 2-stroke engines. Green colour represents substantial decrease in impact compared to MGH, yellow represents same or almost the same impact as MGO, orange represents a clear increase in impact compared to MGO and red represents a considerable increase compared to MGO. NGccs - steam reforming of natural gas with carbon capture and storage, NH3 - ammonia, ICE – internal combustion engine, SOFC - solid oxide fuel cell, e-NH3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass based methanol, e-LMG – electro-methane, CH2 – compressed hydrogen, LH2 – liquefied hydrogen, PEMFC – Proton-exchange membrane fuel cell, Elec-BE – Battery Electric, MGO – marine gas oil, LNG – liquefied natural gas. For full description of the assessed pathways see Table A and Appendix A.

Contents

Nomenclature and terminology

The nomenclature and terminology chapter outlines the definitions and abbreviations as used in this report. However, the exact usage varies within the research community and industry.

Nomenclature

2S	Two-stroke/2-stroke
4S	Four-stroke/4-stroke
AE	Auxiliary engine
ASU	Air separation unit
CC	Carbon capture
CCS	Carbon capture and storage
CH2	Compressed hydrogen
DAC	Direct air capture
DME	Dimethyl ether
CF	Characterisation factor
DF	Dual fuel
e-	electro
FC	Fuel cells
FGCC	Flue gas carbon capture
GHG	Greenhouse gas
GT	Gross tonnage
GWP	Global warming potential
HFO	Heavy fuel oil
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
IMO	International Maritime Organization
LBG	Liquefied biogas
LCA	Life cycle assessment
LCI	Life cycle inventory
LH2	Liquid hydrogen
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MDO	Marine diesel oil
ME	Main engine
MEA	Monoethanolamine
MG	Methane gas
MGO	Marine gas oil
NG	Natural gas
NGccs	Steam reforming of natural gas with carbon capture and storage
NGOs	Non-governmental organizations
PEMFC	Proton-exchange membrane fuel cell
RME	Rapeseed methyl ester
SCR	Selective catalytic reduction
SOFC	Solid oxide fuel cell
VLSFO	Very low sulphur fuel oil
CO	Carbon monoxide
CO_2	Carbon dioxide
CH_4	Methane
NO_X	Nitrogen oxides
N_2O	Nitrous oxide
SO_X	Sulphur oxides
PM	Particulate matter

Terminology

Acidification	Acidification is typically associated with atmospheric pollution arising from anthropogenically derived sulphur (S) and nitrogen (N) as nitrogen oxides or ammonia. It is a common environmental impact indicator in life cycle assessment.
Allocation	The distribution of flows between multiple units.
Allocation problems	Allocation problems occur in an LCA when several products (or functions) share the same processes and the environmental loads of these processes need to be expressed in terms of a single product. Allocation can be achieved using, for example, a physical relationship or the monetary value of the products. Allocation is described here as one method for solving allocation problems. Thus, allocation methods include both allocation (also called partitioning) and system expansion.
Alternative fuels	Alternative fuels are fuels not commonly used in the shipping sector today i.e., fuels which takes up a small proportion of the current market, are not available commercially in ports or are only used on singular vessels.
Attributional LCA	An attributional LCA is one that strives to be as complete as possible by accounting for all environmental impacts of a product. This type addresses such questions as "What would be the overall environmental impact of marine transportation using Fuel A?"
Blue fuels	Fuels produced from natural gas with carbon capture and storage. In this report, it is hydrogen and ammonia which are assessed with blue production pathways.
Boil-off gas	Gas created by the surrounding heat input (while maintaining constant pressure during storage of a cryogenic liquid such as liquefied natural gas) is called boil-off gas. Boil-off gas is inherent to the storage of a cryogenic gas due to the heat input from the surroundings.
By-product	By-products can be defined as additional products, which occurs due to the main product. In some assessments, several by-products are viewed together acting as the main product of the system, and by-products are in most assessments attributed i.e., allocated, environmental burdens.
Characterization factors	Characterization factors are factors derived from a characterization model, which are applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator, e.g. global warming potential or acidification potential. This is done to assess the total impact on the category. There are characterization factors both at midpoints and endpoints.
Consequential LCA	A consequential LCA is one that compares the environmental consequences of alternative causes of actions and evaluates the effects of change on a surrounding system. This type addresses such questions as "What would be the environmental consequence of using Fuel A instead of Fuel B?"
Environmentally sustainable fuels	Fuels with low impact on a broad set of environmental impact categories which are not associated with significant negative impacts on the environment when used in large scale.
Electrofuels	Liquid or gaseous hydrogen-containing fuels produced by combining energy from electricity, hydrogen from water (via electrolysis), and carbon, or possibly nitrogen.
Elemental flows	Elemental flows are the flows between the environment and the technical system associated with each process in the system.
Endpoint	The endpoint is a point of interpretation of the aggregated emission flows. It represents the end in a cause-effect chain and may be of direct relevance to society's understanding of the final effect, such as measures of biodiversity change.
Eutrophication	Eutrophication is the increased availability of one or more limiting growth factors needed for photosynthesis leading to excessive plant and algal growth. Nitrogen and phosphorus are the most common growth-limiting nutrients.
Functional unit	A functional unit is a quantitative unit representing the function of the system. The use of a functional unit enables comparisons of various products that fulfil the same function.

Goal and scope	Goal and scope is the first step in an LCA. It describes the system under study and the purpose of the study. The goal should include, for example, the intended application and reasons for the study.
Green fuels	Fuels produced from mainly renewable electricity or biomass.
Human health	Human health is an area of protection. Damage to human health is measured by mortality and morbidity over space and time.
Impact assessment	Impact assessment is the third step in an LCA. It includes classification of the elemental flows into various impact categories and the characterization of these flows, e.g., the calculated relative contributions of the emissions and resource consumptions to the impact categories.
Inventory analysis	Inventory analysis is the second step in an LCA. It consists of three parts: the construction of a flow model based on the system boundaries, the data collection and the calculation of resource use and emissions of the system in relation to the functional unit.
Life cycle inventory	The phase of LCA involving the compilation and analysis quantification of inputs and outputs for a product throughout its life cycle.
Methane slip	Methane slip is the leakage of methane from marine engines.
Midpoint	Midpoints are links in the cause-effect chain (environmental mechanism) of an impact category. Common examples of midpoint characterization factors include ozone depletion potentials and global warming potentials.
Natural environment	The natural environment is an area of protection. The impact on the natural environment is measured by the loss or disappearance of species and the loss of biotic productivity.
Natural resources	Natural resources are an area of protection. The natural resources can be divided into the following subcategories: atmospheric resources, land resources, water resources, mineral resources, metal ores, nuclear energy, fossil fuels and renewable resources.
Photochemical ozone	Photochemical ozone is an impact category that accounts for the formation of ozone at the ground level of the troposphere. Ozone formation is complex and depends on several factors, e.g., the concentrations of NO, NO_2 and VOC and on the level of ultraviolet radiation.
Product	A product is something produced on purpose and acts as a driver to why the human activities are occurring. A product should therefore be attributed environmental burdens, as it is the driver of those emissions
Prospective	This term, meaning forward looking, is used to denote LCAs looking at future systems.
Renewable fuels	Renewable fuels are fuels produced from renewable energy sources, where renewable energy sources refer to energy which is generated from natural processes and are constantly regenerated, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases.
Retrospective	This term, meaning backward looking, is used to denote historic perspectives on LCA.
Ro-pax ferry	A Ro-pax ferry is a roll-on/roll-off ship with high freight capacity and limited passenger facilities.
System	Connected objects, concepts, functions, etc. how they interact, and their purpose, goal, or effects makes up a system.
System expansion	System expansion is an allocation model in an LCA. It implies the expansion of the system to include affected processes outside the cradle-to-grave system, or to include multiple functions into the system boundary.
Tank-to-propeller	In this study, this term is used for the part of a marine fuel's life cycle beginning when the fuel is delivered to the vessel's onboard tank and ending when it is combusted for transportation of goods and/or passengers.
Waste	A waste flow is by definition an unwanted by-product where the environmental burden is allocated to the initial main product.

Well-to-propeller	Used to describe the part of a marine fuel's life cycle from the acquisition of the raw material to when the fuel is combusted for transportation of goods and/or passengers. Another term used for this is well-to-wake.
Well-to-tank	Used to describe the part of a marine fuel's life cycle from the acquisition of the raw material to the delivery to the vessel's tank.
Well-to-wheel	Well-to-wheel is a term commonly used in LCAs of road fuels. These studies usually consider only energy use and climate impact.
Well-to-wake	Used to describe the part of a marine fuel's life cycle from the acquisition of the raw material to when the fuel is combusted for transportation of goods and/or passengers. Another term used for this is well-to-propeller.
Zero-carbon fuels	Fuels with potential zero climate impact throughout their lifecycle

1 Introduction

To solve the climate challenge requires a transition to the use of fuels associated with zero or very low greenhouse gas (GHG) emissions throughout their life cycle, in all sectors. The Nordic countries are at the forefront of this transition. DNV with partners Menon, Chalmers, IVL Swedish Environmental Research Institute, MAN Energy Solutions, and Litehauz have been assigned by The Norwegian Ministry of Climate and Environment on behalf of the Nordic Council of Ministers the Nordic roadmap for introduction of sustainable zero-carbon fuels in shipping project [2]. The project has an overall aim "to reduce key barriers to implementation and establish a common roadmap for the whole Nordic region and logistics ecosystem towards zero emission shipping". In reply to the defined scope of work, this task report summarizes the results from Task 1C (LCA of selected fuels). The work in Task 1C has been managed and carried out by Chalmers and IVL, with support from the other partners.

Globally, there is work ongoing to develop and agree on life cycle methodology for calculating GHG emissions associated with marine fuels. The reason is that there is a need for a common basis for regulations and policy that are under development. The International Maritime Organization (IMO) is developing guidelines for estimating lifecycle GHG emissions for marine fuels [2]. In addition, the EU has proposed a lifecycle GHG emissions standard through the suggested FuelEU Maritime regulation, which includes initial guidance on how to calculate lifecycle emissions as well as a GHG reduction requirement energy used on-board ships [3]. The introduction of potential sustainable zero-carbon fuels in shipping, in the Nordic countries as well as globally, will be supported by the implementation of relevant proposed policies such as the concept of green shipping corridors (presented in the Clydebank Declaration for Green Shipping Corridors in 2021).

To reach the overall aim of the project, one of the objectives is that the Nordic countries have gained a technical knowledge base and provided a framework for regulatory development of promising alternative fuels. As part of this objective there is a need to assess the climate and environmental impact of potential zero-carbon fuels for marine use. This to increase the knowledge of the sustainability of various marine fuels that are relevant for the Nordic region, and to verify under what conditions that they fulfil the criteria's for being sustainable zero-carbon fuels, as well as potential trade-offs connected to other environmental impact categories. As there are limited life cycle assessment (LCA) studies with a Nordic perspective that consider a broad range of possible future marine fuels with comparable system boundaries and assumptions, a specific LCA for the Nordic context is called for and will be presented in this report.

The findings from this Task will be used as input primarily in Task 2-C (Development of Nordic Roadmap), and in Task 3-B for the development of pilots for the introduction of potential zero-carbon fuels and will be further disseminated as part of Task 3-A (Establish a platform for cooperation and networking in the Nordic region).

1.1 What is a zero-carbon fuel?

As mentioned above, the term zero-carbon fuel is used throughout this report to indicate fuels with potential zero climate impact throughout their lifecycle. Zero climate impact from a full lifecycle perspective means that there can be no net greenhouse gas (GHG) emissions added to the atmosphere when considering all parts of the lifecycle of the fuel. Fuel based on biomass can potentially be zero-carbon fuels as the same amount of CO_2 emissions generated during combustion of the fuel is extracted from the atmosphere during biomass growth. However, it also requires that all supporting processes will not result in any additional GHG emissions. The actual climate impact from biomass

[2] https://futurefuelsnordic.com/partners-and-contributors/

versus fossil fuels over time is a more complex issue [4] not captured with current conventional LCA approaches and not addressed in this work.

Fuels are currently associated with GHG emissions in more or less all parts of their life cycles, but the majority originates from the use of fuel onboard ships and from the production of the fuel itself. However, transport of fuel, the steel used to build the infrastructure for fuel production as well as the ships are also associated with GHG emissions and so are also most of the supporting processes and products going into the life cycle of a marine fuel. If our society transforms to a low carbon society, the GHG emissions linked to fuel production, infrastructure etc. will be reduced.

To reduce the GHG emissions from fuel production, it is important to use renewable energy sources or energy sources without any GHG emissions as well as to limit the direct emissions of GHGs during production. During the operation of the ship, there is a need to make sure that no GHGs are emitted. This can be done in at least the following ways: (1) use a carbon-free energy carrier and make sure no other GHGs (e.g., nitrous oxide (N_2O) or methane (CH_4)) are formed or leaked from the ship, (2) use a carbon containing energy carrier but capture the CO_2 emissions formed and all other GHGs. In addition to this, there is a potential to capture the CO_2 emissions elsewhere from the atmosphere for example during the fuel production stage. In this way, the CO_2 can be considered included in a closed cycle. Only contributing to additional climate impact during the time it is added to the atmosphere before it is removed. Some potentially zero-carbon fuels are shown in Figure 1.

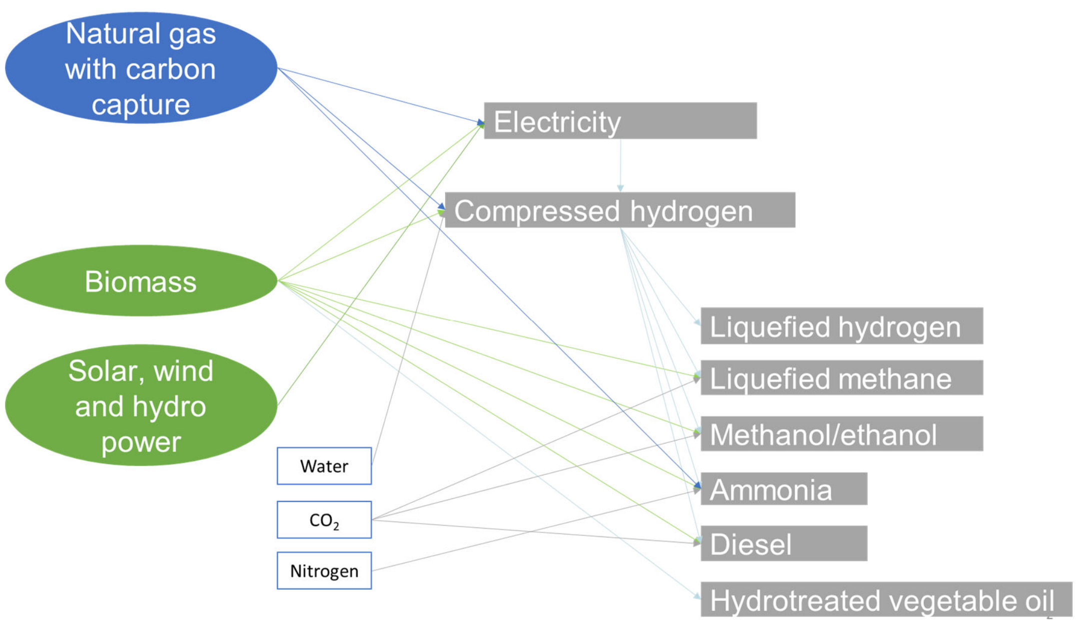

Figure 1 Examples of some possible blue (from natural gas with carbon capture) and green (from renewable energy sources) fuel production pathways.

From an environmental and LCA perspective, it is not only the climate impacts of fuels that are important to reduce; it is also important that there are no other significant negative impacts on the environment and on humans. When using LCA, a broad range of environmental impact categories can be considered including for example potential impact on acidification and on human health. What to target is not only zero-carbon fuels but zero-emission fuels or environmentally sustainable fuels. There is no clear definition of an environmentally sustainable marine fuel, but a way to work towards more environmentally sustainable fuels is to consider a broad range of environmental impact categories in the assessment of marine fuels. In LCA, there are some voluntary methods suggested for weighting of the impact of different environmental impacts in order to try to compare the overall environmental performance of different options. It is however, outside the scope of this report to apply the weighting step in the LCA as the aim is not to identify the most environmentally sustainable option. It is also not recommended nor common to perform this step in the case of technologies that are under development (as in the case of most options explored in this study). There are also economic and social parts of sustainability, but these are outside the scope of this report.

1.2 Aim

The aim of this report is to assess the climate and other environmental impact of the selected potential zero-carbon fuels for marine use (including e.g., hydrogen, ammonia and methanol) using life cycle assessment (LCA). This to increase the knowledge of the sustainability performance of various marine fuels that are relevant for the Nordic region, and to verify under what conditions they fulfil the criteria for being potentially sustainable zero-carbon fuels, as well as potential trade-offs connected to other environmental impact categories. Hydrogen, ammonia, and methanol are in focus in the LCA performed within this project, but liquefied methane gas and electricity used in batteries are also included as well as MGO and LNG for comparison. The literature review and to some extent the comparative assessment also covers a broader range of marine fuel options.

The novelty with this study includes (i) that it assesses the fuel and propulsion options from a Nordic perspective, (ii) that it assesses a range of different fuel and propulsion options relevant for Nordic shipping with the same LCA approach (making them comparable) while covering also several other environmental impact categories than climate impact, (iii) that it includes recent and updated estimates for emissions linked to hydrogen, ammonia and methanol for marine application, (iv) that it besides presenting the findings in terms of well-to-wake fuel life cycle impacts also perform LCA assessments for representative Nordic ships for selected shipping categories, (v) that it includes environmental impacts from the construction of the propulsion system in the representative ship LCAs and (vi) that it relates the LCA approach used to the discussed LCA guidelines for marine fuels in the IMO.

1.3 Overall approach

The Nordic countries already have production of alternative fuels such as biogas, biodiesel, ethanol, and are gearing up to produce hydrogen (blue and green) and other fuels including ammonia in larger scale. To ensure that the end-use of such fuels contribute to reducing the climate impact and have low other environmental impacts, it is necessary to assess the full value chain; from sourcing of resources and primary energy, through processing and distribution, to use onboard ships.

The work includes the following steps, (1) an in-depth literature review of the potential environmental impacts of the selected potential zero-carbon marine fuels, (2) a complete LCA from well to wake for the selected fuels in a Nordic context, (3) an overall comparative study of the life cycle environmental performance of the selected fuels to a range of marine fuels, and (4) presentation and discussion of findings. A potential update at later stage of the project, given that new key data is available, will be done. The Task is performed mainly by Chalmers and IVL with input from DNV and MAN ES.

1.4 Report structure

Section 2 includes an introduction to life cycle assessment. In Section 3, guidelines for life cycle assessment of marine fuels that are under development are described. The literature review of marine fuels is described in Section 4. The approach and data for the life cycle assessment performed is reported in Section 5 including, e.g., goal and scope definition and inventory analysis. In section 3 and 5 it is also indicated how the approach in the report differs from the LCA guidelines under development for marine fuels in IMO. In Section 6 the assessment of life-cycle environmental impacts is presented, first the well-to-wake fuel life cycle impacts and then Nordic representative ship LCAs including also the construction of the propulsion system. The findings of the report are interpreted and discussed in Section 7 (Discussion and conclusions).

2 General introduction to Life Cycle Assessment

LCA is used to assess the environmental impact of a product or technology by mapping all material and energy flows from each process in the life cycle [5]. These flows are then linked to impacts on the environment. In this way, the environmental impacts of similar options can be quantified and compared, which in turn gives information on how the environment will be affected by choices made. The life cycle model in LCA is a typical example of a system that consists of several processes connected by a flow of goods, material, and energy. LCA belongs to the family of systematic environmental assessment tools.

LCA is useful when trying to avoid shifting problem from e.g., one phase of the life-cycle to another, from one region to another, or from one environmental problem to another [6]. LCA considers a product' full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste (Figure 2). LCA is a fit-for-purpose procedure now used for assessing processes, services, and behaviour and not only products.

ISO14040 (2006) and ISO14044 (2006) standards provide basis for LCA studies and include general requirements for all aspects of a product or system's lifecycle. The broad scope of LCA and need for fit-for-purpose choices makes the ISO standards the foundation for an LCA study, leaving many methodological aspects to be further defined by the LCA practitioner. The four phases of the methodology used in this study are consistent with the guidelines of ISO 14040 covering 4 steps: 'goal and scope definition', 'inventory analysis', 'impact assessment', and 'interpretation' (Figure 2). Several GHG calculation methods and tools are available, some of the larger ones that are also relevant for the context of this report are:

- the Greet model (The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model by Argonne National Laboratory) *(tool)*
- the European Union Renewable Energy Directive, RED II (which is currently undergoing revision) *(method including data)*
- the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) *(method)*
- the JRC (the Joint Research Centre of the European Commission), EUCAR and Concawe continuously update their joint evaluation of the Well-to-Wheels energy use and greenhouse gas (GHG) emissions for a wide range of potential future fuel and powertrain options, where the well-to-tank data in many cases can be relevant for shipping *(method/tool)*

These are not reviewed in detail but for a discussion on the potential use of these methods and tools we refer to Campbell et al. [7]

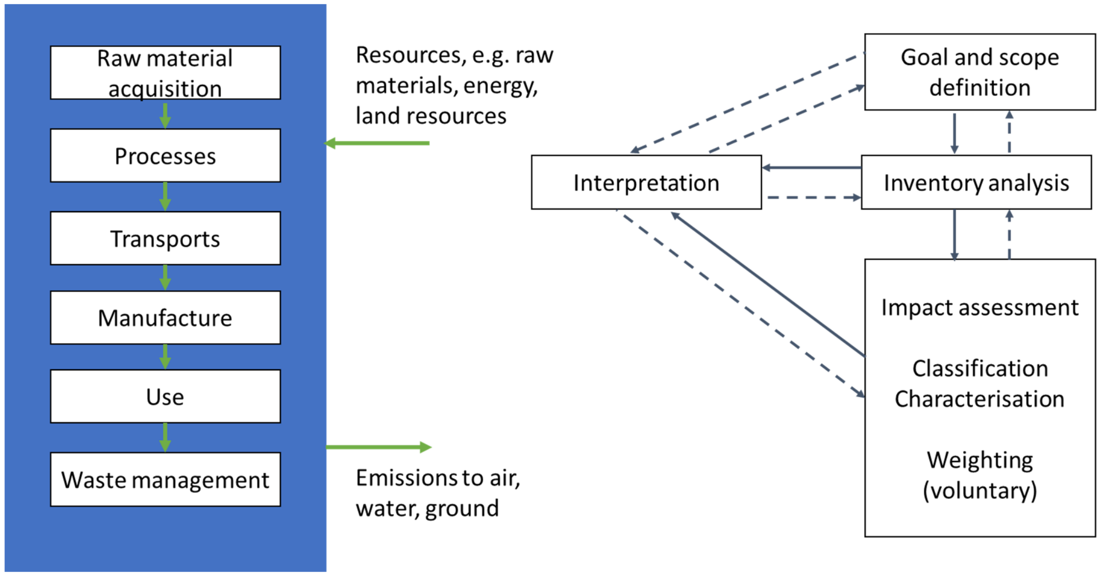

Figure 2 General system boundaries used in life cycle assessment (LCA) and the LCA procedure according to the ISO standards.

First *goal and scope* are identified, which sets the stage for the assessment. During this stage, what to compare is established, both in terms of which unit that is directly compared and the system surrounding it. The aim of this step is to describe the studied system as well as the purpose of the study and includes for example reasons for carrying out the study and its boundaries [8]. To compare different options, a quantitative unit called the functional unit is defined in detail [9]. This unit represents the function of the system i.e., what it is that specifically is compared and represents the desired function of the system, and this unit should be kept the same for all the different options being analysed. This could be, e.g., a certain quantity of fuel (measured as energy content) or a specified transport work. The system boundaries of the LCA will include all major parts of the life cycle and consider both the fuel life cycle, as well as the impact from manufacturing and end-of-life of the propulsion system (see Figure 3 for an illustration of possible system boundaries).

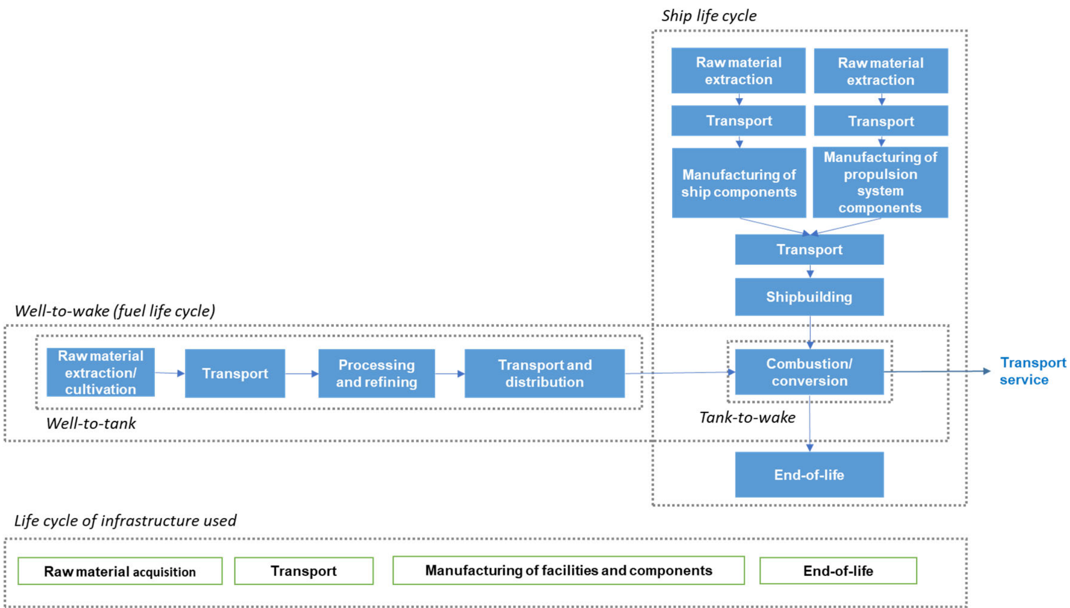

Figure 3 Illustration of different system boundaries.

In the *inventory analysis*, a system flow model is made from "cradle-to-grave" showing the activities included in the system with the material and energy flows between the activities [10]. This inventory is the basis for the calculations and acts like an outline of the investigated unit and the surrounding. Here, resources and emissions related to the functional unit are calculated, a model for materials and energy flows within and over the system boundaries is constructed, and data are collected. For example, in terms of GHGs, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) will be included in the assessment in this report and for all processes in the life cycle, these will be quantified. The system boundaries determine which processes are included in the LCA and are set in accordance with the goal of the study. System boundaries is needed for a consistent framework when comparing alternatives, which in this report are marine fuels and propulsion systems, and are crucial to avoid potentially drawing misleading conclusions. System boundaries can be wide, trying to include all environmental impacts, but it is also possible to focus on only certain environmental impacts. However, in both cases the system boundary needs to be clearly defined.

During the *impact assessment phase*, potential environmental impacts are evaluated for the systems throughout the life cycle. The environmental impacts are calculated from the environmental loads quantified in the inventory analysis phase. These impacts are categorized based on what they are affecting in the environment and varies depending on which type of LCA methodology is used. However, the basic principle is the same: everything crossing the system boundary (emissions, energy, materials) is added together based on how much they affect a specific category of impact compared to a reference emission/substance [6]. The different categories are referred to as "impact categories". In this way the result is a total amount of the reference emission/substance, which can be compared between different technology options etc. The number converting emission from the system to reference emission/substance is called the characterization factor. The total environmental impact results (IR) for different categories (C) can be calculated from the characterization factor (CF) of the substance (i) and the amount of substance (m_i) emitted to the environment using equation 1. The main impact categories considered in this report are global warming potential (for GHGs), particulate matter formation potential and acidification potential (see more in section 5.9 Impact categories).

$$IR_C = \sum_i CF_i \times m_i \qquad (1)$$

The goal and scope, inventory analysis and impact assessment steps are done iteratively, going back and forth, while interpreting the results to make sure that everything is coherent and to create depth in the study. In LCA, the impact from method choices on the results should be acknowledged. What you include and not include is always important in scientific settings, but for LCA, how to make this choice and what to investigate can directly affect your end recommendation [9]. Conducting an LCA includes many assumptions of the context investigated and the technologies used. The result can appear as a singular number for each specific impact category, but the model as such contains more information.

In LCA there are some voluntary methods suggested for weighting of the different environmental impacts in order to try to compare the overall environmental performance of different options. It is however, outside the scope of this report to apply the weighting step in the LCA as the aim is not to identify the most environmentally sustainable option. It is also not recommended nor common to perform this step in the case of technologies that are under development (as in the case of most options explored in this study). An example of weighting tested on existing transportation fuels can be found in Ekener et al. [11].

Sensitivity analysis is also mentioned as a part of the LCA approach with the aim to determine the robustness of the assessment and identify assumptions, or unknown variables, which may change the results of the study [9]. The method is commonly used by establishing the range of uncertainty in the input data and analyse how the result shifts over the uncertainty range. Three approaches to address uncertainty were proposed in Finnveden et al. [12], the "scientific way", the "social way" and the "statistical way". The scientific way includes further development of the scientific approach by, for example, identifying better data and develop better models. The social way limits uncertainties by discussions with stakeholders, with the aim to reach consensus on the methodology choices and data used. The statistical way looks at ways to incorporate uncertainties into the analysis. Monte-Carlo simulations is an often-used statistical method in LCA [13].

There are various types of LCAs, and the most common division of LCA types in the literature has been between attributional [3] and consequential [4] studies. The view of the differences between the types and how they interact are still being discussed, and additional types of assessments are being proposed such as s prospective and/or ex-ante [15-18] as a type of LCA where future assessment of emerging technologies and systems are assessed [15, 19].

Attributional studies explore the system and its causes, whereas consequential studies explore the system's effects. Attributional LCAs are designed to be as complete as possible, accounting for all environmental impacts of a product, whereas consequential LCAs are intended to describe the environmental consequences of alternative courses of action. An attributional LCA addresses such questions as "What would be the overall environmental impact of marine transportation using Fuel A?" A consequential LCA addresses such questions as "What would be the environmental consequence of using Fuel A instead of Fuel B?" Prospective LCA is used for assessing emerging technologies that are in an early phase of development (e.g., small-scale production) and when the impact you want to assess, and model, is the technology in a future, more-developed phase (e.g., large-scale production), which is the case in this study.

As there are different types of LCAs, there are also different ways to set-up the life cycle inventory (LCI) data. In this report, the bottom-up approach process-based LCA is used. This method models the LCI using knowledge about industrial processes within the life cycle of a product, and the physical flows connecting them. To define the function of the system and the system boundaries knowledge of

[3] The term *accounting* is also used, e.g., by Baumann and Tillman [14].
[4] The term *change-oriented* is also used, e.g., by Baumann and Tillman [14].

how the product or technology will be/are used is required [9]. As the goal often is to assess the impacts of a real system, this requires modelling and thereby simplifications and assumptions of how the system looks. The design of the life cycle model sets the scope of the assessment.

If a system has several products, multiple functions can be identified, and a choice has to been made in how to solve this multifunctionality issue. There are several methods for this, where the main tools are called “system expansion” and “allocation”. System expansion is the process of expanding the function of the system to include the full set of functionalities, or to subtract the function, which would be replaced by a by-product on the market. System expansion is the preferred LCA approach according to the recommendations given by the ISO 14044 standard, and it also recommended by the ILCD handbook [20]. Allocation is defined as separating the input and output from a process, or separating the inputs and outputs of a product systems between product systems [21]. Allocation can be based on a physical unit such as mass or energy or on economic flows. For fuels, energy allocation is used extensively as it is a less complex and subjective approach. It can for example be noted that two international legislative measures connected to fuels, RED II and CORSIA (the latter for aviation) both adopt the simpler energy allocation approach [7]. Campbell et al. [7] further suggests that “… system expansion is the preferred approach to co-product allocation, but given the complexities associated with system expansion, and, to a lesser extent, also with economic allocation, an energy allocation approach as set by RED II and CORSIA could be used”. The choice of how to solve for multifunctionality does affect the results of an LCA, and despite a recommended hierarchy in the ISO standard, discrepancies occur depending on research question and feasibility.

Thus, in order to fully understand and use the outcome of a specific LCA study it facilitates to know about the methodological choices made. Data availability is another important aspect. The outcome of a LCA depends on the data used and its accuracy (e.g., to what extent it is specific for the pathway studied and the relevant geographical region). In prospective LCAs there are generally uncertainties for some emissions as the technologies are under development.

3 Status for guidelines for life cycle assessment of marine fuels

Development of guidelines for life cycle GHG emissions of marine fuels are ongoing within IMO and several submissions was discussed at the 11th Intersessional Meeting of the Working group of GHG Emissions from Ships (ISWG-GHG) 14-18th of March 2022. According to the summary document presented at MEPC 78 “the Group agreed to use annex 1 to document ISWG-GHG 11/2/3 (Australia et al.) as a new base document for the further development of the draft LCA guidelines, with the understanding that it would be reviewed in detail and that additional text from the other relevant documents, in particular document ISWG-GHG 11/2/4 (Angola et al.), considered at this session could be further incorporated in the next consolidated”. It is expected that more work will be done at MEPC 79.

ISWG-GHG 11/2/3 includes a well-to-wake methodology on a full lifecycle assessment using an attributional LCA approach, it includes a tank-to-wake methodology in line with the IPCC Guidelines for National Greenhouse Gas Inventories, which enables accounting of GHG emissions while avoiding double counting across sectors. ISWG-GHG 11/2/3 also define sustainability criteria for eligible marine fuels and contain provisions for applying a Fuel Lifecycle Label (FLL), which characterizes fuels per type, feedstock, production pathway, and relevant sustainability criteria. Some of the most important aspects when carrying out an LCA of marine fuels from ISWG-GHG 11/2/3 is highlighted below.

ISWG-GHG 11/2/3 suggest the IMO LCA guidelines to include the GHGs CO_2, CH_4 and N_2O emissions considering the global warming potential over a 100-year horizon (GWP100), using the values given in the IPCC Sixth Assessment Report, for CO_2, CH_4 and N_2O (Table 1). The climate impact varies depending on time perspective and if climate carbon feedbacks are considered or not which is exemplified in Table 1 that also illustrates the increased understanding of the climate impact of non-CO_2 greenhouse gases. It is recommended by the authors of this report to always provide the data for the emissions of specific greenhouse gases as a complement to their combined global warming potential. This to make it possible to update the global warming potential when better data is available or to test the impact connected to different climate metrics. ISWG-GHG 11/2/3 suggest guidelines for how to make sure that there is no double counting across sectors. The life cycle emissions are suggested to be reported per MJ of fuel and divided on the well-to-tank and tank-to-wake phases of the life cycle separately.

Table 1 Overview of different metrics used for estimating climate impact of non-CO_2 greenhouse gases.

	g CO_2-eq./g fossil CH_4	**CO_2-eq./g non fossil CH_4**	**CO_2-eq./g renewable N_2O**
IPCC Sixth Assessment Report, GWP100	29.8	27.0	273
IPCC Sixth Assessment Report, GWP20	82.5	79.7	273
IPCC Fifth Assessment Report, GWP100 without climate-carbon feedbacks	28	30	265
IPCC Fifth Assessment Report, GWP20 without climate-carbon feedbacks	84	86	264
RED II	25	25	298

ISWG-GHG 11/2/3 further suggest that default emission values to be provided in the guidelines should reflect, for each fuel, the higher end of the possible emissions range to cater for uncertainty and encourage the use of verified actual values. It further suggests that an attributional life cycle assessment should be used. Thus, considering the actual current GHG emissions of the fuels. However, it still remains to decide on which default emission values that will be used and if they are based on current or prospective values.

In ISWG-GHG 11/2/3 it is suggested that as the actual emissions depend both on the properties of the fuel and on the efficiency of the energy conversion (e.g., engine) the CO_2 emission factors should be based on the molar ratio of carbon to oxygen multiplied with the carbon mass of the fuel, assuming that all the carbon in the fuel is oxidized. While the CH_4 and N_2O emissions factors should be related to the combustion or conversion process in the energy converter. It is also suggested that these factors need to consider the year the energy converter and engine was produced as more mature technologies typically have better emission profile.

Linked to the source of carbon (which is important for the outcome) ISWG-GHG 11/2/3 suggest the use of a carbon source factor (S_F). This might differ to some extent from the approach of handling this by assuming that the CO_2 was removed from the atmosphere during biomass growth, used in our study. However, it is unsure to what extent and if the outcomes of the two approaches differ.

The factor S_F determines if the tank-to-wake CO_2 emissions should be accounted for in the IMO GHG inventory for international shipping ($S_F = 1$) or not ($S_F = 0$) as it is to be multiplied with the CO_2 emission factor (C_F) for the specific fuel (tank-to-wake). It is however suggested that CH_4 and N_2O emissions should be reported regardless of carbon source and are not affected by S_F. It can however be noted that in the IPCC Sixth Assessment report different values are used for CH_4 dependent on fossil or biogenic origin. This is not considered in ISWG-GHG 11/2/3.

ISWG-GHG 11/2/3 notes that the SF only applies to the tank-to-wake phase and that energy carriers with zero carbon can be associated with GHGs during the well-to-tank phase.

During the well-to-tank phase it is suggested that credits should be included when CO_2 is captured by biomass growth, or direct air capture or any other type of capture process.

During the well-to-tank phase the following aspects are suggested to be considered: emissions from the extraction or from the cultivation of raw materials, annualized emissions from carbon stock changes caused by land-use change (over 20 years), emissions from processing, including electricity generation, emissions from transport and distribution, emissions credits generated by biomass growth, emission savings from soil carbon accumulation via improved agricultural management, emission savings from CO_2 capture and geological storage and emission savings from CO_2 capture and utilization. There are some descriptions in the proposal what exactly is included, but there is a need for further specifications. It is for example not clear if infrastructure used to produce marine fuels and electricity should be included or not. It is also so far not specified how to handle the issue with several product flows from one process. The following is stated "Allocation of emissions to co-products based on their energy content should be used as the most appropriate and reliable methodology [further work is needed]."

Fugitive emissions are also mentioned in ISWG-GHG 11/2/3 and are suggested to be considered using a slip factor. It is suggested that the slip factor should be calculated at 50% of the engine load (E2/E3 test cycle can also be considered as method of reference in the certification guidelines). The assumptions linked to potential leakages and slip in this study is specified in Section 5.12.

A similar methodology as in ISWG-GHG 11/2/3 is suggested in Annex I to the EU Fuel Maritime proposal for establishing the greenhouse gas intensity limit on the energy used on-board by a ship. The default values are to some extent based on EU MRV and RED II directives (which to some extent are based on a prospective approach) but the sources for hydrogen and ammonia GHG emissions are somewhat uncertain.

4 Literature review of LCA of selected potential zero-carbon marine fuels

In this section, the environmental impacts of the selected potential zero-carbon marine fuels presented in the existing literature are mapped. The mapping is based on an in-depth literature review, which covers publications from 2014 to 2022. The literature review covers a range of marine fuels i.e., more than the selected potential zero-carbon marine fuels, that however are assessed in more detail.

The relevant existing scientific literature (including scientific articles, and conference proceedings) is identified based on specific search phrases used in Scopus (for title, abstract, and keywords). The literature search was based on the following search phrase:

TITLE-ABS-KEY (("Life cycle" OR "Life-cycle" OR "environmental assessment" OR "environmental analysis" OR "climate analysis") AND ("climate" OR "environment" OR "emission*") AND ("ship" OR "Marine fuel" OR "marine fuel" OR "maritime") AND (fuel OR engine OR power))*

So-called snowballing using the reference lists in the identified papers and other publications found to identify additional publications were also applied to some extent following traditional literature review procedure, to identify all the important publications from the chosen study period. In total, 51 relevant publications were found in the literature review.

LCAs of marine fuels have been conducted for a multitude of different fuels (see Figure 4 for an overview based on the literature review). From competing fossil-fuels options [22-32] to biofuel alternatives [33-42] and other options such as hydrogen, ammonia and other electrofuels/power-to-X fuels [43-57] or electricity [43, 51, 52, 57-68].

Fossil fuels assessed include heavy fuel oil (HFO), marine gas oil (MGO), marine diesel oil (MDO)/diesel, liquefied natural gas (LNG), liquefied petroleum gas (LPG), very low or low sulphur oil (VLSFO). Methanol can be produced from both fossil fuels and renewable energy. There are several assessments for each of these options, in total 16 (Figure 4). Biofuel options assessed include e.g. biodiesel (RME, HVO etc.), biogas, dimethyl ether (DME), ethanol, methanol, FT diesel, and liquefied biogas (LBG). Electricity in the form of batteries is also assessed in a range of publications. Hydrogen is included in 17 publications, ammonia in 10 publications, renewable methanol (including electro-methanol and biomass-based methanol) in 11 publications while electrofuels is addressed in total (besides hydrogen) only in 7 (E-LNG, E-ammonia, E-methanol, E-diesel).

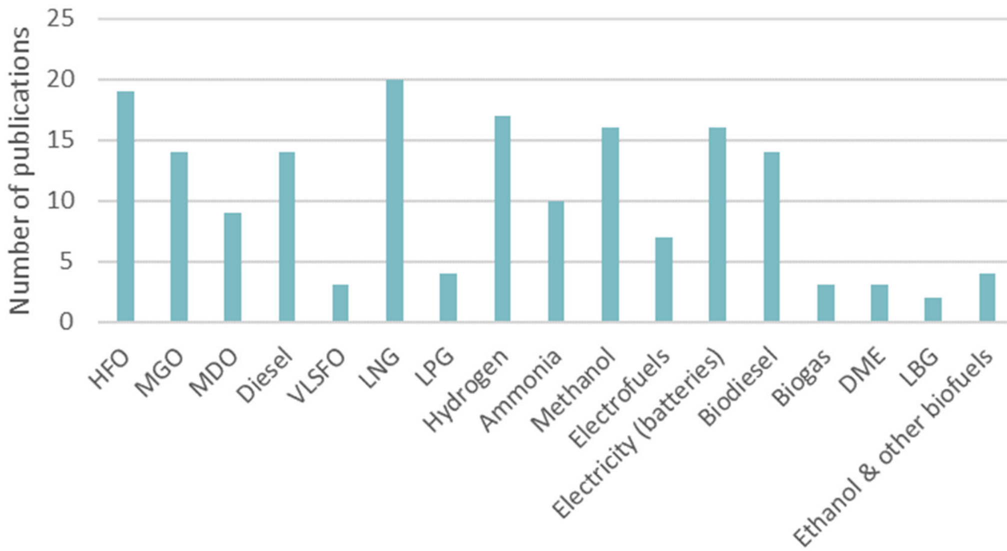

Figure 4 Number of publications assessing environmental impacts that cover different marine fuel options found in the literature review from 2014-2022. Since some articles cover several fuels, the sum of the numbers in the bars does not represent the total number of publications identified. HFO represent heavy fuel oil, MGO - marine gas oil, MDO - marine diesel oil/diesel, LNG - liquefied natural gas, LPG - liquefied petroleum gas, VLSFO - very low sulphur oil, LBG - liquefied biogas.

The specific fuels included in each study found in the literature review is described in Table 2. For the environmental impact of fuels, the raw material used is important, in particular if it is based on renewable or fossil energy sources. This has been specified to the extent possible in Table 2. In total, 11 publications include grey hydrogen i.e., produced from natural gas [26, 43-46, 50, 63, 69, 70], 5 publications include blue hydrogen i.e., hydrogen produced from natural gas but where the CO_2 is captured and 14 publications include green hydrogen i.e., produced from renewable energy [7, 26, 44-47, 50, 53-55, 63, 69]. For ammonia, a total of 7 publications study grey ammonia [7, 33, 45, 46, 69], 3 publications study blue ammonia [7, 45, 47] and 9 publications study green ammonia [7, 26, 45-47, 54, 55, 69]. For methanol, in total, 16 publications include methanol of which 11 include biomass-based methanol and/or electro-methanol [26, 39, 46, 47, 49, 69-74] (and 12 fossil-based methanol).

Many studies include the emissions of several GHGs while others only include the emissions of carbon dioxide (CO_2), see Table 2. LCA publications generally have different system boundaries (technical, geographical, time etc.), which could influence the results, for example the possibility to reach zero GHG emissions. If well-to-wake/propeller, well-to-tank, or tank-to-wake/propeller is included in the studies identified in the literature, it is also included in Table 2. Most of the existing assessments include a well-to-wake/propeller perspective, which make them comparable from that perspective. The GHG emissions reported from different LCA studies for hydrogen, ammonia and methanol are compared in Section 4.1, for the cases where it is possible to express them in the same unit.

Some of the reviewed papers are limited to climate change impact, but some look at a wider scope of environmental impacts [22-26, 34-39, 43-45, 47, 48, 53-55, 58-60, 64-68]. The specific environmental impacts, except climate impact, that is considered in each of the identified studies is listed in Table 2.

The most common impact categories in the reviewed literature include climate change, acidification, and eutrophication and the most common emissions besides CO_2 and other GHGs include nitrogen oxides (NO_X), sulphur oxides (SO_X), and particulate matter (PM). Climate change/global warming was considered in all reviewed publications.

Key critical methodology choices that influence the outcomes of LCAs of marine fuels include choice of system boundaries (including technical, geographical, time aspects for example, which part of the life cycle that is included, which impact categories and emissions that are covered and how it has been represented, if first-of-a kind or more established production is assumed etc.), functional unit, modelling tools used, data used, databases and LCA approach that has been used etc. If different system boundaries are used and assumptions made, the studies are not completely comparable. Therefore, to compare the selected potential zero-carbon marine fuels in this study, a specific LCA for the Nordic context is called for.

Table 2 Overview of the reviewed LCA publications published in 2014-2022 including author names, included fuels, covered GHG emissions, life cycle phases covered and other environmental impacts than climate change considered. The publication year and publication type are indicated (A-article, R-report or other publication).

References (year, publication type)	Fuels included	GHG emissions considered	System boundary	Other environmental impacts considered
Balcombe et al. [26] (2021, A)	LNG, HFO, MDO, fossil methanol, fossil and renewable/green hydrogen and ammonia, biogas and biomethanol	CO_2, CH_4	Well-to-Wake/Prop	Nitrous oxides (NO_X), sulphur oxides (SO_X), carbon monoxide (CO), particulate matter (PM)
Bengtsson et al. [38] (2014, A)	HFO, MGO, biomass-to-liquid fuel, RME, LNG, LBG	CO_2, CH_4, N_2O	Well-to-Wake/Prop	Acidification potential, Eutrophication potential, Human toxicity, Photochemical ozone formation, Human health damage by particles and ozone
Bicer and Dincer [55] (2018, A)	Green hydrogen, green ammonia, HFO	CO_2, CH_4, N_2O	Well-to-Wake/Prop	Abiotic depletion, Acidification, Stratospheric ozone layer depletion, Marine eco-toxicity and Marine sediment ecotoxicity
Bicer and Dincer [54] (2018, A)	Hydrogen, ammonia (biomass, municipal waste, geothermal energy), HFO and hydrogen/ammonia	CO_2, CH_4, N_2O	Well-to-Wake/Prop	Abiotic depletion (ADF), acidification (SO_2 eq.), stratospheric ozone layer depletion (CFCs), marine eco-toxicity and marine sediment ecotoxicity (1,4-DB eq.)
Bilgili [33] (2021, A)	Biogas, dimethyl ether (DME), ethanol, liquefied natural gas (LNG), liquefied petroleum gas (LPG), fossil methanol (MeOH), fossil ammonia (NH3) and biodiesel	CO_2, CH_4, N_2O	Well-to-Wake/Prop.	Human health (DALY): Climate change, Ozone depletion, Human toxicity, Photochemical oxidant formation, PM-formation; Ecosystem quality (species*yr): Climate change, Terrestrial acidification, Freshwater eutrophication, Terrestrial ecotoxicity, Freshwater Ecotoxicity, Marine Ecotoxicity, Agricultural land occupation, Urban land transformation; Resources ($): Mineral resource depletion, Fossil fuel depletion
Bilgili [22] (2021, A)	HFO, LFO, VFLSO, ULFSO	CO_2, CH_4, N_2O	Tank-to-Wake/Prop.	NO_X, SO_X, CO, PM, Non-methane volatile organic compounds (NMVOC)
Brynolf et al. [39] (2014, A)	HFO, LNG, LBG, methanol (fossil and biomass)	CO_2, CH_4, N_2O	Well-to-Wake/Prop	Acidification, eutrophication, formation of particulate matter and photochemical ozone formation
Brynolf et al. [25] (2014, A)	HFO, MGO, LNG	CO_2, CH_4, N_2O	Well-to-Wake/Prop	Particulate matter, photochemical ozone formation, acidification potential, terrestrial eutrophication potential, marine eutrophication potential
de Fournas and Wei [49] (2022, A)	HFO, MGO and methanol (biomass and electrolysis)	CO_2, CH_4, N_2O	Well-to-Tank	

References (year, publication type)	Fuels included	GHG emissions considered	System boundary	Other environmental impacts considered
DNV GL [71] (2019, R)	LNG, hydrogen (renewable and fossil), ammonia (renewable and fossil), methanol, LPG, biodiesel - HVO, electricity	CO_2, CH_4, N_2O	Well-to-Wake/Prop	SO_X, NO_X and PM
DNV GL [72] (2019, R)	HFO, MGO, LNG, LPG, methanol (fossil and biomass based), biogas, biodiesel, hydrogen (fossil and renewable)	CO_2	Well-to-Wake/Prop	NO_X
El-Houjeiri et al. [75] (2019, A)	HFO, MGO, LNG	CO_2, CH_4	Well-to-Wake/Prop	
Fan et al. [62] (2021, A)	LNG, battery, solar energy, hybrid power	CO_2	Well-to-Wake/Prop	
Fernández-Ríos et al. [44] (2022, A)	Hydrogen (H2) (PEMFC and ICE), diesel (ICE)	CO_2, CH_4, N_2O	Well-to-Wake/Prop	Acidification Potential, Eutrophication Potential, Ozone Layer Depletion Potential, Abiotic Depletion Potential elements and fossil, Freshwater Aquatic Ecotoxicity Potential, Human Toxicity Potential, Marine Ecotoxicity Potential, Terrestrial Ecotoxicity Potential and Photochemical Ozone Creation Potential
Gilbert et al. [36] (2018, A)	HFO, MDO, LNG, RE and NG hydrogen + CCS, fossil methanol, soy SVO, rape SVO, soy and rape biodiesel, bio-LNG	CO_2, CH_4, N_2O	Well-to-Wake/Prop	NO_X, SO_X, PM
Hawkins et al. [76] (2019, R)	HFO, MGO, MDO, LNG, VLSO, FT-diesel (biomass and fossil based), pyrolysis oil, biodiesel, renewable diesel, vegetable oil	CO_2, CH_4, N_2O	Well-to-Wake/Prop	SO_X, NO_X, PM2.5, and CO
Hwang et al. [23] (2020, A)	MGO, LNG, fossil hydrogen (H2)	CO_2, CH_4, N_2O	Well-to-Wake/Prop	Acidification potential, Photochemical potential, Eutrophication Potential, PM2.5
Ling-Chin and Roskilly [66] (2016, A)	Electricity (Li-ion batteries) and MDO	CO_2	Well-to-Wake/Prop	Marine and freshwater aquatic ecotoxicity potential, Human toxicity potential, Acidification potential, Eutrophication potential, Abiotic depletion, Photochemical ozone creation potential, Terrestrial ecotoxicity potential, Ecotoxicity for aquatic freshwater, PM, Resource depletion
Ling-Chin and Roskilly [67] (2016, A)	Hybrid system with electricity (cold ironing, PVs and Li-ion batteries), MDO as prime mover	CO_2	Well-to-Wake/Prop	NO_x, sulphur dioxide (SO_2), CO, hydrocarbons (HC) and PM

References (year, publication type)	Fuels included	GHG emissions considered	System boundary	Other environmental impacts considered
Ling-Chin and Roskilly [68] (2016, A)	HFO, MDO and hybrid system with electricity (diesel genset as prime mover, PV and Li-ion battery and cold-ironing)	CO_2	Well-to-Wake/Prop	NOx, SO_2, CO, HC and PM
Jeong et al. [64] (2018, A)	Electricity (Battery hybrid), MDO	CO_2 and CH_4	Well-to-Wake/Prop	Acidification potential, Eutrophication potential and Photochemical ozone creation potential
Jeong et al. [59] (2020, A)	Battery and diesel	CO_2	Well-to-Wake/Prop	Acidification potential, Eutrophication potential and Photochemical ozone creation potential
Kramel et al. [24] (2021, A)	HFO, MGO, LNG	CO_2, CH_4, N_2O	Well-to-Wake/Prop	NMVOC, SOx, NOx, CO, organic carbon (OC), elemental carbon (EC), black carbon (BC)
Law et al. [47] (2021, A)	HFO, LNG, blue hydrogen (H2) and ammonia (NH3), grey and blue methanol (MeOH), NG electricity, blue and green E-H2, E-NH3, E-MeOH, biodiesel, bio-MeOH	CO_2, (CH_4)	Well-to-Wake/Prop	NOx, SOx, PM
Lindstad et al. [46] (2021, A)	LPG, HFO, VLSFO, MGO, LNG, LPG (ICE or DF-engines), grey ammonia (NH3), grey hydrogen (H2), E-fuels (E-LNG, E-ammonia, E-liquid hydrogen, E-methanol, E-diesel)	CO_2, CH_4, N_2O	Well-to-Wake/Prop	
Lloyd´s Register and UMAS [69] (2020, R)	MDO, LSHFO, biodiesel, e-diesel, bio-methanol, e-methanol, bio-LNG, e-LNG, ammonia (electro and natural gas based) and hydrogen (electro and natural gas based)	CO_2	Well-to-Wake/Prop	
Malmgren et al. [48] (2021, A)	Methanol (biogenic, fossil, electro), MGO	CO_2, CH_4, N_2O	Well-to-Wake/Prop	Acidification, Human toxicity, Marine eutrophication, Terrestrial eutrophication, Ozone depletion, Ozone formation, PM, black carbon, CO, NOx, SO_2, ammonia (NH_3), CH_2O, NMVOC
Menon and Chan [50] (2022, A)	Hydrogen (fossil and electrolysis) in fuel cell and ICE, MDO in ICE	CO2 (CH4, N2O)	Well-to-Wake/Prop	
Mestemaker et al. [53] (2020, A)	LNG (DF with diesel as pilot fuel), renewable/green hydrogen (FC with hybrid drive and batteries)	CO_2 and CH_4	Well-to-Wake/Prop	Acidification potential, Aerosol formation potential, Eutrophication potential

References (year, publication type)	Fuels included	GHG emissions considered	System boundary	Other environmental impacts considered
Nguyen et al. [37] (2015, Conf. paper)	Biodiesel fuel from jatropha curcas oil and waste cooking oil, diesel	CO_2	Well-to-Wake/Prop	NOx, CO, HC and PM
Park et al. [60] (2022, A)	Diesel-electric (MGO), battery (grid and solar PV system)	CO_2, CH_4, N_2O	Tank-to-Wake/Prop.	Acidification potential, Eutrophication potential, Photochemical ozone creation potential
Pavlenko et al. [77] (2020, R)	LNG, MGO, VLSO, HFO	CO_2, CH_4, N_2O	Well-to-Wake/Prop	
Perčić et al. [45] (2022, A)	Grey, blue and green hydrogen (H2) and ammonia (NH3) (PEMFCs and SOFCS), diesel	CO_2, CH_4, N_2O	Well-to-Wake/Prop	Acidification Potential, Aerosol Formation Potential, Human toxicity, Depletion of fossil fuel
Perčić et al. [63] (2020, A)	Diesel, electricity Li-ion battery, fossil methanol, natural gas DME, LNG, renewable hydrogen powered by Li-ion battery, fossil hydrogen, B20 (20% biodiesel 80% fossil fuel)	CO_2, CH_4, N_2O	Well-to-Wake/Prop	
Perčić et al. [51] (2021, A)	Diesel, Electricity, fossil methanol, LNG, NG hydrogen, NG ammonia and biodiesel	CO_2, CH_4, N_2O	Well-to-Wake/Prop	
Perčić et al. [58] (2021, A)	Diesel, Li-ion battery, PV cell battery-powered ship	CO_2, CH_4, N_2O	Well-to-Wake/Prop	NOx, SOx, PM10
Perčić et al. [52] (2020, A)	Diesel, Li-ion battery from Croatian electricity mix, PV cell battery-powered ship	CO_2, CH_4, N_2O	Well-to-Wake/Prop	
Horton et al. [70] (2022, R)	HFO, MDO, LNG, bioLNG, hydrogen (grey, blue and green), ammonia (grey, blue and green), methanol (grey and green), FAME, HVO	CO_2, CH_4, N_2O	Well-to-Wake/Prop	
Tan et al. [34] (2021, A)	HFO, MDO, MGO, FT-diesel (NG, biomass and coal, biomass and NG, biomass), LNG, renewable diesel, SVO, pyrolysis oil (wood), biodiesel	CO_2, CH_4	Well-to-Wake/Prop	SOx, PM2.5, NOx, and CO

References (year, publication type)	Fuels included	GHG emissions considered	System boundary	Other environmental impacts considered
Tanzer et al. [41] (2019, A)	Several lignocellulosic based marine biofuels (including e.g., biodiesel)	CO_2, CH_4, N_2O		NOx, SO_2
Trillos et al. [43] (2021, R)	Diesel, diesel hybrid, FC + battery ship (hydrogen from PEM electrolyser)	CO_2 (CH_4, N_2O)	Well-to-Wake/Prop	Stratospheric ozone depletion, Ionizing radiation, Ozone formation (human health), Fine particulate matter formation, Ozone formation (terrestrial ecosystems), Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Human carcinogenic toxicity, Human non-carcinogenic toxicity, Land use, Mineral resource scarcity, Fossil resource scarcity, Water consumption
Wang et al. [65] (2018, A)	Hybrid (battery electric and diesel gen), diesel electric (DE), diesel mechanical (DM)	CO_2, CH_4, N_2O	Well-to-Wake/Prop	Acidification potential, Eutrophication potential, Photochemical ozone creation potential
Wang et al. [61] (2021, A)	MDO engine, battery powered system	CO_2, CH_4, N_2O	Well-to-Wake/Prop	
Yacout et al. [35] (2021, A)	Biodiesel and bioethanol (from pulp and paper mills), MGO and HFO	CO_2, CH_4, N_2O	Well-to-Wake/Prop	Human toxicity non-cancer effects and cancer effects, PM, Photochemical ozone formation, Acidification potential, Terrestrial eutrophication, Freshwater eutrophication, Marine eutrophication, Freshwater ecotoxicity
Zhou et al. [74] (2020, R)	FAME, hydrotreated renewable diesel, FT diesel, DME, bio-methanol	CO_2, CH_4, N_2O	Well-to-Wake/Prop	SOx, NOx, PM (but only via literature review)

4.1 Comparative assessment of life-cycle environmental impacts

For the selected potential zero-carbon marine fuels assessed in this project (i.e., hydrogen, ammonia, and methanol) the climate impact in terms of GHG emissions (converted to g CO_2 equivalent/MJ fuel) in a well-to-wake/propeller perspective based on the reviewed literature is compiled in Table 3. Relatively many studies did not report the climate impact in such a way that it was possible to convert easily into g CO_2 equivalent/MJ fuel and are therefore not included in the table. The result for grey, blue, and green pathways are reported separately and for methanol fossil-, electro- and biomass-based pathways are separated. None of the existing studies assessed all the fuel and propulsion pathways included in this study.

The GHG emissions found in the literature varies between studies also for the same fuel production pathways (Table 3). When comparing the result from different studies but considering the relation between the options from the same studies, grey hydrogen has as expected higher GHG emissions than blue hydrogen which in it turn has higher emissions than green hydrogen (with the exception of one report where the latter are similar, but which seem mainly based on other studies). The same result is valid for ammonia. There are too few studies that have analysed ammonia and hydrogen to be able to draw any conclusions about which of these alternatives has the lowest climate impact. In addition, the results from different studies are not completely comparable as the methods for calculating the environmental impacts varies somewhat in the included studies (different system boundaries). Thus, the intervals presented for blue pathways and green pathways respectively cannot be used for drawing conclusions about their relative GHG impact, but the summary can be used to illustrate the approximate range in the literature. The same conclusion holds for methanol. For methanol none of the identified studies, for which the result could be expressed in g CO2 eq./MJ included both grey, electro- and biomass-based methanol, and in general there were relatively few studies identified.

For comparison with the current policy development, Annex II in the proposed Fuel EU Maritime Regulation (which is not reported in Table 3 since it is not decided upon yet) contains the following proposed default values for GHG emissions well-to-propeller; for green hydrogen 3.6 g CO_2eq/MJ (does not include tank to propeller emissions of N_2O for use in internal combustion engines) and for electro-ammonia 0 g CO_2eq/MJ (emissions of N_2O are not included, EP&C, 2021). For biomass-based methanol as marine fuel the GHG emissions well-to-propeller ,linked to this draft proposal, is estimated by the authors to 15.6 g CO_2eq/MJ based on (i) the average default GHG value for methanol pathways in the Renewable Energy Directive (REDII, referred to in Annex II of Fuel EU Maritime) and based on (ii) the proposed default values in the proposed Fuel EU Maritime Regulation for CH_4 and N_2O emissions tank-to-propeller (EP&C, 2021). Thus, the comparative assessment also highlights the need for the LCA performed in this study in order to have comparable climate impacts for different fuel and propulsion pathways. For a detailed literature review of the environmental impacts of different electrofuels and their different system boundaries and GHG emission the reader is referred to [78].

Table 3 Summary of GHG emissions from the production and use of hydrogen, ammonia and methanol identified in the reviewed publications in a well-to-wake perspective. For hydrogen and ammonia blue, grey and green production pathways are reported separately and for methanol biomass-based, fossil fuel based, and electro-methanol are reported separately. The values from different studies are not completely comparable due to differences in the underlying studies but is used to illustrate the approximate range in the literature. The publication year and publication type are indicated (A-article, R-report or other publication).

Well-to-wake GHG emission (g CO_2 eq./MJ)									
Grey H_2	**Blue H_2**	**Green H_2**	**Grey NH_3**	**Blue NH_3**	**Green NH_3**	**Grey methanol**	**E-methanol**	**Bio-methanol**	***Reference (year, publication type), comment***
151		0	127		5		1		Lindstad et al. [46] (2021, A)
99	22	22	101	21	22	98	22		Horton et al. [70] (2022, R)
222	31	17							Fernández-Ríos et al. [44] (*PEMFC*) (2022, A)
14	8	1							Fernández-Ríos et al. [44] (*ICE*)
			226					72	Bilgili [33] (2021, A)
		14 (Wind power) 43 (Photo-voltaics)							Trillos et al. [43] (2021, R)
303 (Coal power) 197 (Nuclear energy) 198 (Renew. energy) 258 (South Korean gridmix)									Hwang et al. [23] (2020, A)
113		38							Menon and Chan [50] – ICE (2022, A)
264	156	32				185			Gilbert et al. [36] (2018, A)
						165			Balcombe et al. [26] (2021, A) *N_2O not included*
20		*0*	*20*		*0*		*0*		Lloyd´s Register and UMAS [69] *(2020, R) Only CO_2*
181 (14-303) n=7	**54 (8-156) n=4**	**21 (1-43) n=7**	**151 (20-226) n=3**	**21 n=1**	**9 (5-22) n=2**	**149 (98-185) n=3**	**12 (1-22) n=2**	**72 n=1**	**Average (interval in parenthesis, n=number of studies)[a]**

[a]As the report by Lloyd´s register and UMAS does only include CO_2 emissions it is not included in the average value.

5 Method and data

In this study, prospective life cycle assessment (LCA) based on best available information is used to quantify the environmental impact that may be associated with the selected potential zero carbon fuels and fuel production pathways in a Nordic context. The selected fuels for this task are based on the pre-selection of fuels in the assignment description (hydrogen and ammonia) and the screening performed in Task 1-A (Screening and selection of sustainable zero-carbon fuels) [79].

5.1 Goal

The goal is to assess the climate and main environmental impact of the selected potential zero-carbon fuels for marine applications using life cycle assessment (LCA). The selected fuel pathways include compressed and liquefied hydrogen, ammonia and methanol produced from the Nordic electricity mix and from natural gas in combination with carbon capture (the last pathway will only be assessed for hydrogen and ammonia). This to increase the knowledge of the sustainability of various marine fuels and propulsion systems that are relevant for the Nordic region, and to verify under what conditions they fulfil the criteria for being sustainable zero-carbon fuels, as well as potential trade-offs connected to other environmental impact categories.

5.2 Target audience

The results are intended to be used as decision support regarding the potential for ships to reduce their climate and environmental impact, for shipowners when investing in newbuildings and for regulatory bodies involved in relevant policy making. The target audience for this study is Nordic shipping stakeholders including policy makers (e.g., IMO, EU), shipowners and operators, cargo owners, classification societies, the public, academia, shipowners' associations, and non-governmental organizations (NGOs).

5.3 Functional unit

The functional unit is 1 kWh of mechanical energy to the propeller shaft. Emission data for 1 MJ fuel used onboard is provided as well (in Appendix B). This since fuel users also want to understand the environmental impacts for their specific ship and fuel conversion efficiencies.

As pointed out by Campbell et al. [7], the choice of functional unit is somewhat more complex for marine fuels and ships than for fuel use in road vehicles. In case of the latter, the functional unit often used is "transport work" (i.e., CO_2 per tonne-km) for a specified vehicle. The use of the analogue for marine fuels and ships is CO_2 per tonne-nautical mile, which is challenging for example as marine vessels have much greater variation in physical and operational characteristics, including e.g., tankers to container ships to offshore service vessels and as the relevant cargo "unit" associated with the transport work above differs depending on vessel categories [7].

Some studies consider vessel independent LCA of a broad range of marine fuels (see section 3). However, vessel specific LCA is also needed. Since no ship are the same and have a great variation in physical and operational characteristics even among the same ship types, vessel specific LCA is challenging.

In this study, representative ships from average AIS data for selected Nordic ship categories developed in Task 2A is used as a compromise between detailed LCAs done for a specific ship and LCAs only considering the fuel life cycle (i.e., well-to-wake LCA). This is done by considering the power requirement of the vessel and the distance they travel, which makes it possible to include the impact from constructing the propulsion system, i.e., power train and energy storage. In this study, AIS data developed by DNV in Task 2-A of the project is used (see further description in Section 5.5).

Difference to what is proposed in the draft IMO guidelines for life cycle GHG emissions of marine fuels (ISWG-GHG 11/2/3): All emissions are reported only per MJ of fuel in ISWG-GHG 11/2/3.

5.4 Fuel production pathways and ship propulsion systems assessed

There are several potential fuel production pathways and ship propulsion system that could potentially be zero-carbon and/or environmentally sustainable. For an overview of possible options screened within this project see the Task 1A report [79] .

In this report we assess three groups of fuel production pathways, (i) green from biomass and/or mainly renewable electricity (represented by Nordic electricity mix), (ii) blue from natural gas with combined carbon capture and (iii) fossil without carbon capture as reference cases. These production pathways can include different energy carriers that can be used in different ship propulsion system. In total seven different energy carriers (or forms of energy carriers) including ammonia, compressed hydrogen, liquid hydrogen, methanol, liquid methane gas (LMG), liquid natural gas (LNG), and marine gas oil (MGO) are considered. In addition, using electricity directly is considered through the use of batteries. Dependent on the type of energy carrier, different types of propulsion system setups are possible. We consider in total five types of propulsion systems, (i) 2-stroke diesel engine propulsion configurations, (ii) 4-stroke diesel propulsion configurations, (iii) proton-exchange membrane (PEM) fuel cell (FC) propulsion configurations including batteries for managing load changes (iv) solid oxide fuel cell (SOFC) propulsion configuration including batteries for managing load changes and (v) battery-electric propulsion systems configurations. The most relevant engine and fuel combinations chosen for assessment have been based on input from partners and other shipping actors.

In total, 32 fuel and propulsion options are investigated (see overview in Table 4 and full list of the pathway names in Appendix A). It is important to note that the maturity level of the options differs and the expected potential use in 2030 varies (some are already in use). However, it is expected that all options could at least be used in pilot scale by 2030.For more information on the current use of different marine fuels and expected deployment the reader is referred to DNV [80].

Table 4 Overview of the combined fuel production pathways and ship propulsion options included for each energy carrier in the assessment. Thus, the different fuel production pathways are combined with the relevant possible propulsion options considered. In total 32 options are investigated.

	Fossil fuel production pathways without carbon capture	**Blue fuel production pathways**	**Green fuel production pathways**		**Main propulsion options considered**[a]							**Total # of combinations considered**
		Steam reforming of natural gas with carbon capture and storage (NGccs-)	Biomass (bio-)	Nordic electricity mix (e-)	2-stroke engines (2S ICE)	2-stroke dual-fuel engines (2S-DF ICE)	4-stroke engines (4S ICE)	4-stroke dual-fuel engines (4S-DF ICE)	Proton-exchange membrane fuel cells (PEMFC)	Solid oxide fuel cells (SOFC)	Battery electric (Elec BE)	
Ammonia (NH3)[c]		Yes		Yes		Yes		Yes		Yes		6
Compressed hydrogen (CH2)[c]		Yes		Yes		Yes		Yes	Yes			6
Liquid hydrogen (LH2)[c]		Yes		Yes		Yes		Yes	Yes			6
Methanol (MeOH)[c]			Yes	Yes		Yes		Yes		Yes		6
Liquid methane gas (LMG)[c]			[b]	Yes		Yes		Yes		Yes		3
Electricity				Yes							Yes	1
Liquid natural gas (LNG)	As reference					Yes		Yes				2
Marine gas oil (MGO)	As reference				Yes		Yes					2

[a]SOFC and PEM fuel cell (FC) propulsion systems also includes batteries to manage load changes.

[b]Biomass-based pathways are only considered for the relevant fuels in focus in the Nordic roadmap project (mainly assessing ammonia, hydrogen and methanol), and thus not for LMG. For assessments of renewable methane from anaerobic digestion and biomass gasification see for example Jivén et al. [1].

[c]Hydrotreated vegetable oil (HVO) is assumed to be used as pilot fuel for the alternative to use only potential zero-carbon in the operational phase.

5.5 Representative ships assessed

For the representative ship LCAs average AIS from Task 2-A [81] (that includes an AIS analysis of the Nordic ship traffic and energy use) are used (Table 5). The ship types assessed in a Nordic perspective are representative chemical tankers, general cargo and Ro-pax. The presently installed power of engines is used to select the propulsion system components, however, the efficiencies of different propulsion configurations described in section 5.4 are also considered when the components are selected. The fuel tank and batteries are sized based on the 90-percentile voyage fuel consumption from AIS data for the representative ship operation in 2019 [81], efficiencies of the propulsion system configuration, type of storage tank (cryogenic insulated tanks for liquid hydrogen, methane, natural gas, and pressurized tanks for ammonia and compressed hydrogen), specific heat and density of the fuel. This might underestimate the environmental impact from the fuel tank manufacturing somewhat as more fuel margin might be included in the tank capacity during ship design, resulting in a larger fuel tank. However, it is a compromise to not use a too conservative assumption when using AIS data for 2019 and extrapolating that for ships operating in 2030 as the ships need to improve their energy efficiency.

The size of the components is used for calculating the environmental impacts associated with the manufacturing of the components. The components like fuel cell stack, batteries, and SCR would degrade at a higher rate than other components (it is considered in this report that the components have to be replaced after losing 20% capacity). The replacement of these required during the ship life cycle is calculated based on the rate of degradation and ship life cycle[82]. For fuel cells the rate of degradation is assumed as 0.4% per 1000 hrs, and the batteries are assumed to have similar lifetime of fuel cell due to cell degradation. It may be noted that there would be lesser maintenance for the fuel cell and battery-operated vessels during operation compared to ICE as there are no moving parts in the system. The impact from materials and operation due to such maintenance is however not included in the report. These environmental impacts from the *manufacturing phase* and *replacement phase* of ship components are then converted to the functional unit of the report, which is 1 kWh of mechanical energy to the propeller shaft using the ship life cycle and annual energy use based on the AIS assessment.

The operational emission and fuel consumption change with the cargo loads which vary from ship to ship. For simplicity, in this report, two modes of engine operation are considered that are 20% engine load while manoeuvring and 80% engine load while cruising or transit. It is assumed that by 2030 shore power would be available for the ships when they are in ports. In addition to the propeller load (driven by main engines), there are additional auxiliary and boiler loads also should be considered while assessing the operational emissions and the fuel required. Since the functional unit used in the report is 1 kWh propeller all the loads are recalculated towards it. Further, the 1kWh propeller load is divided between manoeuvring and cruising. For the share of 1kWh propeller in manoeuvring, the percentage time manoeuvring (speed <= 5 knots) from AIS data along with the 20% engine load point is used to calculate the manoeuvring share of propeller load.

For the general well-to-wake assessment without adding details for representative ships from the AIS data the average value from the ships in Nordic ship traffic, i.e., ships sailing to and from Nordic ports, are used normalised based on the ships fuel consumption at sea. 79% of the energy demand are on average used at sea, 3% during manoeuvring and 18% in port. This corresponds to that 96% of the 1kWh propeller for cruising and the remaining 4% for manoeuvring[5]. No auxiliary demand or heat demand is considered in the well-to-wake assessment.

Auxiliary load and thermal load are derived from the fuel consumption data based on AIS assessment. The auxiliary and thermal load are calculated as the ratio of auxiliary engine energy use to main engine energy use and boiler energy use to main engine energy use respectively. The emission factors of

[5] The shares are recalculated so that propulsion power (cruising and manoeuvring) in total represent 1 kWh.

engine/FC operation are used to calculate the environmental impact during the ship *operation phase*. The total fuel required for the operation is calculated by summing the fuel consumed for all loads (propeller, auxiliary, and boiler). The fuel consumed for each load in MJ is calculated using the respective efficiencies of the propulsion system configuration which includes the specific fuel consumption of main fuel (also pilot fuel wherever applicable). The sum-product of the quantity of fuel (and pilot fuel) for ship operation and well-to-tank environmental impact of the respective fuel type (and pilot fuel) and shore electricity (during port) is used to calculate the average ship-specific impact on the *fuel production phase*.

Table 5 Ship data representative for Nordic shipping used in this study for the Nordic ships life cycle assessment (based on AIS data). NA represent data not available. Domestic represents ships sailing primarily within one country, International represents ships sailing primarily between Nordic countries and other countries and Intra Nordic represents ships sailing primarily between Nordic countries.

	Ship types selected				
	Chemical tanker,10000-25000GT, international	**Chemical tanker, 25000-50000GT, international**	**General cargo ship, 1000-5000GT, domestic**	**General cargo ship, 5000-10000GT, intra Nordic**	**Ro-Pax, 10000-25000GT, intra Nordic**
Average GT	16200	29500	2700	6800	15100
Average DWT	17337	36232	3830	9263	2681
Time at Sea	47%	54%	46%	52%	42%
Time in port	48%	40%	48%	44%	45%
Time manoeuvring (0.3>speed<5 knots)	5%	6%	6%	4%	12%
Installed Power (kW)	9483	12015	2040	4906	17325
Annual fuel consumption (Mtonnes MGO eq.)	5038	6404	933	2542	7237
90 percentile voyage fuel consumption (Mtonnes MGO eq.)	219	480	22	109	25
ME annual fuel consumption (Mtonnes MGO eq.)	3221	4698	762	1984	4126
AE annual fuel consumption (Mtonnes MGO eq.)	1354	1307	170	439	1528
Boiler fuel consumption (Mtonnes MGO eq.)	463	399	NA	120	1584
Fuel consumed at port (Mtonnes MGO eq.)	740	562	77.48	246	2430
Average lifetime of ship (years)[82]	30	30	35.4	35.4	38.4

Due to the increased volume of the marine fuels and propulsion systems considered a screening similar to what is done in Task 2A [80] is performed for the representative ship LCAs. The volumes of the main fuels and pilot fuels as well as the battery are calculated. If the volume of the main fuel and pilot fuels divided with the gross tonnage (GT) is greater than 3 times the average GT for existing fleet using traditional fuel the option is considered infeasible. For a more detailed description of the feasibility approach see DNV [80].

5.6 Technical system boundaries

The technical system boundaries include fuel production and its infrastructure, transport of the fuel to site of use, the use of the fuel onboard and, in case of the Nordic representative average ship LCAs, the construction of the propulsion system. The reason for including environmental impacts also from the propulsion system, in the average ship LCAs, is that there is a need to also better understand the role of this part. For the facilities and equipment used for fuel production and the ship propulsion system, generic data are used. To consider the potential for the use of on-shore power in ports it is assumed in the average ship LCAs that all ships when in port use on-shore power. The ship hull, deck, propeller, accommodation areas and other technical systems is not included in the assessment as it is outside the scope of the study. However, the implementation of the assessed fuels may influence the ship design of new vessel.

Difference to what is proposed in draft IMO guidelines for life cycle GHG emissions of marine fuels (ISWG-GHG 11/2/3): Only the fuel life cycle is considered in ISWG-GHG 11/2/3 and not, as in this study, the impacts from producing the propulsion system. Furthermore, it is unclear where the system boundaries in relation to infrastructure for producing the fuels are drawn in the guidelines.

5.7 Geographical boundaries

The assessment considers Nordic ship traffic, i.e., ships sailing to and from Nordic ports. The fuels are also considered to be produced in the Nordic countries. For the use of electricity, a Nordic electricity mix is used. Norwegian natural gas is assumed. The components for the propulsion systems are assumed to be produced in Europe. A large part of the component manufacturing is however currently in Asia with expected larger GHG emissions from electricity production than in Europe implying that this might be an optimistic scenario for 2030. However, the carbon intensity of the future electricity mix is expected to decrease both in Asia and in Europe.

Difference to what is proposed in the draft IMO guidelines for life cycle GHG emissions of marine fuels (ISWG-GHG 11/2/3): Global values are reported in most case in the guidelines.

5.8 Time perspective

Two different time perspectives for ship operation are used in this study. The first and main time perspective considers ship operation in the near future, around 2030. Near term performance is collected from experts in the consortia, from suppliers and from literature and reports. The potential for improvements during the ship lifetime, for example connected to extended lifetime of ship components, will not be considered. The second time horizon considers potential operation in the more distant future around 2050 and this 2050 outlook represents a sensitivity assessment. Assumptions are made for how the assessed technical systems will change between 2030 and 2050. The changes are detailed in Table 6.

Table 6 Overview of assumptions for background data in the two timeframes: ship operation in 2030 and ship operation in 2050.

Parameter	Assumption used in 2030	Assumption used in 2050
Electricity used for fuel production	Nordic grid mix forecasted by Nordic Clean Energy Scenarios (24.7 g CO_2/kWh)	Low emission power production (2.4 g CO_2/kWh)[83][1]
Fuel pathways	Green and blue	Green
Electrolysers	Alkaline	SOEC
Production and refining of materials used	Today's production	Assumed new process with close to zero GHG emissions
Urea production	From natural gas	From renewable resources
ICE emissions of CH_4 and N_2O	As in Table 10 and 11	As in Table 10 and 11/a lower estimate for emission needing additional exhaust abatement technologies

[1] *Represents electricity from offshore wind power in a 2050 scenario reaching low GHG emissions.*

Difference to what is proposed in the draft IMO guidelines for life cycle GHG emissions of marine fuels (ISWG-GHG 11/2/3): The time horizon is not specified in the draft guidelines. However, based on the overall description the present situation for the fuels, when the guidelines are implemented and applied is likely the aim.

5.9 Impact categories

The main environmental impact categories included in this study are global warming potential in a 20 and 100-year time perspective using the data from the IPCC Six Assessment report [84], acidification potential, and particulate matter formation potential using the Environmental Footprint 3.0 method [85].

In addition to this, a broad set of environmental impact categories are included for screening purposes to identify potential environmental trade-offs including for example:

- Eutrophication marine
- Eutrophication terrestrial
- Eutrophication freshwater
- Ecotoxicity freshwater inorganics
- Ecotoxicity freshwater organics
- Ecotoxicity freshwater metals
- Human toxicity, cancer effects
- Human toxicity, cancer effects - metals
- Human toxicity, non-cancer effects
- Human toxicity, non-cancer effects inorganics
- Human toxicity, non-cancer effects organics
- Human toxicity, non-cancer effects metals
- Ionising radiation
- Ozone depletion
- Photochemical ozone formation
- Resource use fossil
- Resource use minerals and metals
- Land use

Difference to what is proposed in in the draft IMO guidelines for life cycle GHG emissions of marine fuels (ISWG-GHG 11/2/3): ISWG-GHG11/2/3 only considers global warming potential and in a 100-year time perspective from the IPCC Six Assessment report [84].

5.10 Analysing the robustness of the result

For some parts of the life cycle and for some of the selected fuels, there is a lack of data or at least to some extent uncertain data. The reason is that the studied fuel alternatives and technology pathways are under development and have not yet been used to a large extent in marine applications. One example is emission measurements from engines that run on fuels currently not used extensively within shipping such as hydrogen and ammonia. The LCA from well-to-wake of selected fuel options will be based on the best available information and well-founded assumptions when needed. The results can be updated at a later stage when more data is available.

5.11 Model set-up

The LCA is performed using the software OpenLCA version 1.11.0 and Excel.

5.12 Data

As shown in Figure 3, the inventory data for the fuel life cycle and the ship life cycle are analysed. The result and inventories in the report are arranged into four phases; 1. The fuel production phase, 2. Component manufacturing phase, 3. Ship operation, 4. Component replacement. The inventory data includes raw material, energy carriers, products, waste, and emissions to the environment. The four phases are assessed separately in OpenLCA based on the output flows, which are described in the sections below. The data for average ships from the AIS analysis in task 2A which are presented in Table 5 is used to connect the different parts of the life cycle. Possible future changes of the ships, besides the change of fuel and propulsion technologies, such as implementation of energy efficiency measures is outside the scope of this project.

Data is collected from previous and ongoing projects, from knowledge and data available within the project consortia and from LCA databases such as Ecoinvent 3.7.1. The data used is presented below.

5.12.1 Fuel production overview

Seven main energy carriers (besides electricity) and one pilot fuel (HVO) is included in the study whose properties are given in Table 7. These energy carriers are associated with different production pathways and some of the energy carriers have multiple pathways assessed in this report (for e.g., green hydrogen and blue hydrogen, see Section 5.4). There are several different possibilities connected to the different choices of fuel production pathways. For example, on the carbon source for the electrofuel production pathways, the choice of electrolyser for hydrogen production, the choice of methane reforming etc. The choices made linked to the pathways used for the study is described in the sections below.

Table 7 Properties of the fuels considered in this study.

	Liquid Ammonia [86]	**Liquid Hydrogen [86]**	**Compressed Hydrogen (700 bar) [86]**	**Methanol [87]**	**Liquid Methane/LNG [87]**	**HVO [88]**	**MGO**
Boiling point [ºC] [89]	-33.4	-253		65	-161	180-360	200-385
Lower heat value [MJ/kg]	18.6 (17.2)[a]	120	120	19.9	50/48	44	42.7
Auto ignition temperature [ºC]	651	571	571	439	585	204	250
Flammability Limits in air [vol.%]	15-28	4.7-75	4.7-75	7.3-36	5.3-15		0.5 -5
Density (kg/m^3)	682.6	70.8	42	791.4	468.1	780	855

[a]In the engine it is only the heating content after vaporization of ammonia that can be used, and the values 17.2 MJ/kg is therefore used for the engine efficiency and emission calculations. The heat of vaporization of ammonia is about 1.4 MJ/kg.

5.12.2 Hydrogen production pathways

Hydrogen is used as fuel and also feedstock for the production of ammonia, methanol, and methane. Hydrogen can be produced from different feedstocks, but this study focuses on green and blue hydrogen. However, presently over 95% of the current hydrogen is produced from fossil fuel-based energy sources [90].

Green hydrogen: Green hydrogen is produced by electrolysis of water using renewable energy. The study from Delpierre et al. [91] suggests that there is no significant variation in environmental impact between the PEM electrolyser and the alkaline electrolyser. Another possibility is to use a solid oxide electrolyser, however, the cost of solid oxide electrolysers is high and it is currently not cost-competitive with other electrolysers [92] and hence not considered in the study. As the alkaline electrolyser is more mature and less expensive, this study only considers alkaline electrolyser. The inventory data for green hydrogen for this study is taken from Delpierre et al. [91], which considers 50 kWh of electricity, 10 kg of water, and 1-2 g of potassium hydroxide for producing 1 kg of hydrogen. The LCI data for the electrolyser construction is assumed from the same study.

Blue hydrogen: Blue hydrogen is produced by methane reforming of natural gas, combined with CO_2 capture and storage. The methane reforming of natural gas can be done either via steam methane reforming or auto thermal reforming. Simulation results from the study by Antonini et al. [93] show that auto thermal reforming have an advantage to attain high CO_2 capture rates, hence auto thermal reforming is considered. Also, amine-based absorption is considered for CO_2 capture technology with a capture rate of 90%. The inventory data for the blue hydrogen is from the LCA study by Antonini et al. [93]. The data for natural gas is presented in section 5.12.7. It is assumed that CO_2 captured from these facilities is then de-bunkered at the port of Gothenburg and transported and further injected into the geological storage at Northern Lights and the inventory data is taken from the study by Kanchiralla et al. [94].

5.12.3 Hydrogen as energy carrier

Irrespective of the different production pathways of hydrogen, the uncompressed gaseous hydrogen has very low volumetric energy content and very low density. It is technically difficult to use it as an energy carrier in terms of storage, and distribution. The hydrogen needs to be compressed to high pressures or liquefied.

Compressed hydrogen: For increasing the density and volumetric energy content, the most common method is to compress the gas and store it in pressurised tanks. The study considers 700 bar compressed hydrogen and assumes electricity required for compression at 0.1 kWh/kWh of hydrogen [95].

Liquid hydrogen: Liquid hydrogen has higher energy density by volume than compressed hydrogen but to liquefy 1 kg of hydrogen whose boiling point is -253°C, theoretically, a minimum of 3.3 kWh of energy is required [90]. The results from the IDEALHY project show that the liquefaction of H_2 can be achieved with 6.4 kWh/kg hydrogen using a reverse Brayton cycle [96], which is assumed for this study assuming that it could achieve commercial operation by 2030. The LCI data for the hydrogen liquefaction plant infrastructure are taken from the IDEALHY project [96].

5.12.4 Ammonia production pathways

Presently, ammonia is produced in Haber Bosch plants using fossil feedstocks – natural gas (70%), coal (around 20%), and oil (less than 5%) [97]. This study focuses on green and blue ammonia.

Green ammonia: There are multiple pathways for producing green ammonia such as the Haber Bosch process (TRL 9), electrochemical process (TRL 1-3), photocatalytic (TRL 1-3), biological (TRL 1-3), and non-thermal plasma (TRL 1-3) [98]. In this study, it is considered that green ammonia is produced using the Haber Bosch process using green hydrogen and nitrogen. The production of 1 kg NH_3 is assumed to require 0.177 kg H_2, 0.823 kg nitrogen, and 0.472 kWh of electricity. In addition to the electricity required for production hydrogen and separating nitrogen air there is also an electricity demand for the Haber Bosch process which is stated above. The LCI for the NH_3 synthesis and air separation unit production facilities are taken from Ecoinvent 3.7.1.[98]. From this process, the output is liquid NH_3. Nitrogen can be obtained with an air separation unit, cryogenic air distillation is a low-cost technology that can deliver high purity nitrogen in high volumes [99]. For separating 1 kg of nitrogen through cryogenic air distillation, 0.314 kWh of electricity is required [99]. The LCI for the NH_3 synthesis and air separation unit production facilities are taken from Ecoinvent 3.7.1.

Blue ammonia: Similar to blue hydrogen, blue ammonia is produced from the reforming of methane from natural gas and combined with CO_2 capture and storage. However, additional energy is required for Haber Bosch process, which is assumed in the study provided by additional natural gas in the furnace. It is assumed that the CO_2 from the flue gas is also captured, which is designed for the study by modifying the Ecoinvent data base. Parameters for autothermal reforming and CO_2 capture technology are assumed similar to the blue hydrogen production mentioned in 5.1.1.

Ammonia can be liquefied by pressurization or cooling (or a combination of the two) and is assumed to be stored and distributed in liquefied form.

5.12.5 Methanol production pathways

Methanol can be produced from different feedstock including biomass and renewable energy sources but is also presently produced mainly from fossil fuels [100]. Electro methanol is produced from renewable energy, green hydrogen, and captured CO_2. This study, uses inventory details from Kiss et al. [101] and feedstock required for 1 kg of electro methanol are 1.375 kg of carbon dioxide, 0.189 kg hydrogen, and 0.858 kWh of electricity and heat (of additional demand except for what is used when producing hydrogen and carbon dioxide). The carbon capture process is assumed to be a post-combustion absorption technology with monoethanolamine (MEA) (potassium and sodium hydroxide) scrubbing of flue gases from biogenic energy processes (i.e., biomass-based). The parameters used are based on Ravikumar et al. [102] in which liquefied CO_2 at high pressure is produced from flue gases containing high concentrations of CO_2. The production emissions for used chemicals and deionised water are taken from Ecoinvent 3.7.1.

There are different ways to capture carbon for the production of electrofuels. Due to the Nordic perspective of this study in which there are substantial sources of biogenic flue gases (i.e., from pulp and paper production, biofuel production and combined heat and power, see e.g., Hansson et al. [103]) we have chosen to assume carbon capture via MEA from biogenic flue gases for the assessed e-fuel pathways (methanol and methane). The LCI for the methanol synthesis infrastructure are taken from Ecoinvent 3.7.1.

The bio-methanol production in the study is based on methanol produced from the energy crop willow. The willow is grown in Sweden and four major processes are included: collection of willow (including direct land use), transportation, pre-treatment, and the methanol synthesis. The methanol synthesis goes via syngas and the pre-treatment process only uses electricity to dry the biomass. The first two processes are based on data presented by Börjesson [104] in combination with Rytter [105]. The two later processes are based on CPM [106] and CPM [107]. The transport distance for cultivated willow is assumed to be an average of 30 km one way. Energy consumption for this transport includes empty backhaul.

Willow is a short rotation coppice crop possible to grow in areas with low soil quality or high pollution levels. When cultivation takes place in northern European conditions the competition with food production and forest management is low, but some indirect land use effects are possible. In this study the direct land use change is included but the indirect land use effects are assumed to be low. However, if the biogenic methanol is utilized for a significant part of the shipping fleet other biomass pathways should also be considered.

5.12.6 Methane production pathways

Green methane can be produced from renewable energy, green hydrogen, and captured CO_2 [108]. The study assumes that methane is produced by the Sabatier reaction process, which requires 2.939 kg of carbon dioxide, 0.506 kg of hydrogen, and 0.33 kWh of electricity and heat [108]. The carbon capture technology assumed is the same as in the methanol section. The green hydrogen production pathway is assumed to be the same as the one described in section 5.1.1. The LCI for the methane synthesis infrastructure are taken from Ecoinvent 3.7.1.

5.12.7 Marine gas oil and liquefied natural gas

Inventory details for marine gas oil are taken from the Ecoinvent 3.7.1 (diesel production, low-sulfur, petroleum refinery operation | diesel, low-sulfur | Cutoff). Inventory details for LNG are also taken from the Ecoinvent 3.7.1 (market for natural gas liquids | natural gas liquids | Cutoff). As natural gas is assumed to be produced in Norway and distributed only to the Nordic countries no boil-off to atmosphere is assumed. It should however be noted that there are risks of boil-off that cannot be used as fuel in the LNG supply chain and these leakages have in a global context been found to be significant.

5.12.8 Hydrotreated vegetable oil

Hydrotreated vegetable oil (HVO) will be used as pilot fuel for the cases that needs pilot fuel. The HVO is assumed to be produced from slaughterhouse waste, which is considered a residue (meaning no additional upstream emissions are considered). The process data is gathered from [109, 110]. The chemicals are assumed to be produced on the global market and the electricity used is European average at 446 g CO_2-eq./kWh.

5.12.9 Electricity pathways

Electricity is used for three applications, i) fuel production/liquefaction, ii) component production, and iii) charging batteries. For production of the green fuels included in this study, Nordic electricity mix corresponding to 24.7 g CO_2/kWh is considered in this study which is calculated based on the electricity mix presented for 2030 in the Nordic clean energy scenarios [111]. For the component production application, electricity is assumed from the European electricity mix as the component is assumed to be produced in different locations in Europe. Electricity mixes are based on projected scenarios for the time horizon 2030 by the EU Commission based on the reference year 2020 and including present policies [112] as shown in Table S3. For charging batteries, Nordic electricity mix is considered [113].

5.12.10 Facility and infrastructures for fuel production

The study includes the fuel production infrastructure required to produce the above fuels. The LCI details of the infrastructures considered in this study are given in Table 8.

Table 8 Fuel production infrastructure included in this study and references used.

Infrastructure	Description	Ref	Service life
Hydrogen liquefaction/compressor plant	Hydrogen liquefaction plant based on reverse Brayton cycle	[114]	25
Carbon capture plant	Carbon capture plant based on temp-vacuum swing adsorption	[115]	30
Electrolysis plant	Alkaline electrolysis plant	[91]	30
Electro-methanol plant	methanol factory construction | methanol factory | Cutoff, S	Ecoinvent 3.7.1	30
Air separation unit	air separation facility construction | air separation facility | Cutoff	Ecoinvent 3.7.1	30
Ammonia plant	chemical factory construction, organics | chemical factory, organics | Cutoff	Ecoinvent 3.7.1	30
Methane plant	natural gas processing plant production | natural gas processing plant | Cutoff, S	Ecoinvent 3.7.1	30
Auto thermal reformer plant	chemical factory, organics | chemical factory, organics | Cutoff, S - GLO	Ecoinvent 3.7.1	30
Methane liquefaction plant	natural gas processing plant production | natural gas processing plant | Cutoff, S	Ecoinvent 3.7.1	30

5.12.11 Component manufacturing and end-of-life

In this phase, only major components which differs between the different propulsion systems are considered in the study, which includes engines, SCR, PEMFC, SOFC, batteries, motor, alternator, heat pump, and fuel tanks. Boilers are traditionally used onboard ships and only a few have looked into the feasibility of heat pumps in ships [116, 117], but in this study is assumed that heat pumps would be used in ships by 2030. This assumption has a very limited impact on the result and will not affect the comparison between the different options, but results in lower overall fuel consumption and emissions for ships with significant heat demand. Residential and industrial sectors are now widely replacing boilers with heat pumps. The sizes of the engine or fuel cell and associated components depend on the maximum power required to be delivered to the propeller, auxiliary electrical load, heating load, and additional requirement like start-up and power ramping and is different for different propulsion system setup. There are five propeller configurations covered in the study including SOFC propulsion, PEMFC propulsion, 2-stroke diesel engine propulsion, 4-stroke diesel engine propulsion configuration, and battery electric propulsion (see Figure 5 and Table 9). The equations used for component sizing (including engine, generator, control unit, fuel cell stack, fuel tank size, battery capacity) based on ship parameters are included in the figure/table.

The type of tank depends on the energy carrier. Vacuum insulated tanks for liquid hydrogen, liquefied methane and liquefied natural gas, pressurized tanks for ammonia and compressed hydrogen, and marine fuel tank for MGO and methanol. The size of the tank is in the ship LCA performed in this assessment determined based on the 90th percentile fuel consumption trip and efficiency of the propulsion system. This might underestimate the environmental impact from the fuel tank production somewhat as more fuel margin might be included in the tank capacity during ship design, resulting in a larger fuel tank. However, it is a compromise to not use a too conservative assumption when using AIS data for 2019 and extrapolating that for ships operating in 2030 as the ships need to improve their energy efficiency. The tanks are assumed to be made of stainless steel.

Engine and SCR: The typical raw material composition for engine used in the study is from Kanchiralla et al. [118]. Selective catalytic reduction (SCR) is used for engines operated with MGO, green methanol, and green ammonia. However, SCR requires high exhaust gas temperature and the addition of Urea or NH_3 for efficient reduction. If SCR is available, the engine can operate on a high fuel-efficient setting often associated with higher NO_X from the engine (before SCR) [119]. This ensures that there is no major loss of efficiency. The activating element on the catalyst is assumed as TiO_2 and is around 0.25% of the weight of SCR [120].

PEMFC: Fuel cells convert the chemical energy of H_2 to electricity through electrochemical oxidation. As the conversion is direct and no need for high combustion temperatures, fuel cells offer higher energy conversion efficiency than conventional energy systems[121]. Low-temperature polymer electrolyte membrane fuel cell (PEMFC) systems are currently the most preferred technology for most transport applications since they have a high power density and allow fast cold start-up and load transient, if pure H_2 is available [122]. The materials for PEMFC cell and balance of plant (BoP) are adopted from the study by Usai et al. [123]. An addition battery system is assumed for power ramping.

SOFC : The manufacturing inventory for SOFC used in the study is from Kanchiralla et al. [118] and Al-Khori et al [124]. The efficiency of the SOFC depends on the Gibbs energy and enthalpy change and other parameters like cathodic flow and parasitic losses. The efficiency considered in the study is different for different fuel: methane-65%, ammonia-60%, and methanol-60%. SOFC needs additional battery system for start-up and power ramping and sized for 30 minutes at 20% load.

Batteries: Presently, lithium-ion batteries are the most predominant power source for electric vehicles, of which lithium-rich NMC batteries have a high economic energy density [125]. For this study, lithium-ion battery with NMC 811 cathode and a graphite anode is considered. The material data is adopted from the LCA study on a Giga factory for battery manufacturing, Chordia et al [126]. The material data required for cooling system, battery management system, and battery packaging apart from battery cells adopted from Ellingsen et al. [127].

Electric motor and alternator: The manufacturing inventory for motor and alternator used in the study is adopted from Kanchiralla et al. [118].

Heat pump: A heat pump is considered for supplying heat to general areas on board. The material specification and weight are calculated from the manufacturing catalogue and material composition is taken from the study by Lozano Miralles et al. [128].

The end-of-life is included using cut-off approach during the input of raw material, where a share of secondary raw material is assumed in the upstream input for manufacturing. By using this method, i.e. assuming a share of the secondary material, it avoids the burden of the primary production but includes the burdens caused by the recovery and upgrading processes [129].

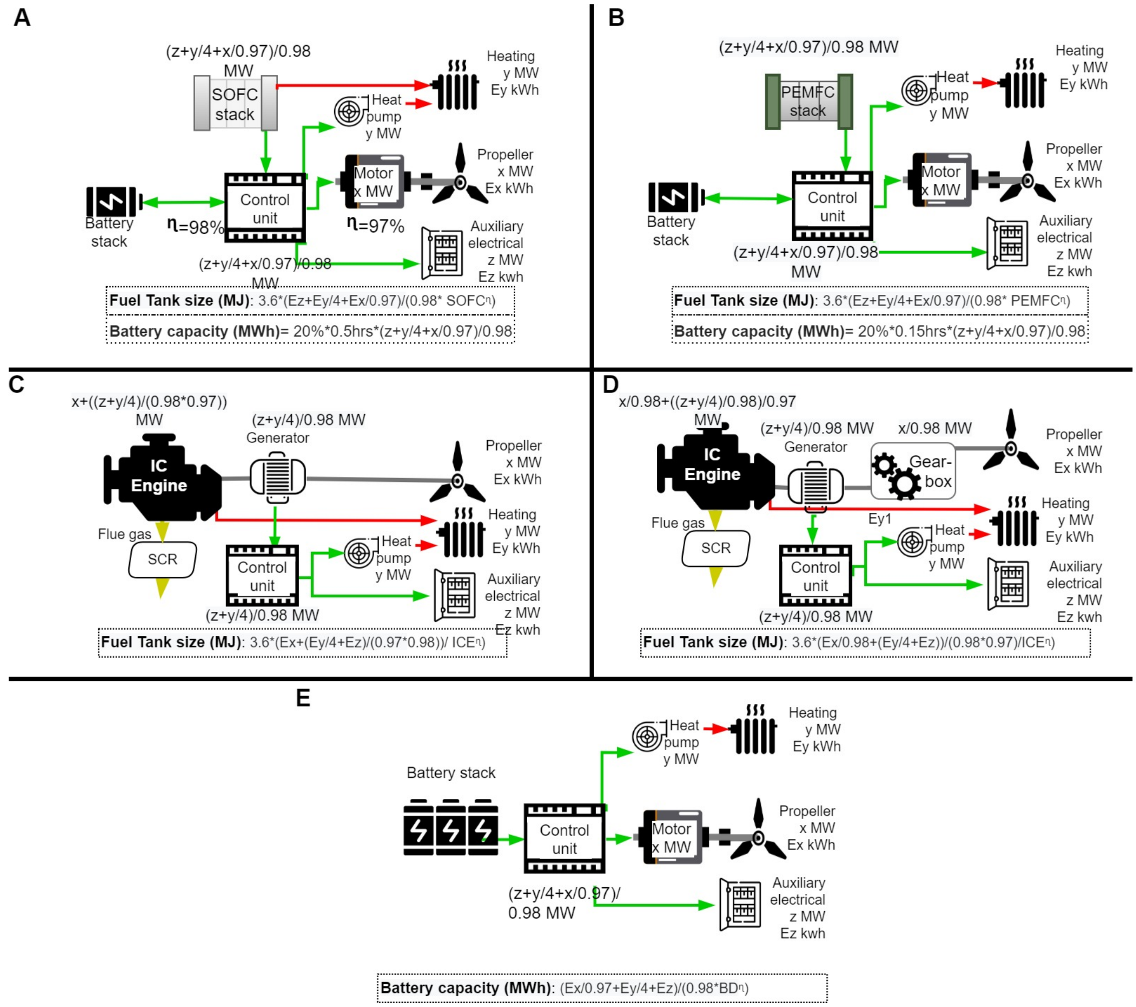

*Figure 5 Six propulsion system configurations along with the component sizing derivations based on ship parameters. Box A represents SOFC propulsion configuration, Box B represents PEMFC propulsion configuration, Box C represents 2-stroke diesel engine propulsion configuration, Box D represents 4-stroke diesel engine propulsion configuration, and Box E represents battery electric propulsion combination. x is the maximum propeller power required, y is maximum heat power required, and z is maximum auxiliary power required for ship operation. Similarly, Ex is propeller energy, Ey is thermal energy, and Ez is auxiliary energy for the longest trip/most fuel consuming trip. * η-efficiency, BDη- battery discharge efficiency, ICEη-engine efficiency.*

Table 9 Tank-to-wake efficiencies for the ship propulsion systems calculated from the formulas in Figure 5 for the propeller and auxiliary efficiency. The relationship between the propeller and auxiliary energy demand varies for the different representative average ships.

	2S engine **MGO, LNG, LMG, MeOH, H_2, (NH_3 in parenthesis)**	**4S engine** **MGO, LNG, LMG, MeOH, H_2, (NH_3 in parenthesis)**	**PEMFC** **H_2**	**SOFC** **LMG, (NH_3 + MeOH in parenthesis)**	**BE**
Tank-to-wake propeller efficiency	50% (46%)	47% (43%)	52%	59% (57%)	84%
Tank-to-wake auxiliary efficiency	46% (42%)	46% (42%)	54%	61% (59%)	86%

5.12.12 Operation phase

During the operation phase, emissions from the engine and other energy converters primarily depend on the type of fuel used and the fuel consumption. Both 2-stroke, 4-stroke and fuel cells are in this project considered as main energy converters.

The engines considered in this study are in various stages of development, from diesel engines that has been on the market for decades to dual fuel H_2 and NH_3 engines that still need extensive testing for marine applications. As an example, the engine manufacturer Wärtsilä is presently testing a dual fuel engine running on NH_3 and a pilot fuel and anticipates further developments to reach lower emissions and lower use of pilot fuel by the year 2023 [130]. MAN Energy Solutions is also developing an NH_3 fuelled 2-stroke dual fuel engine (also requiring a pilot fuel) and is anticipated to be ready by 2024 [131].

The emission inventory data and fuel consumption data for engines are based on different studies [25, 132-137] and from discussions with engine manufacturers. For ICEs the fuel consumption varies with engine load and for this study, an average engine load of 80% during cruising and 20% during manoeuvring is assumed (see Table 10 and 11). All engines are modelled to comply with the Tier III NOx requirement as they must be fulfilled in the North Sea and Baltic Sea in 2030. There are, dependent on engine type, different possibilities to reduce the NOx emissions. To be consistent it is in this report assumed that a SCR is used in combination with urea as reducing agent, with the exception of NH_3 engines, which are assumed to use ammonia as reducing agent instead, for the cases where abatement is required to reach Tier III. For dual fuel engines, HVO (see section 5.12.8 for production data) is assumed to be used as pilot fuel except for LNG engines where MGO is the assumed pilot fuel.

The data used for 4-stroke engines are presented in Table 10. All 4-stroke engines are assumed to have an overall engine efficiency of 48% at high engine load and 40% at low engine load. The 4-stroke engine using MGO and 4-stroke dual fuel engine using NH_3 as main fuel are operating according to the diesel principle with high injection pressure and thus with higher NOx emissions and are assumed to use SCR. The other 4-stroke dual fuel engines are assumed to operate according to the otto principle with lean burn combustion and associated lower NOx emission levels and these options are thus assumed to reach Tier III NOx emissions without exhaust abatement. The data used for the 4-stroke engines are presented in Table 10.

All 2-stroke engines are assumed to have an overall engine efficiency of 50% for both 80% and 20% engine load. For the dual fuel two stroke engines 5% of the energy is coming from the pilot fuel. The dual fuel 2-stroke engines considered are operating according to the diesel principle with high injection pressure of the fuel. There are also dual fuel 2-stroke engines operating with the otto principle on the market and under development (but they are not considered in this report). All 2-stroke engines are assumed to need exhaust abatement for reducing the NOx to Tier III levels. For all option except the 2-stroke dual fuel NH_3 engine SCR and urea is assumed to be used. The urea is assumed to be produced from natural gas in the 2030 case. Based on discussions with engine experts, the NH_3 engine is not assumed to need an external reducing agent as unburned NH_3 can act as the reducing agent. The amount of urea and NH_3 assumed to be used in the SCR is shown in Table 11. For 2-stroke engines the same emission profile is assumed for cruising and manoeuvring, this is a simplification done in this study, but it is recognised that the emission profile depends on engine load and that this is important to consider in future studies.

When urea is used there is additional emissions of CO_2 as urea contains carbon. This is included in the assessment. An ammonia slip of 0.05g have been assumed for all engines using SCR.

The black carbon emissions from hydrogen and ammonia are based on assuming similar emissions as from methane and methanol respectively and should be considered conservative and very uncertain.

From all NH_3 engines there is a risk of formation of nitrous oxide (N_2O) which is a strong greenhouse gas. N_2O could potentially also be reduced to nitrogen in a catalyst and trials to investigate this is ongoing. As no NH_3 engines are on the market the emission values used are uncertain and needs to be updated when more information is available.

For PEMFC, during the electrochemical reaction, only water is produced as a by-product and for SOFC, nitrogen and water are by-products of combustion and based on discussion with experts, there will not be any notable emission of pollutants from fuel cells (see Table 12 for the assumed efficiencies and emissions from the fuel cells), when carbon based fuels are used in fuel cells the CO_2 emissions is based on the efficiency of the fuel cell and the carbon content of the fuel. The SOFC operates at high temperatures and the heat from the exhaust can be used for general heating on board. The efficiency of different components also affects fuel consumption.

Except for the engines and fuel cells additional energy converters are considered in some of the propulsion systems. The following assumptions for efficiency are considered in the study: 97% for electric motor [138], 97% for alternator [139], 98% for the gearbox [138], 98% for the control unit [140], and for the heat pump a coefficient of performance (COP) of 4 [141].

Table 10 Emissions factors used for the 4-stroke engines.

Technology used	Dual fuel, 4 stroke (otto)		Dual fuel, 4 stroke (diesel cycle)		Dual fuel, 4 stroke (otto)		Dual fuel, 4 stroke (otto)		Four-stroke (diesel cycle)		Dual fuel, 4 stroke (otto)	
Fuel used	H_2		NH_3		Methanol		LMG		MGO		LNG	
LHV (MJ/kg)	120		17.2		19.9		50		42.7		48	
Pilot fuel	HVO		HVO		HVO		HVO		-		MGO	
LHV (MJ/kg)	44.1		44.1		44.1		44.1		-		42.7	
Engine load	80%	20%	80%	20%	80%	20%	80%	20%	80%	20%	80%	20%
Fuel consumption (g/kWh)	62	72	410	421	369	432	147	172	176	211	153	279
Carbon content main fuel (g CO_2/g fuel)	0	0	0	0	1.38	1.38	2.75	2.75	3.21	3.21	2.75	2.75
Pilot fuel consumption (g/kWh)	2	8	10	40	3.5	9	3.5	9.0	-	-	3.5	9.0
Efficiency (%)	48%	40%	48%	40%	48%	40%	48%	40%	48%	40%	48%	40%
Carbon content pilot fuel (g CO_2/g fuel)	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	-	-	3.2	3.2
Urea consumption (g/kWh)	0	0	0	0	0	0	0	0	15.3	20	0	0
CO_2 from urea (g CO_2/g urea)	0	0	0	0	0	0	0	0	0.73	0.73	0	0
Ammonia instead of urea (g/kWh)			8.6	11.4								
Emissions (g/kWh):												
CO_2	6	24	30	123	518	621	402	436	574	682	420	458
BC	3.6E-06	1.1E-05	0.001	0.005	0.001	0.005	3.6E-06	1.1E-05	0.0058	0.036	3.6E-06	1.1E-05
CO	0.30	0.70	0.30	0.70	0.50	1.00	1.90	6.15	0.30	0.70	1.90	12.40
N_2O	-	-	0.30	0.40	-	-	0.01	0.01	-	-	0.01	0.01
CH_4	-	-	-	-	-	-	3.5	20	0.001	0.001	3.5	20
NOx	2.1	2.7	2.1	2.7	2.1	2.7	2.1	2.7	2.1	2.7	2.1	2.7
NMVOC	0.1	0.2	0.3	0.4	0.5	4	0.5	4.0	0.3	0.4	0.5	4.0
PM10	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.20	0.20	0.04	0.04
SOx	-	-	-	-	-	-	-	-	0.38	0.47	0.01	0.02
NH_3	-	-	0.05	0.05	-	-	-	-	0.05	0.05	-	-
Formaldehyde	-	-	-	-	0.0005	0.0005	0.0005	0.0005	-	-	0.0005	0.0005

Table 11Emissions factors used for the 2-stroke engines.

Technology used	Two-stroke, diesel cycle		Two-stroke, diesel cycle		Two-stroke, diesel cycle		Two-stroke, diesel cycle		Two-stroke, diesel cycle		Two-stroke, diesel cycle	
Fuel used	H_2		NH_3		Methanol		LMG		LNG		MGO	
LHV (MJ/kg)	120		17.2		19.9		48		50		42.7	
Pilot fuel	HVO		HVO		HVO		HVO		MGO			
LHV (MJ/kg)	44.1		44.1		44.1		42.7		44.1			
Engine load	80%	20%	80%	20%	80%	20%	80%	20%	80%	20%	80%	20%
Fuel consumption (g/kWh)	57	57	398	398	344	344	137	137	143	143	167	167
Carbon content main fuel (g CO_2/g fuel)	0.0	0.0	0.0	0.0	1.38	1.38	2.75	2.75	2.75	2.75	3.21	3.21
Pilot fuel consumption(g/kWh)	8	8	8	8	8	8	8	8	8	8	0	0
Engine efficiency (%)	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Carbon content pilot fuel (g CO2/g fuel)	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.21	3.21	-	-
Urea consumption (g/kWh)	7	7	0	0	7	7	7	7	7	7	7	7
CO_2 from urea (g CO2/g urea)	0.73	0.73	0	0	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
Ammonia instead of urea (g/kWh)	-	-	3.99	3.99	-	-	-	-	-	-	-	-
Emissions (g/kWh):												
CO2	30	30	25	25	502	502	403	403	421	421	540	540
BC	3.60E-06	3.60E-06	0.001	0.001	0.001	0.001	3.60E-06	3.60E-06	3.60E-06	3.60E-06	0.0058	0.0058
CO	0.30	0.30	0.30	0.30	0.50	0.50	1.90	1.90	1.90	1.90	0.30	0.30
N2O	-	-	0.09	0.09	-	-	0.01	0.01	0.01	0.01	0.02	0.02
CH4	-	-	-	-	-	-	0.20	0.20	0.20	0.20	-	-
NOx	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
PM10	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.20	0.20
SOx	-	-	-	-	-	-	-	-	0.02	0.02	0.33	0.33
NH3	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Formaldehyde	-	-	-	-	-	-	-	-	-	-	-	-

Table 12 Efficiencies [142] and emissions factors used for the fuel cells[143].

	H_2 PEMFC	NH_3 SOFC	MeOH SOFC	LMG SOFC
Efficiency	55%	60%	60%	62%
LHV (MJ/kg)	120	18.6	19.9	50
SFC (g/kWh)	55	319	301	121
CO (g/kWh)	-	-	0.0091	0.0150
CO_2 (g/kWh)	-	-	413.9	332.7
NOx (g/kWh)	-	0.0031	0.0008	0.0008
PM (g/kWh)	-	-	0.0001	0.0001

5.12.13 Replacement phase

Batteries, fuel cell stacks, and SCR catalysts are assumed to be replaced during a vessel's lifetime. The number of replacements depends on the operating hours. For fuel cells, the rate of degradation is assumed as 0.4% per 1000 hrs, and the batteries are assumed to have a similar lifetime to fuel cells due to cell degradation. It may be noted that there would be lesser maintenance for the fuel cell and battery-operated vessels during operation compared to ICE as there are no moving parts in the system. The impact from materials and operation due to such maintenance is however not included in the report. It may be noted that the battery would either discharge during manoeuvring and cruising or charge during mooring, making it in active operation for the entire period. Whereas fuel cells would be idle during the mooring. In the case of SCR, only the catalyst needs to be replaced. For fuel cells, the balance of plant need not be replaced. The same material content for manufacturing is assumed in case of replacement.

The second life of batteries is under discussion, and it may be a possibility that the batteries could be used in other applications after their use onboard a ship. A possible second life of batteries is not considered in this study.

6 Assessment of life-cycle environmental impacts

In this section the assessment of life-cycle environmental impacts is presented, first the well-to-wake fuel life cycle impacts (not including propulsion system production) and then the LCAs for the representative average ships also including the construction of the propulsion system, auxiliary energy, and heat demand. The section ends with an outlook to 2050.

6.1 Well-to-wake fuel life cycle impacts

This section presents the LCA results for the fuel production including infrastructure and distribution and transport of the fuel and for the fuel used onboard. Energy use in port is not considered nor the production of the propulsion system (see section 6.2 for this).

6.1.1 Well-to-tank energy use

The well-to-tank energy use depend on the conversion losses for the different fuel production pathways These conversion losses depend on the production pathway and type of energy carrier as shown in the Figure 6. Energy losses during the fuel production show great differences between the pathways and depend on the type of feedstock and processes involved during fuel production. The e-LMG pathway has the highest conversion losses resulting in higher energy use followed by e-MeOH. For e-fuels, the major share of energy loss is for electrolysis to produce hydrogen. For methane and methanol, the fuel synthesis process results in loss of hydrogen in water molecules, unlike for hydrogen and ammonia pathways (Methane: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$; Methanol: $CO_2 + 3H_2 \rightarrow CH_3OH + 2H_2O$). In addition, electricity is required for the operating flue gas carbon capture system. The hydrogen pathways have the lowest energy conversion losses.

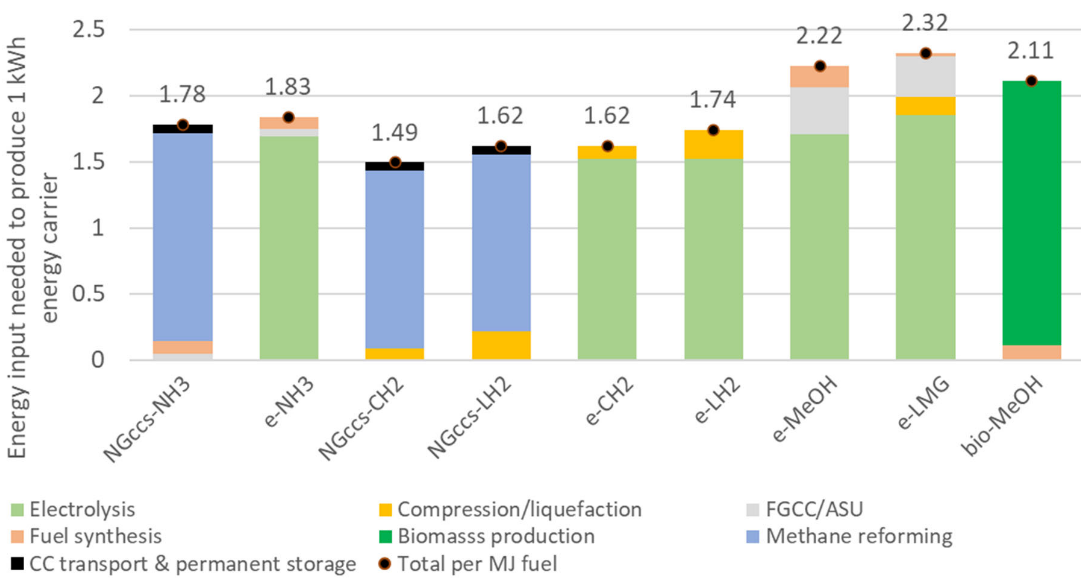

Figure 6 Well-to-tank energy use for the production of different fuels. Abbreviations: FGCC=flue gas carbon capture, ASU= air separation unit.

6.1.2 Global warming potential

Compared to the traditional fuels used in shipping, as marine gas oil and liquefied natural gas, all options could reduce GHG emissions by 2030 (Figure 7). For GHG emission data for 1 MJ fuel used onboard see Appendix B. The green fuel production pathways (from biomass or Nordic electricity mix) are associated with lower GHG emissions compared to the corresponding blue fuel production pathways (from natural gas with carbon capture and storage). There is a better performance in terms of climate impact of the fuel cells compared to the 2-stroke ICE pathways, which in turn performs better than the corresponding 4-stroke engine pathway, which is due to differences in efficiency of the propulsion options.

For the global warming potential, the well-to-wake results are rather similar in impact when considering both a 100-year (Figure 7) and a 20-year time perspective (Figure 8). The exceptions are methane and LNG used in 4-stroke internal combustion engines (e-LMG 4S, LNG 4S) where the methane leakages during the life cycle causes higher climate impact in a shorter time perspective than in a longer time perspective.

The biomass-based methanol pathways result in the lowest climate impact. All, the green fuel pathways have, with the exception of electro-methane in 4-stroke engines (which are associated with emission of methane from the ICE compared to the other options), show lower total climate impacts compared to blue fuel pathways. This is caused by leakages of methane from natural gas extraction and that not all CO_2 can be captured due to technical limitation of the carbon capture technologies. The assumed carbon capture rate for blue hydrogen production is 90%.

Green carbon-based fuel pathways assessed, i.e., methanol and methane, use captured carbon in the fuel production phase which makes the carbon impact negative for this step (Figure 7 and 8).

The ammonia-based pathways seem, in the 2030 case in this study, to have somewhat higher climate impact than the corresponding hydrogen pathways but the relation is uncertain due to uncertainties linked to future emissions from ammonia propulsion systems. Ammonia-based propulsion systems have challenges with emissions of nitrous oxides (N_2O) when used in marine engines. However, the N_2O emission from marine ammonia engines when they are in production is still largely unknown and engine manufacturers will work on reducing these emissions. The emission levels assumed in this report also require further reduction in emissions compared to data from test engines. The use of ammonia in fuel cells is still an unmature pathway and it is difficult to know the future performance

When looking at the same fuel, the use in fuel cells seem to result in lower climate impact than use in different types of ICEs and use in 2-stroke engine has somewhat lower climate impact than use in 4-stroke engine. This is driven by the higher efficiency of the 2-stroke ICEs and fuel cells and for fuel cells the zero emissions of CH_4 and N_2O.

In Table 13, the results from the LCA of the included fuels in this study, well-to-wake, in terms of GHG emissions (expressed in g CO_2 eq./MJ) is compared to the ranges identified based on the literature review. The difference in terms of ammonia and methanol depend on the very limited number of existing studies and are due to different system boundaries and assumptions applied. For the specific paper investigating bio-methanol [33] there is a lack of detailed description about assumptions and system boundaries making comparison with this study difficult. An outlook for the potential global warming potential for the assessed options in 2050 is presented in Section 6.3. The impact on global warming of also including the production of the propulsion system is illustrated in the average ship LCAs presented in Section 6.2.

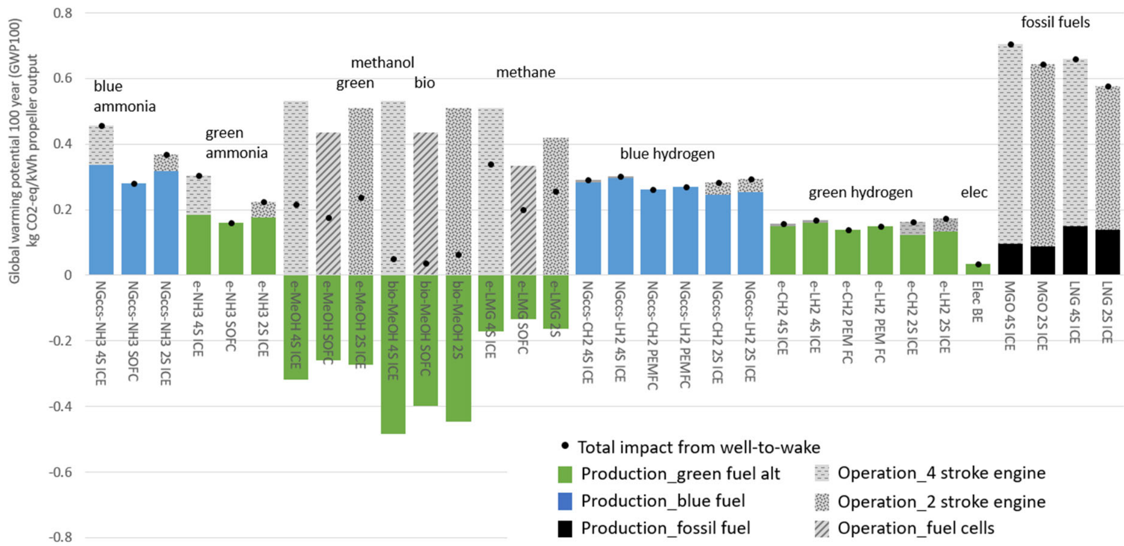

Figure 7 Global warming potential (in kg CO_2-eq.) in a 100-year time perspective for the investigated potential zero-carbon fuels in Nordic shipping in 2030 for 1 kWh propeller output. The global warming potential is illustrated for fuel/energy carrier production including distribution and transport (and for the battery-electric option the production of electricity) and for operation onboard the ship. ***The dots represent the net value from well-to-wake****. NGccs - steam reforming of natural gas with carbon capture and storage, NH3 - ammonia, 4S – 4-stroke engine, 2S – 2-stroke engine, ICE – internal combustion engine, SOFC - solid oxide fuel cell, e-NH3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass based methanol, e-LMG – electro-methane, CH2 – compressed hydrogen, LH2 – liquefied hydrogen, PEMFC – Proton-exchange membrane fuel cell, Elec-BE – Battery Electric, MGO – marine gas oil, LNG – liquefied natural gas. For full description of the assessed pathways see Table 4 and Appendix A.*

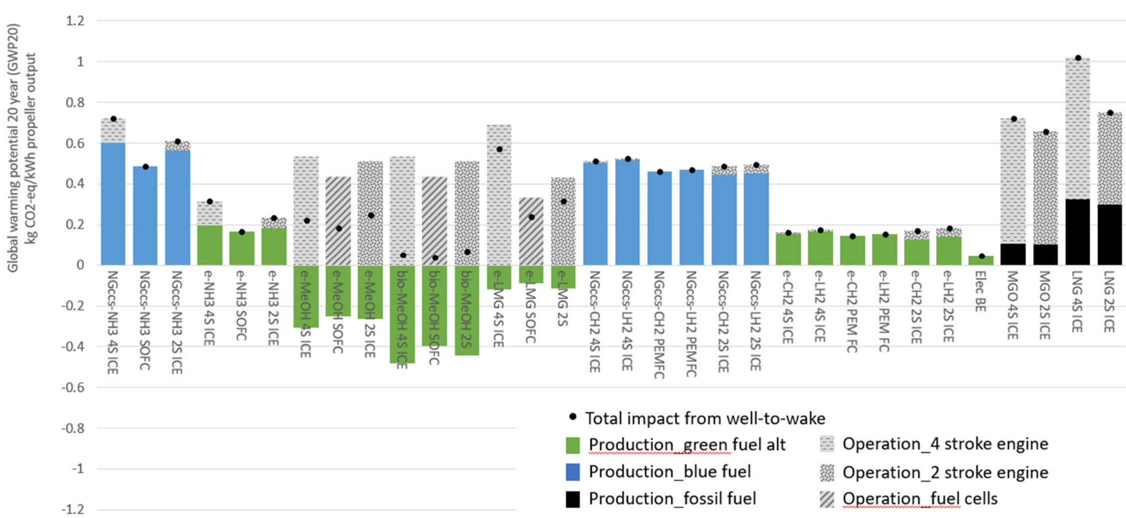

Figure 8 Global warming potential (in g CO_2-eq.) in a 20-year time perspective for the investigated potential zero-carbon fuels in Nordic shipping in 2030 for 1 kWh propeller output. The global warming potential is illustrated for fuel/energy carrier production including distribution and transport and for operation onboard the ship. ***The dots represent the net value from well-to-wake****. NGccs - steam reforming of natural gas with carbon capture and storage, NH3 - ammonia, 4S – 4-stroke engine, 2S – 2-stroke engine, ICE – internal combustion engine, SOFC - solid oxide fuel cell, e-NH3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass based methanol, e-LMG – electro-methane, CH2 – compressed hydrogen, LH2 – liquefied hydrogen, PEMFC – Proton-exchange membrane fuel cell, Elec-BE – Battery Electric, MGO – marine gas oil, LNG – liquefied natural gas. For full description of the assessed pathways see Table 4 and Appendix A.*

Table 13 Comparison of the GHG emissions for hydrogen, ammonia and methanol from a well-to-wake perspective with the LCA approach used in this study and the ranges of GHG emissions from these fuels identified in the reviewed publications.

Well-to-wake GHG emission (g CO_2 eq./MJ)									
Grey H_2	**Blue H_2**	**Green H_2**	**Grey NH_3**	**Blue NH_3**	**Green NH_3**	**Grey methanol**	**E-methanol**	**Bio-methanol**	***Reference (year, publication type), comment***
181 (14-303) n=7	54 (8-156) n=4	21 (1-43) n=7	151 (20-226) n=3	21 n=1	9 (5-22) n=2	149 (98-185) n=3	12 (1-22) n=2	72 n=1	Average (interval in parenthesis, n=number of studies)
-	38-39	20-23	-	45-54	26-36	-	28-33	6-9	This study 2030

6.1.3 Acidification

The acidification potential -for the investigated potential zero-carbon propulsion systems is shown in Figure 9. Alternatives using ICEs have a higher acidification potential than the options using fuel cells and batteries. This is mainly associated with the NO_X emissions from the engines (2S ICE respective 4S ICE options). In most cases, the 2-stroke engines are associated with more NO_X emissions and also higher acidification potential. There is also some contribution from the fuel production and distribution phase. All assessed options are indicated to have lower acidification potential compared to the corresponding MGO option. Battery electric followed by biomass-based methanol in SOFC, hydrogen in PEMFC and ammonia in SOFC have the lowest acidification potential. Compared to LNG, the 2-stroke engine options result in higher acidification potential and for the 4-stroke engine there is higher and lower acidification potential for different options.

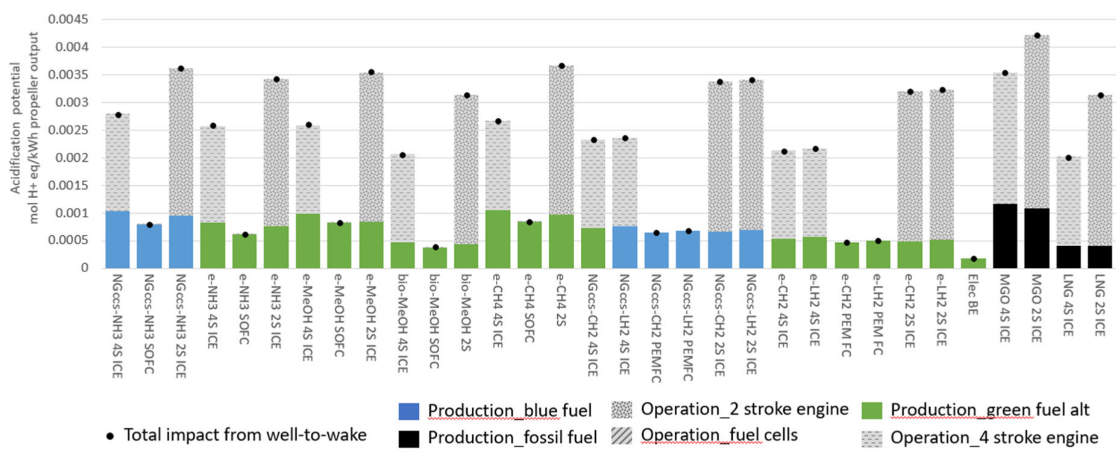

*Figure 9 Acidification potential (in mol H+) for the investigated potential zero-carbon fuels in Nordic shipping in 2030 for 1 kWh propeller output. The acidification potential is illustrated for fuel/energy carrier production including distribution and transport and for operation onboard the ship. **The dots represent the net value from well-to-wake**. NGccs - steam reforming of natural gas with carbon capture and storage, NH3 - ammonia, 4S – 4-stroke engine, 2S – 2-stroke engine, ICE – internal combustion engine, SOFC - solid oxide fuel cell, e-NH3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass based methanol, e-LMG – electro-methane, CH2 – compressed hydrogen, LH2 – liquefied hydrogen, PEMFC – Proton-exchange membrane fuel cell, Elec-BE – Battery Electric, MGO – marine gas oil, LNG – liquefied natural gas. For full description of the assessed pathways see Table 4 and Appendix A.*

6.1.4 Particulate matter

Figure 10 shows the results for the investigated fuel and propulsion options investigated for the impact category particulate matter. All assessed options are indicated to have lower particulate matter potential compared to the corresponding MGO option with the exception of electro-methane in 2-stroke engine which is estimated to have the same impact. Biomass-based methanol in SOFC, natural gas based compressed, battery electric and liquefied hydrogen in PEMFC has the lowest particulate matter followed by natural gas-based ammonia in SOFC. Compared to LNG many of the options including 2- and 4-stroke engines result in higher particulate matter potential.

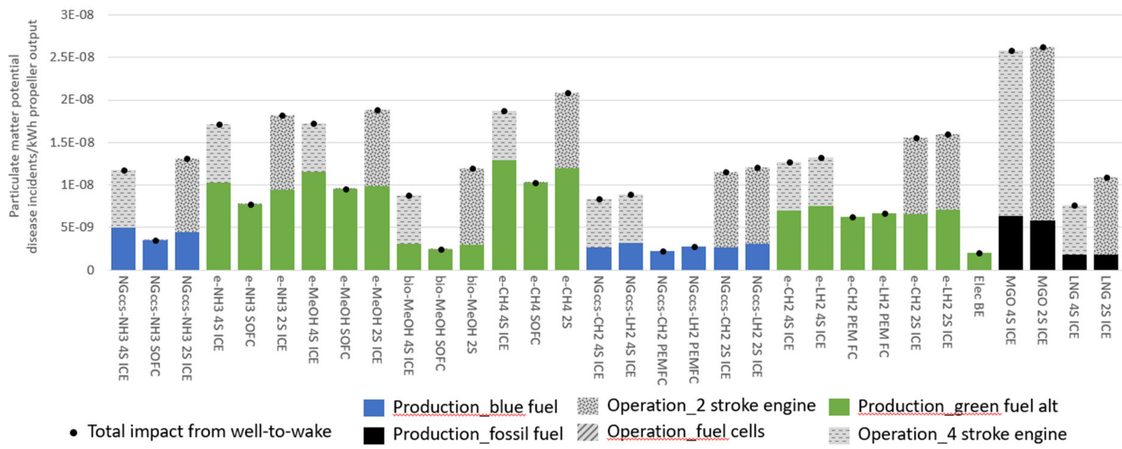

Figure 10 Particulate matter potential for the investigated potential zero-carbon fuels in Nordic shipping in 2030 for 1 kWh propeller output. The particulate matter potential is illustrated for fuel/energy carrier production including distribution and transport and for operation onboard the ship. ***The dots represent the net value from well-to-wake****. NGccs - steam reforming of natural gas with carbon capture and storage, NH3 - ammonia, 4S – 4-stroke engine, 2S – 2-stroke engine, ICE – internal combustion engine, SOFC - solid oxide fuel cell, e-NH3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass based methanol, e-LMG – electro-methane, CH2 – compressed hydrogen, LH2 – liquefied hydrogen, PEMFC – Proton-exchange membrane fuel cell, Elec-BE – Battery Electric, MGO – marine gas oil, LNG – liquefied natural gas. For full description of the assessed pathways see Table 4 and Appendix A.*

6.1.5 Other environmental impacts

An overview of how the investigated fuel and propulsion options perform for the other environmental impact categories in the Environmental Footprint method (listed in Section 4.8) is presented in Figures 11 and 12. Figure 11 indicates the relative impact compared to MGO (decrease or increase) estimated for each included environmental impact category. The impacts of all alternative fuel options with 4-stroke engines and fuel cells are normalized by the impact of 4-stroke engine MGO and with MGO in 2-stroke engines for the options with 2-stroke engines. The share of the total impact categories assessed, for each assessed option, with a potentially higher impact than MGO is summarized in Figure 12. As much data gathered for underlying emissions are uncertain, the result in Figure 12 is a screening of potential impacts and should be considered with care. More investigation is called for on these impact categories in order to verify the results. However, there is an indication that some of the studied options could have significantly higher impact on human toxicity, ionising radiation, land use and resource use potential than MGO (see Figures 11-12), indicating potential goal conflicts. This stresses the importance of making further assessments in this area. The overall increased impact for all investigated potential zero-carbon fuels on human toxicity are mainly linked to the electricity use. The increased production of renewable electricity in power plants results in emissions of toxic emissions, particles and other emissions to the environment, as concluded in earlier work on electrofuels, such as [73, 144]. The exact emissions and their amount vary between renewable energy power plant types and construction sites.

	NGccs-NH3 4S ICE	NGccs-NH3 SOFC	NGccs-NH3 2S ICE	e-NH3 4S ICE	e-NH3 SOFC	e-NH3 2S ICE	e-MeOH 4S ICE	e-MeOH SOFC	e-MeOH 2S ICE	bio-MeOH 4S ICE	bio-MeOH SOFC	bio-MeOH 2S	e-CH4 4S ICE	e-CH4 SOFC	e-CH4 2S	NGccs-CH2 4S ICE	NGccs-LH2 4S ICE	NGccs-CH2 PEMFC	NGccs-LH2 PEMFC	NGccs-CH2 2S ICE	NGccs-LH2 2S ICE	e-CH2 4S ICE	e-LH2 4S ICE	e-CH2 PEM FC	e-LH2 PEM FC	e-CH2 2S ICE	e-LH2 2S ICE	Elec BE
Acidification	0.8	0.2	0.9	0.7	0.2	0.8	0.7	0.2	0.8	0.6	0.1	0.7	0.8	0.2	0.9	0.7	0.7	0.2	0.2	0.8	0.8	0.6	0.6	0.1	0.1	0.8	0.8	0.1
Ecotoxicity, freshwater	0.9	0.7	1	1.9	1.5	1.9	2	1.7	1.9	0.2	0.2	0.3	2.2	1.7	2.2	0.5	0.6	0.4	0.5	0.5	0.6	1.2	1.3	1.1	1.2	1.3	1.3	0.2
Ecotoxicity, freshwater - inorganics	0.3	0.2	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.1	0.1	0.1	0.3	0.2	0.3	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0
Ecotoxicity, freshwater - metals	1.5	1.2	1.6	3.2	2.5	3.3	3.4	2.8	3.2	0.4	0.3	0.4	3.6	2.9	3.7	0.8	0.9	0.7	0.8	0.8	0.9	2.1	2.2	1.9	2	2.2	2.3	0.3
Ecotoxicity, freshwater - organics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eutrophication, freshwater	4.5	3.6	5.6	5.8	4.6	7.2	3.4	2.8	4	1.2	1	1.7	4.4	3.6	5.6	1.4	1.5	1.3	1.4	1.9	2.1	2.4	2.6	2.2	2.3	3.1	3.3	1.1
Eutrophication, marine	1.1	0.2	1.1	1.1	0.2	1.1	1.1	0.2	1	1	0.1	1	1.1	0.2	1.1	1	1.1	0.2	0.2	1	1	1	1	0.1	0.2	1	1	0
Eutrophication, terrestrial	1.1	0.2	1.1	1.1	0.2	1.1	1.1	0.3	1.1	1	0.1	1	1.1	0.3	1.1	1	1	0.2	0.2	1	1	1	1	0.1	0.2	1	1	0
Human toxicity, cancer	3.7	2.9	4.1	4.6	3.6	5.2	3.1	2.5	3.1	2.3	1.8	2.5	5.9	4.7	6.4	1.5	1.7	1.3	1.5	1.7	1.9	2.2	2.4	2	2.2	2.5	2.7	0.6
Human toxicity, cancer - metals	4.3	3.4	4.8	5.1	4	5.7	2.9	2.4	3.1	2.7	2.3	3.1	5.3	4.3	5.9	1.6	1.8	1.4	1.6	1.8	2.1	2.2	2.4	2	2.2	2.5	2.8	0.7
Human toxicity, non-cancer	2	1.6	2.2	3.6	2.8	3.9	2.9	2.4	2.9	0.8	0.6	0.8	3.2	2.5	3.4	0.8	0.9	0.7	0.8	0.9	1	2.1	2.2	1.8	2	2.2	2.4	0.7
Human toxicity, non-cancer - inorganics	0.8	0.6	0.8	1.7	1.3	1.8	1.8	1.5	1.7	0.2	0.2	0.2	2.3	1.9	2.4	0.5	0.6	0.5	0.5	0.5	0.6	1.3	1.4	1.2	1.2	1.3	1.4	1.1
Human toxicity, non-cancer - metals	2.6	2	2.8	4.5	3.5	4.9	3.3	2.8	3.4	0.9	0.8	1.1	3.6	2.9	3.9	0.9	1.1	0.8	1	1	1.2	2.4	2.6	2.2	2.4	2.6	2.8	0.6
Human toxicity, non-cancer - organics	3	2	4.6	2.1	1.3	3.1	1.3	0.4	0.9	1.4	0.5	1.2	1.3	0.4	1	1.2	1.2	1	1	2	2	0.4	0.5	0.3	0.3	0.7	0.7	0.2
Ionising radiation	1	0.8	1.1	9.7	7.6	9.9	10.9	9.1	10	0.6	0.5	0.6	10.9	8.8	10.8	0.9	1.4	0.8	1.3	0.9	1.4	8	8.6	7.2	7.8	7.9	8.5	3.2
Land use	1	0.8	1	7.1	5.6	7.2	7.8	6.5	7.2	1.3	1.1	1.3	7.8	6.3	7.8	0.7	1.1	0.6	1	0.7	1.1	5.7	6.1	5.2	5.5	5.7	6.1	0.1
Ozone depletion	0.7	0.6	0.7	0	0	0	0	0	0	0	0	0	0	0	0.1	0.6	0.6	0.5	0.5	0.6	0.6	0	0	0	0	0	0	0
Particulate matter	0.5	0.1	0.5	0.7	0.3	0.7	0.7	0.4	0.7	0.3	0.1	0.5	0.7	0.4	0.8	0.3	0.3	0.1	0.1	0.4	0.5	0.5	0.5	0.2	0.3	0.6	0.6	0.1
Photochemical ozone formation	1.1	0.2	1.1	1	0.1	1	1.1	0.2	1	1	0.1	0.9	1.1	0.2	1	0.9	0.9	0.2	0.2	1	1	0.8	0.8	0.1	0.1	0.9	0.9	0
Resource use, fossils	1.4	1.1	1.4	0.9	0.7	1	1	0.9	1	0.1	0.1	0.1	1	0.8	1.1	1.1	1.2	1	1.1	1.2	1.2	0.8	0.8	0.7	0.7	0.8	0.8	0.3
Resource use, minerals and metals	17	13.4	29.3	13.7	10.8	23.6	1.4	1.2	2.9	5.3	4.4	9.5	1.4	1.2	3.1	3.7	3.8	3.4	3.4	6.8	6.9	0.9	0.9	0.8	0.8	2.1	2.2	0.3
IPCC 2021 GWP 100	0.6	0.4	0.6	0.4	0.2	0.4	0.3	0.2	0.4	0.1	0.1	0.1	0.5	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.2	0.2	0.2	0.2	0.3	0.3	0
IPCC 2021 GWP 20	1	0.7	0.9	0.4	0.2	0.4	0.3	0.3	0.4	0.1	0.1	0.1	0.8	0.3	0.5	0.7	0.7	0.6	0.6	0.7	0.8	0.2	0.2	0.2	0.2	0.3	0.3	0.1

Figure 11 The relative impact of the assessed fuel options on the studied environmental impact categories compared to MGO in 4-stroke engines (MGO 4S) for all 4-stroke and fuel cell options and compared to MGO in 2-stroke engines (MGO 2S) for all 2-stroke engines. Green colour represents substantial decrease in impact compared to MGH, yellow represents same or almost the same impact as MGO, orange represents a clear increase in impact compared to MGO and red represents a considerable increase compared to MGO. NGccs - steam reforming of natural gas with carbon capture and storage, NH3 - ammonia, ICE – internal combustion engine, SOFC - solid oxide fuel cell, e-NH3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass based methanol, e-LMG – electro-methane, CH2 – compressed hydrogen, LH2 – liquefied hydrogen, PEMFC – Proton-exchange membrane fuel cell, Elec-BE – Battery Electric, MGO – marine gas oil, LNG – liquefied natural gas. For full description of the assessed pathways see Table 4 and Appendix A.

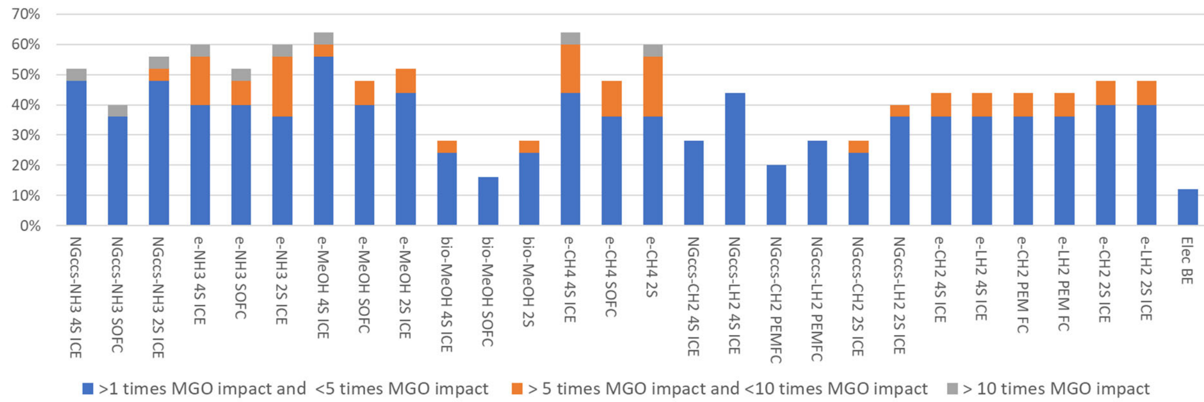

Figure 12 Overview of the share of the total number of impact categories assessed, for each assessed fuel and propulsion option, for which the environmental impact from a LCA perspective is higher compared to the impact from MGO. The comparison is made with MGO in 4-stroke engines (MGO 4S) for all 4-stroke engine and fuel cell options assessed and with MGO in 2-stroke engines (MGO 2S) for all 2-stroke engine options assessed. NGccs - steam reforming of natural gas with carbon capture and storage, NH3 - ammonia, ICE – internal combustion engine, SOFC - solid oxide fuel cell, e-NH3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass based methanol, e-LMG – electro-methane, CH2 – compressed hydrogen, LH2 – liquefied hydrogen, PEMFC – Proton-exchange membrane fuel cell, Elec-BE – Battery Electric, MGO – marine gas oil, LNG – liquefied natural gas. For full description of the assessed pathways see Table 4 and Appendix A.

6.2 Life cycle impacts for representative average ships

The total life cycle impacts vary, to some extent, between different ship types, see Figure 13. Results are only shown for options that are screened as feasible according to what is described in section 5.5. It is differences in operational pattern e.g., different auxiliary energy demand, different energy demand while in port, that contributes to the main differences in the results and not the manufacturing and replacement of the propulsion system for the impact categories global warming potential, acidification potential, and particulate matter potential. For options where the battery-electric option is screened infeasible, the manufacturing of the battery may contribute to a visible part of the environmental impacts.

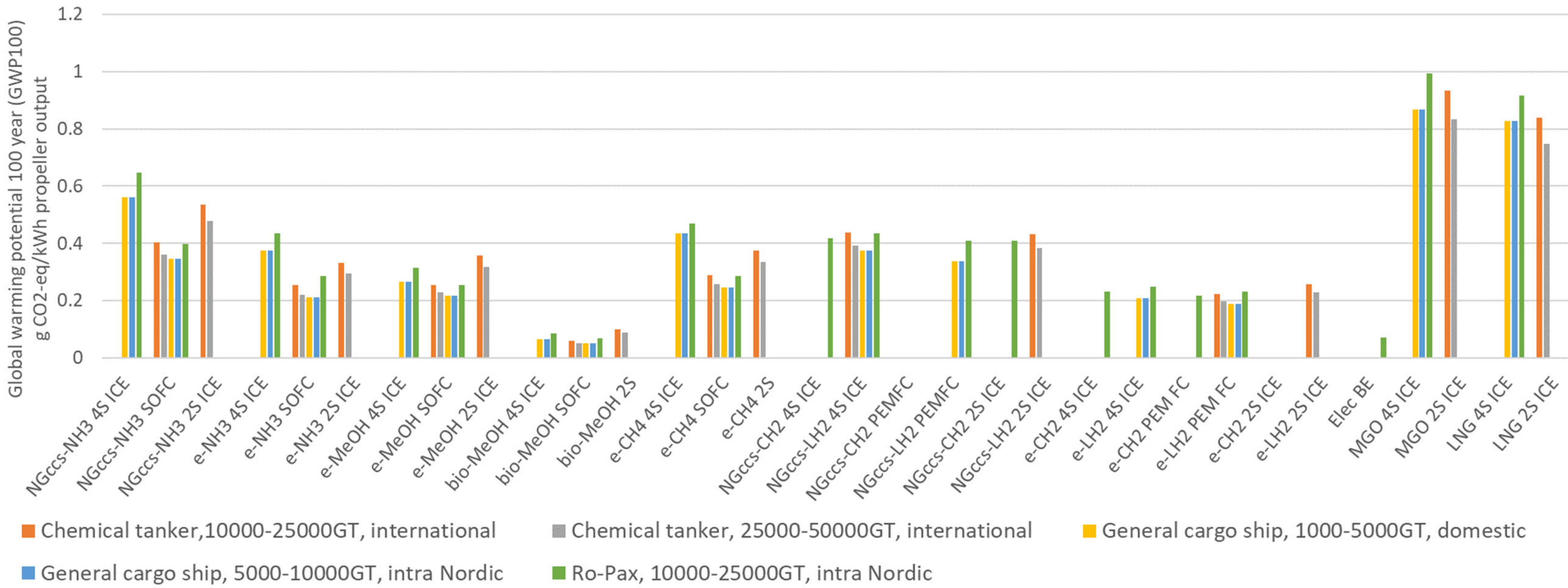

Figure 13 Overview of global warming potential (in kg CO_2-eq.) in a 100-year time perspective for the investigated potential zero-carbon fuels in Nordic shipping in 2030 for 1 kWh propeller output. The global warming potential includes fuel/energy carrier production including distribution and transport, use of shore-power in port, operation onboard the ship, manufacturing, and replacement of the ship propulsion system. NGccs - steam reforming of natural gas with carbon capture and storage, NH3 - ammonia, 4S – 4-stroke engine, 2S – 2-stroke engine, ICE – internal combustion engine, SOFC - solid oxide fuel cell, e-NH3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass based methanol, e-LMG – electro-methane, CH2 – compressed hydrogen, LH2 – liquefied hydrogen, PEMFC – Proton-exchange membrane fuel cell, Elec-BE – Battery Electric, MGO – marine gas oil, LNG – liquefied natural gas. For full description of the assessed pathways see Table 4 and Appendix A.

6.3 2050 outlook

In the 2050 outlook the climate impact of the green fuel pathways is reduced compared to the 2050 case and show close to zero life-cycle climate impact. A possible reduction of CH_4 and N_2O emissions from LMG and NH3 dual fuel engines ate indicated with the dashed line (below the dots) in Figure 14.

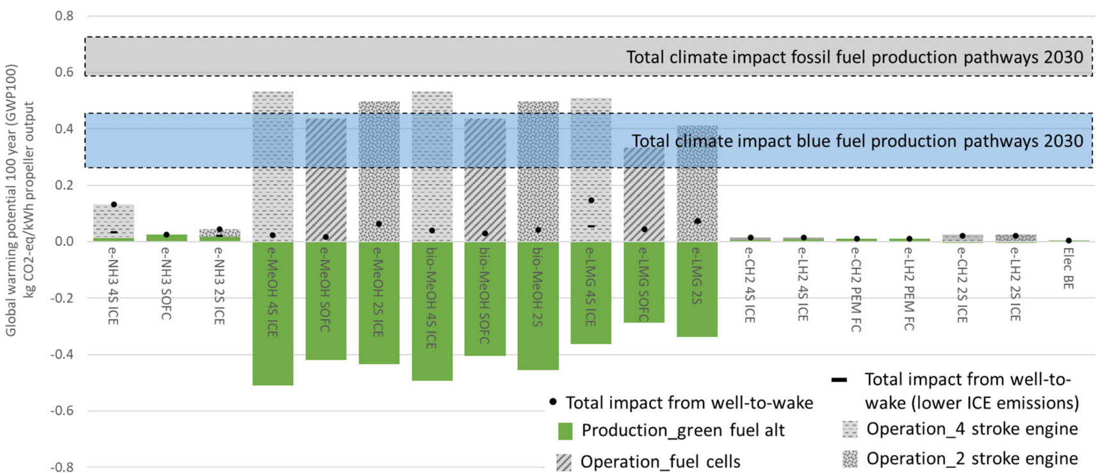

Figure 14 An outlook for the global warming potential (in kg CO2-eq.) in a 100-year time perspective for the investigated potential zero-carbon fuels in Nordic shipping in 2050 for 1 kWh propeller output. The global warming potential is illustrated for fuel/energy carrier production including distribution and transport (and for the battery-electric option the production of electricity) and for operation onboard the ship. ***The dots represent the net value from well-to-wake and the dash the net value using lower ICE emission estimates and the short black line the total climate impact in case of lower emissions of methane and nitrous oxides in ICE from ammonia and methane.*** *NGccs – steam reforming of natural gas with carbon capture and storage, NH3 – ammonia, 4S – 4-stroke engine, 2S – 2-stroke engine, ICE – internal combustion engine, SOFC – solid oxide fuel cell, e-NH3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass based methanol, e-LMG – electro-methane, CH2 – compressed hydrogen, LH2 – liquefied hydrogen, PEMFC – Proton-exchange membrane fuel cell, Elec-BE – Battery Electric, MGO – marine gas oil, LNG – liquefied natural gas. For full description of the assessed pathways see Table 4 and Appendix A.*

As one of the main influential factors on the climate impact which remains uncertain for engines running on methane is the methane slip a Monte Carlo simulation varying the methane slip and engine efficiency for using e-LMG in 4 stroke engines as well as the share of maneuvering was performed. The results are presented in the Figure 15. The methane emissions were varied between 2 g/kWh to 5.5 g/kWh when cruising and between 3 g/kWh to 42 g/kWh when operating at lower speeds for the 2030 scenario, and 3 g/kWh to 20 g/kWh for the 2050 scenario. This corresponds to the lowest and highest estimates for 4-stroke ICE identified in project discussions and literature [132, 145-148]. The share of maneuvering/low-speed operation performed by the vessel is varied between 2% and 10%. 10 000 iterations were performed. The difference between the best case scenario and the worst-case scenario for 2050 is large and indicates the importance of maintaining low methane emissions from the combustion process. The assessment results from this study are marked with a red dot in the graph and are for all the cases in the lower range of the graph, indicating that these might be positive scenarios.

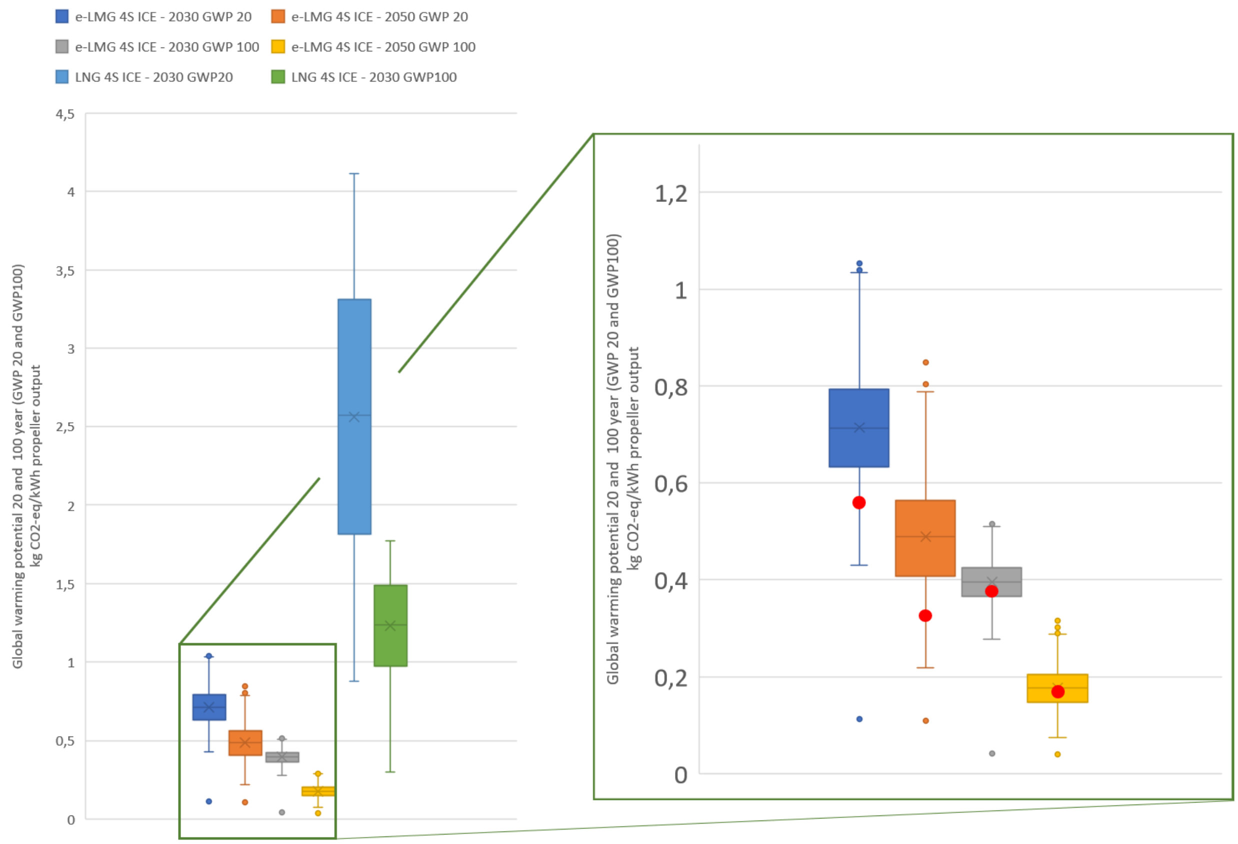

Figure 15 The results from a Monte Carlo analysis of the net global warming potential (in g CO2-eq.) from well-to-wake in a 20-year and 100-year time perspective for using green methane in Nordic shipping presented per 1 kWh propeller output. The red dots show the results in the base assessment. The box in the plot shows the 25th and 75th percentile of probability and the outliers in the simulated data are marked by singular points. The global warming potential includes distribution, transport, and operation onboard the ship. The data is presented as boxplots of the probability of the different outcomes when all parameters are varied. e-LMG – electro-methane, LNG – liquefied natural gas, 4S ICE – four-stroke internal combustion engines, GWP – global warming potential.

7 Discussion and conclusions

To summarize, there is a potential to decarbonize the shipping industry through changing fuels both in the short and long term. This report illustrates that it is possible to substantially reduce the GHG emission/climate impact by introducing the assessed fuel-propulsion options by 2030. However, it does not seem possible to reach completely zero carbon marine fuels by 2030 in a LCA perspective with the chosen approach and system boundaries. The electro-methane used in 4-stroke engines and natural gas-based ammonia in 4-stroke engines pathways need to reduce the emissions of CH_4 and N_2O even further than what is assumed in the 2030 perspective in order to reduce the climate impact substantially.

Generally, it is possible to receive lower GHG emissions/climate impact with green pathways than corresponding blue pathways. It is possible to provide very low climate impact for most of the assessed pathways when/if the society transform to a low GHG society (around 2050) as it means that also steel, cement and electricity production will reach zero or close to zero carbon emissions. Thus, there is a clear link between the transport sector and the development in other sectors and industries.

The climate impact of the assessed pathways in the 2030 perspective may be reduced by e.g., (i) an increased share of renewable energy in the assumed electricity mix (in particular the green fuel production pathways), (ii) solid-oxide electrolysers used for hydrogen production instead of alkaline electrolysers, (iii) reduced impact from production of materials used for propulsion systems, storage etc., (iv) renewable urea instead of natural gas-based urea (v) lower assumed emissions of N_2O and CH_4 for the ammonia and methane cases. The potential impact of such changes is illustrated in the 2050 outlook presented in this report.

Further studies of the climate impact of ammonia and hydrogen pathways are needed as knowledge about their performance in marine operations increase. One key message is that the implementation of policies, that besides CO_2, regulate CH_4 and N_2O emissions are called for. The required reduction in GHG emissions linked to ammonia and methane will likely not materialize without such policies and regulations. The reduction of emissions of CH_4 and N_2O also come with a cost, which is uncertain.

Another aspect not to forget is the indirect climate effects connected to emissions of hydrogen [149, 150]. These are not considered in this study (as it is typically not common to consider indirect climate effects in LCA) but they should be included in future studies to make sure that potential leakages in the hydrogen supply chain will not change the climate impact of hydrogen pathways significantly.

A change of fuel from MGO is in this report indicated to reduce some other environmental impacts (including acidification and particulate matter formation). However, the opposite is also possible for some impacts and fuels including, e.g., eutrophication (mainly in freshwater), human toxicity, resource use, land use, and ionising radiation. As an example, a potential challenge with ammonia is that ammonia emissions contribute to eutrophication. This can be especially critical in sensitive marine areas as the Baltic Sea. Thus, with a fuel switch there is a risk for other sustainability challenges to arise that need to be considered. The potential impact on other environmental impacts of changing fuels needs to be assessed in more detail, than assessed in this study, to understand to what extent the effects are problematic. This to ensure the introduction of sustainable low-carbon marine fuels. A way to reduce the risks is to consider a broad set of sustainability criteria when selecting fuels, when producing fuels and when forming policy and regulations, and not solely focus on the climate impact (nor, as already indicated, only CO_2 emissions).

It is important to introduce policy measures that makes it possible to invest in renewable options (green fuel production pathways) in all parts of the life cycle of marine fuels. There is a need of new sustainable fuels to be produced and ships that can use the new sustainable fuels to be built. There is also a need to continuously investing in monitoring and measurement to increase the performance of the new technologies.

Pathways including CCS of fossil carbon also cause some fossil GHG emissions up stream as it is not economically to capture all emissions (at least not in the mid-term) and as the extraction of fossil resources are associated with emissions of GHGs. It is recommended that policies primarily promote green fuel production pathways while requiring strict GHG reductions also from blue pathways.

7.1 Robustness of the result

As several of the studied fuel and powertrain options including ammonia and hydrogen are in the development phase, their actual climate and environmental performance in 2030 (and even more in 2050) are uncertain which is due to the lack of knowledge around e.g., emissions of GHGs and other pollutants. This knowledge will improve further as the fuel and propulsion options are further developed, tested, and monitored.

Ammonia-based propulsion systems have challenges with emissions of nitrous oxides (N_2O) when used in marine engines (in this study estimated to correspond to about 60-85% of the operation related emissions of GHGs, as GWP100, of the studied ammonia ICE pathways based on what is considered relevant for the 2030 case). However, the N_2O emission from marine ammonia engines when they are in actual operation is still largely unknown and engine manufacturers will work on reducing these emissions. It should be noted that the emission levels assumed in this report are lower than preliminary test engine data and, thus, we assume that further emission reduction will be in place in 2030 and 2050 in the present analysis. The use of ammonia in fuel cells is also still an unmature pathway and it is difficult to know the future performance.

The actual electricity mix assumed is also influencing the results (an estimated future Nordic electric mix is used in this study with close to zero GHG emissions in the 2050 case while somewhat higher in the 2030 case). Also, renewable based electricity production is today associated with GHG emissions from a LCA perspective.

For blue fuels (relying on CCS to reduce their carbon intensity) the GHG emissions are sensitive to the effectiveness of CCS. There are still relatively few established CCS facilities in the world, most of which are only operating at pilot plant scale (Global CCS Institute, 2021). Consequently, a large degree of uncertainty remains on the actual feasibility and effectiveness of this technology at large scale. Blue fuels are also associated with emissions from extraction and transport of natural gas.

For green carbon-based fuels produced using renewable electricity there are several possible sources of CO_2. In this report scrubbing of carbon from flue gas from bioenergy is assumed as it seems representative for the Nordic context. It is also currently the proposed carbon source for many ongoing electrofuels projects. Direct air capture (DAC) is another carbon source under discussion. DAC has higher energy requirements than flue gas scrubbing but has the advantage of being possible to build up on sites without major bioenergy plants. The electrolyser use for hydrogen production is the main user of electricity also when DAC is used, and therefore there are only small differences over the life cycle when using flue gas scrubbing or DAC but the latter result in higher GHG emissions in the 2030 perspective. For more information on LCA data for relevant DAC technology see Deutz and Bardow [151].

This study looks at generalized designs for propulsion systems and fuel production and may act as a general guideline at fleet level. However, it does not contain detailed results for specific use case scenarios for different specific vessels and fuel-propulsion combinations. More detailed assessments are needed to understand how the options investigated in this study will perform under different constraints. Individual ship specific LCAs are required to assess the optimal propulsion alternative for specific vessels, as the specific use case, propulsion design and fuel production supply directly affects the environmental performance. Such LCAs must be performed as separate studies as they, to some extent, will have different goal and scope, and should use specific data that differ depending on for example geographical scope, timeline, required performance parameters etc.

For all pathways including cryogenic fuels there is a need to handle the boil-off gas during storage on land and on ships. As this study considers fuel production in the Nordic region and therefore considers relatively short transport distances (at least compared to the global case) no emissions from boil-off gas are included in the case of hydrogen or methane pathways. However, methane leakages in the LNG supply have in a global context been found to be significant. The estimate in this study that no boil-off is emitted to the atmosphere may be un underestimation of the climate impact of methane-based pathways. To ensure low methane emissions from shipping regulations governing such emissions are crucial.

The included representative ship LCAs based on average ships from the AIS analysis does not consider possible future changes in operational patterns, logistic performance, general changes in ship sizes and speed profiles. In addition, the effect of future lower density fuels on the "utility" and the design of the vessel (more space used by fuel, less available for cargo), and therefore its sustainability, need to be considered but is currently unclear (future vessel designs are being developed though). The impact of this for fuel use and environmental impacts need to be assessed for a specific vessel design and usage and cannot be done on this more general level. The characteristics of vessels differs in terms of e.g., limiting cargo parameter (weight versus volume), bunkering frequency, power ramp up demands as well as travel time and travel distance. However, these uncertainties and the findings from such studies will likely not influence the overall picture but more the situation for specific ships and is thus valuable for shipping owners.

The time horizon considered for the global warming effect (i.e., GWP20 with a 20-year timeframe or GWP100 with a 100-year timeframe) influences the result in particular in case where there are methane emissions. The methane-based fuels perform better in the 100-year timeframe than in the 20-year timeframe due to the large short-term effect methane emissions have on the climate. This means that the use of these fuel can in the short-term increase the pressure on the climate, but in the long term this pressure will decrease as the molecules decay.

Results for 4-stroke and 2-stroke engines should not be used to compare if 4-stroke or 2-stroke engines should be selected for the propulsion option as they are treated somewhat differently in this assessment. For future studies it would be good to consider different efficiency and emission profile for low and high engine load also for 2-stroke engines. It is also important to note that emissions from marine engines are uncertain and may very between different engines based on how they are finetuned and optimised. In this study it has been assumed that HVO is used as pilot fuel. However, this is not the situation today and the use of another polit fuel could impact emissions, but this impact is not investigated in this study.

7.2 Considerations when developing LCA guidelines for marine fuels

When settling LCA guidelines for marine fuels system boundaries are important. It is also important to understand how the guidelines will influence the prospects for different options and if this is in a fair and desired direction from a sustainability perspective. Should fuel production and distribution be included? What electricity mix should be used i.e., to what extent and when could zero carbon electricity be assumed? There might for example be regions or cases where fully renewable carbon electricity is relevant to consider already 2030. How should GHG emissions from engine concept under development be treated?

It is important to consider a well-to-wake perspective as the emission in other sectors are not fully regulated. In terms of default emission values in LCA guidelines, it is important for these to represent the higher end of possible performance as that will encourage the use of verified actual values. It is also crucial to besides CO_2 emissions include also CH_4 and N_2O emissions in order to not promote fuels that risk to lead to climate impact due to other GHG emissions. From a general perspective it is also important that guidelines proposed in one context or by one actor is in line with other guidelines in policies or proposed by other actors etc.

A way to reduce the risk of contributing to other sustainability challenges is to consider a broad set of sustainability criteria when selecting fuels, when producing fuels and when forming policy and regulations and not solely focus on the climate impact. For LCA guidelines for marine fuels, this means that one should consider including more environmental impact categories than climate impact or at least discuss how other environmental impacts should be addressed.

In short, the IMO guidelines being developed mainly focus on GHG emissions and a GWP100 perspective whereas this study also considers a range of other environmental impact categories and also a GWP20 perspective. There is no clear guidance whether and to what extent other environmental impacts categories should be considered in the IMO case. The draft IMO guidelines (document ISWG-GHG 11/2/3) apply a well-to-tank perspective but only consider the fuel life cycle (with unclear system boundaries in terms of infrastructure for producing the fuels) and not the impacts from producing the propulsion system, which is included in the average ship specific LCAs in our study to give a more comprehensive picture. The approach for handling the carbon source for the production of electrofuels (in this study e-methanol and e-methane) also seems to differ somewhat between the draft guidelines and this study. However, it is at present unclear how that impacts the results.

When comparing well-to-tank climate impacts of the fuel production pathways that are included in this study and in the draft guidelines in ISWG-GHG 11/2/3 some differences may be noted (Table 14). This study has a time perspective of 2030 and the Nordic countries as a geographical scope (assuming e.g., GHG emissions from Nordic electricity mix), it can therefore be noted that the values for H_2 and NH_3 proposed in ISWG-GHG 11/2/3 seem too low to represent today's emissions on a global level. This since, current renewable based electricity production is associated with GHG emissions from a LCA perspective.

Table 14 Comparison of the well-to-tank climate impact (g CO2-eq./MJ fuel produced) in this study and similar pathways in ISWG-GHG 11/2/3.

	NGccs-NH3	**e-NH3**	**NGccs-CH2**	**NGccs-LH2**	**e-CH2**	**e-LH2**	**e-MeOH**	**e-LMG**	**bio-MeOH**	**HVO**	**LNG**	**MGO**	**Elec**
This study	44.9	25.7	37.9	39.4	20.2	21.7	-41.1	-18.3	-63.1	-39.7	19.5	12.4	6.9
ISWG-GHG 11/2/3	-	0	-	-	-	3.6	-67.1	-26.6	-	-20.7	18.5	14.9	106.3

Finally, the publication of LCA guidelines will provide useful support for the shipping actors and may have a positive impact on the introduction of alternative marine fuels.

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Appendix A

The fuel and propulsion options assessed, and the pathway names used in the figures in the report are described in the list below.

Pathway name	Pathway description
NGccs-NH3 4S ICE	ammonia from natural gas with carbon capture and storage in 4-stroke engines
NGccs-NH3 SFOC	ammonia from natural gas with carbon capture and storage in solid-oxide fuel cells
NGccs-NH3 4S ICE	ammonia from natural gas with carbon capture and storage in 2-stroke engines
e-NH3 4S ICE	ammonia from Nordic electricity mix in 4-stroke engines
e-NH3 SFOC	ammonia from Nordic electricity mix in solid-oxide fuel cells
e-NH3 4S ICE	ammonia from Nordic electricity mix in 2-stroke engines
e-MeOH 4S ICE	methanol from Nordic electricity mix in 4-stroke engines
e-MeOH SFOC	methanol from Nordic electricity mix in solid-oxide fuel cells
e-MeOH 2S ICE	methanol from Nordic electricity mix in 2-stroke engines
bio-MeOH 4S ICE	methanol from biomass in 4-stroke engines
bio-MeOH SFOC	methanol from biomass in solid-oxide fuel cells
bio-MeOH 2S ICE	methanol from biomass in 2-stroke engines
e-LMG 4S ICE	liquid methane from Nordic electricity mix in 4-stroke engines
e-LMG SFOC	liquid methane from Nordic electricity mix in solid-oxide fuel cells
e-LMG 4S ICE	liquid methane from Nordic electricity mix in 2-stroke engines
NGccs-CH2 4S ICE	compressed hydrogen from natural gas with carbon capture and storage in 4-stroke engines
NGccs-CH2 4S ICE	liquid hydrogen from natural gas with carbon capture and storage in 4-stroke engines
NGccs-CH2 PEMFC	compressed hydrogen from natural gas with carbon capture and storage in proton-exchange membrane fuel cells
NGccs-CH2 4S ICE	liquid hydrogen from natural gas with carbon capture and storage in proton-exchange membrane fuel cells
NGccs-CH2 2S ICE	compressed hydrogen from natural gas with carbon capture and storage in 2-stroke engines
NGccs-CH2 2S ICE	liquid hydrogen from natural gas with carbon capture and storage in 2-stroke engines
e-CH2 4S ICE	compressed hydrogen from Nordic electricity mix in 4-stroke engines
e-CH2 4S ICE	liquid hydrogen Nordic electricity mix in 4-stroke engines
e-CH2 PEMFC	compressed hydrogen from Nordic electricity mix in proton-exchange membrane fuel cells
e-CH2 4S ICE	liquid hydrogen from Nordic electricity mix in proton-exchange membrane fuel cells
e-CH2 2S ICE	compressed hydrogen Nordic electricity mix in 2-stroke engines
e-CH2 2S ICE	liquid hydrogen from Nordic electricity mix in 2-stroke engines
Elec-BE	battery-electric propulsion using Nordic electricity mix
MGO 4S ICE	marine gas oil in 4-stroke engines
MGO 2S ICE	marine gas oil in 2-stroke engines
LNG 4S ICE	liquefied natural gas in 4-stroke ICE
LNG 2S ICE	liquefied natural gas in 2-stroke ICE

Appendix B

Table B1 Life cycle inventory data for the fuel production phase (i.e., well-to-tank) in 2030 for global warming potential (g/MJ fuel produced).

	NGccs-NH3	e-NH3	NGccs-CH2	NGccs-LH2	e-CH2	e-LH2	e-MeOH	e-LMG	bio-MeOH	HVO	LNG	MGO	Electricity
g CO2	26.2	24.6	21.4	22.9	19.5	20.9	-42.1	-26.1	-64.0	-42.4	6.2	11.4	5.1
g CH4	0.62	0.02	0.55	0.55	0.01	0.02	0.02	0.13	0.00	0.08	0.44	0.03	0.05
g N2O	0.0004	0.0012	0.0003	0.0003	0.0010	0.0011	0.0014	0.0014	0.0028	0.0005	0.0001	0.0004	0.0001
GWP100	44.9	25.7	37.9	39.4	20.2	21.7	-41.1	-18.3	-63.1	-39.7	19.5	12.4	6.9
GWP20	77.7	26.8	66.8	68.4	21.0	22.5	-40.1	-4.8	-62.9	-35.0	43.0	14.2	9.9

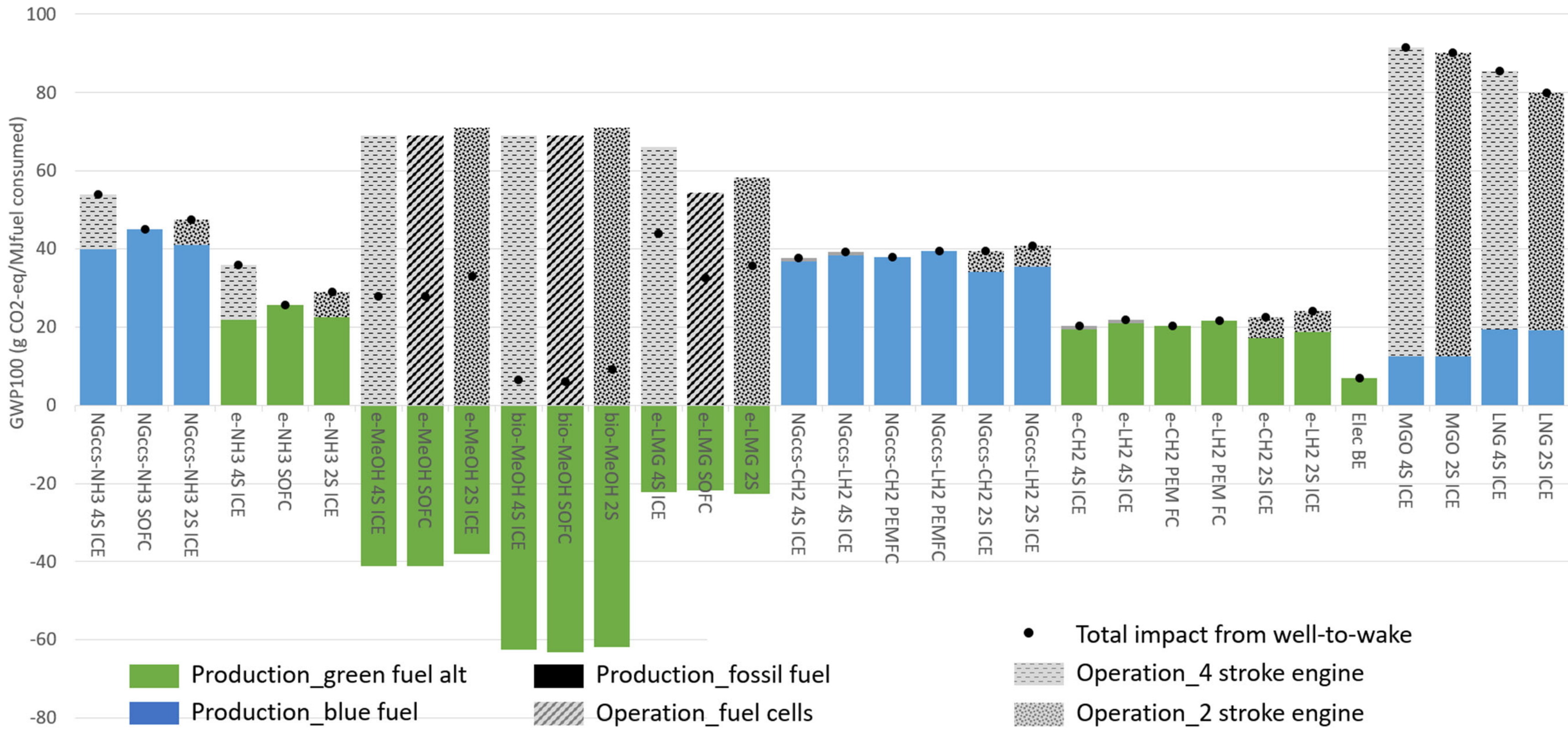

*Figure B2 Global warming potential in a 100-year time perspective in 2030 (in g CO_2-eq./MJ) for 32 potential zero-carbon marine fuels in 2030 compared to 4 fossil fuel alternatives illustrating the contribution from two different phases (fuel production including transport and distribution and ship operation). **The black points show the total climate impact from well-to-wake**. See Table A (and appendix A) for description of the propulsion system options. NGccs - steam reforming of natural gas with carbon capture and storage, NH3 - ammonia, 4S – 4-stroke engine, 2S – 2-stroke engine, ICE – internal combustion engine, SOFC - solid oxide fuel cell, e-NH3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass based methanol, e-LMG – electro-methane, CH2 – compressed hydrogen, LH2 – liquefied hydrogen, PEMFC – Proton-exchange membrane fuel cell, Elec-BE – Battery Electric, MGO – marine gas oil, LNG – liquefied natural gas.*

Table B2 Life cycle inventory data from well-to-wake in 2030 for global warming potential for the blue fuel production pathways (g CO_2-eq./MJ fuel (main and pilot) used).

	NGccs-NH3 4S ICE	NGccs-NH3 SOFC	NGccs-NH3 2S ICE	NGccs-CH2 4S ICE	NGccs-LH2 4S ICE	NGccs-CH2 PEMFC	NGccs-LH2 PEMFC	NGccs-CH2 2S ICE	NGccs-LH2 2S ICE
Fuel consumed for 1kWh propeller output (MJ)	8.5	6.3	7.8	7.7	7.7	6.9	6.9	7.2	7.2
Fuel production (g CO_2-eq./MJ fuel used.)[a]	39.4	44.9	41.0	36.8	38.2	37.9	39.4	34.0	35.4
Operation (g CO_2-eq./MJ fuel used.)	14.1	0.0	6.4	0.9	0.9	0.0	0.0	5.4	5.4
Total (g CO_2-eq./MJ fuel used.)	53.9	44.9	47.4	37.8	39.2	37.9	39.4	39.4	40.9

[a]*The different in fuel production impacts between 4S ICE and 2S ICE depend on different main-to-pilot fuel ratios.*

Table B3 Life cycle inventory data from well-to-wake in 2030 for global warming potential for the green fuel production pathways (g CO_2-eq./MJ fuel (main and pilot) used).

	e-NH3 4S ICE	e-NH3 SOFC	e-NH3 2S ICE	e-MeOH 4S ICE	e-MeOH SOFC	e-MeOH 2S ICE	bio-MeOH 4S ICE	bio-MeOH SOFC	bio-MeOH 2S	e-CH4 4S ICE	e-CH4 SOFC	e-CH4 2S	e-CH2 4S ICE	e-LH2 4S ICE	e-CH2 PEMFC	e-LH2 PEMFC	e-CH2 2S ICE	e-LH2 2S ICE	Elec BE
Fuel consumed for 1kWh propeller output (MJ)	8.5	6.3	7.8	7.7	6.3	7.2	7.7	6.3	7.2	7.7	6.1	7.2	7.7	7.7	6.9	6.9	7.2	7.2	5.0
Fuel production (g CO_2-eq./MJ fuel used.)[a]	21.4	25.7	22.6	-41.1	-41.1	-38.0	-62.3	-63.1	-61.9	-22.4	-21.8	-2.7	19.3	20.8	20.2	21.7	17.2	18.6	6.9
Operation (g CO_2-eq./MJ fuel used.)	14.1	0.0	6.4	69.1	69.1	71.0	69.1	69.1	71.0	66.1	54.5	58.3	0.9	0.9	0.0	0.0	5.4	5.4	0.0
Total (g CO_2-eq./MJ fuel used.)	35.8	25.7	29.0	28.0	28.0	33.0	6.5	6.0	9.1	44.0	32.6	35.6	20.3	21.8	20.2	21.7	22.6	24.1	6.9

[a]*The different in fuel production impacts between 4S ICE and 2S ICE depend on different main-to-pilot fuel ratios.*

Table B4 Life cycle inventory data from well-to-wake in 2030 for global warming potential for the fossil fuel production pathways (g CO_2-eq./MJ fuel (main and pilot) used).

	MGO 4S ICE	MGO 2S ICE	LNG 4S ICE	LNG 2S ICE
Fuel consumed for 1kWh propeller output (MJ)	7.7	7.1	7.7	7.2
Fuel production (g CO_2-eq./MJ fuel used.)[a]	12.4	12.4	19.3	19.2
Operation (g CO_2-eq./MJ fuel used.)	79.2	77.8	66.1	60.8
Total (g CO_2-eq./MJ fuel used.)	91.6	90.2	85.5	79.9

[a]*The different in fuel production impacts between 4S ICE and 2S ICE depend on different main-to-pilot fuel ratios.*