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Life Cycle Assessment of Ammonia as an Alternative Marine Fuel

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Preface

This report is made in collaboration with BIMCO. It has been produced in a 5 ECTS special course at the Technical University of Denmark in the department DTU Management. All four group members have participated actively and contributed equally in all aspects of the project.

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Executive Summary

In 2018, the International Maritime Organisation (IMO) adopted an initial strategy on the reduction of greenhouse gas (GHG) emissions from ships. In this strategy, multiple reduction targets are stated. One of them being that total annual GHG emissions from international shipping should be reduced by at least 50% by 2050 compared to the 2008 level [18]. In order to reach these reduction targets, low carbon or even carbon neutral marine fuels will have to be introduced as alternatives to the currently used fossil fuels. A potential carbon neutral marine fuel is Ammonia - one of the alternative options currently being investigated.

To get the global fleet to change its use of fossil fuels, guidance is needed. This is where an organisation like the Baltic and International Maritime Council (BIMCO) becomes very important. BIMCO is a membership-based non-governmental organisation that provides expert knowledge and practical advice to add value to its members' businesses [4]. As part of this, BIMCO decided to investigate, through the life cycle assessment (LCA) methodology, possible fuel pathways that will support IMO's reduction targets. That is why BIMCO is commissioning a comparative LCA study of Ammonia and the two fossil marine fuels, Very-Low Sulphur Fuel Oil and Marine Gas Oil.

Ammonia can be produced using different production pathways for hydrogen. Four different production pathways for hydrogen were investigated in this report:

- Brown Ammonia using coal gasification
- Grey Ammonia using methane steam reforming
- Blue Ammonia using methane steam reforming and industrial carbon capture and storage technologies to mitigate the release of CO_2
- Green Ammonia using electrolysis and renewable energy

In this LCA study, a specific sea route was chosen by the study commissioner to be from Rotterdam to Singapore, through the Suez Canal. A specific route was modelled to simplify the studied system. As marine fuels are essential for world trade and transport of goods, a major shift in type of fuel used would cause considerable changes in the background system. In addition, it is anticipated that the results of this LCA study will be disseminated to a large audience. According to the 14044 ISO standard, this can be defined as 'Situation B: Macro-Level Decision Support'.

The three types of marine fuels were compared in accordance with the main function that they provide. This being the ability to combust, generating kinetic energy. In this LCA, the main function is set to occur in a two-stroke engine on an average bulk carrier which has been defined as a Panamax bulk carrier with a deadweight (DWT) of 75,000 tonnes. The **Functional Unit** was defined as: Transport of goods on a fully loaded average Panamax bulk carrier with a two-stroke engine and a deadweight of 75,000 tonnes, from Rotterdam to Singapore in 2022. The **Reference Flows** specify how much fuel is needed to fulfil the Functional Unit, see Table 1 below. It should be noted that a pilot oil is needed

when sailing with an Ammonia-fuelled engine. In this LCA study, the chosen pilot oil is VLSFO with SPOC/SFC = 5% - meaning that 5% of the amount of energy injected into the cylinders at full load and at a given speed is VLSFO.

Table 1: Reference Flows that fulfil the Functional Unit.

Marine Fuel	**Fuel Consumption**	**Total Fuel Consumption: Rotterdam to Singapore**
Ammonia	237 kg/nm	1,969,387 kg
Marine Gas Oil	120 kg/nm	996,000 kg
Very-Low Sulphur Fuel Oil	126 kg/nm	1,045,800 kg
Very-Low Sulphur Fuel Oil (Pilot Oil)	6 kg/nm	51,922 kg

The product systems include all life cycle stages from cradle (well) to grave (wake). Thus, extraction of raw materials, pre-processing, production and combustion in the two-stroke engine are all within the system boundaries. Since the marine fuels are combusted during their use phase, the End-of-life phase consists of their exhaust gases being emitted and entering the environment. The system boundaries for all three marine fuels can be seen below in Figure 1.

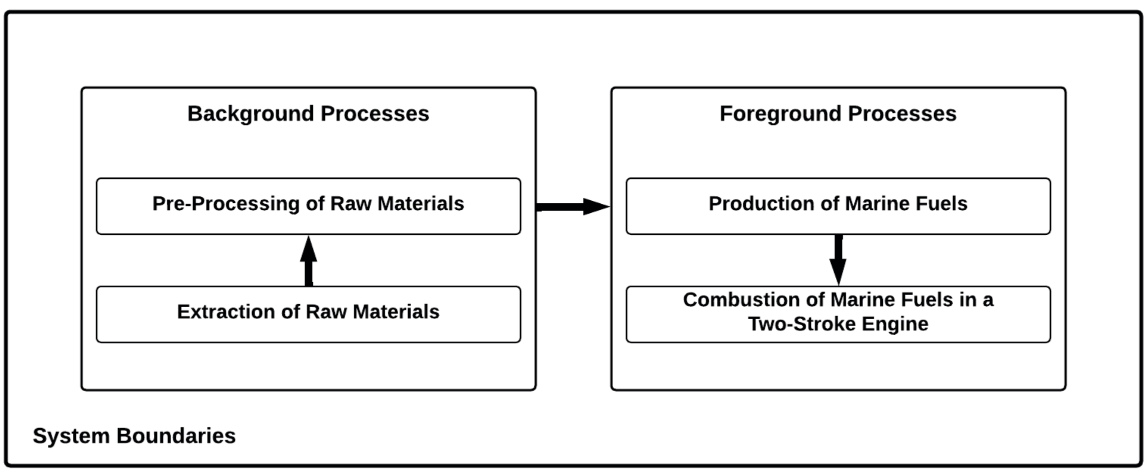

Figure 1: System boundaries for all three marine fuels. To keep the figure simple and readable, emissions such as CO_2 and NOx as well as inputs such as energy and materials have been omitted.

The impact assessment was carried out using the ReCiPe 2016 Midpoint (H) methodology (version 1.05) with all impact categories included. The endpoint results of ReCiPe were also calculated i.e. the ReCiPe 2016 Endpoint (H) methodology (version 1.05), with all three areas of protection included.

The characterised midpoint results showed that, in 9 of the 18 impact categories, MGO had the lowest impact, while Green Ammonia had the lowest impact in 8 out of the 18 impact categories - including 'Global warming'. Furthermore, Green Ammonia had negative impact scores in the categories where it had the lowest impact, which means that the crediting of the production of secondary functions is higher than the impacts. Brown Ammonia had the highest impact score in 13 out of the 18 impact categories. The results also showed that Brown, Grey and Blue Ammonia were the fuels that generally had the highest impact scores, indicating that they are not preferred production pathways for Ammonia as a marine fuel. The characterised results can be seen below in Table 2. A clear weighting of importance between the impact categories has not been done and thus 'the best performing' fuel cannot be stated clearly.

Table 2: Characterised impact scores for the six fuel pathways at midpoint level, calculated using ReCiPe 2016 Midpoint (H) as LCIA methodology. Results are presented in a heat map with graded colours, where green represents the lowest impact and red represents the highest impact in each impact category.

Impact Category	**Unit**	**VLSFO**	**MGO**	**Brown Ammonia**	**Grey Ammonia**	**Blue Ammonia**	**Green Ammonia**
Global warming	kg CO2 eq	4.67E+06	3.77E+06	2.49E+07	1.32E+07	1.09E+07	-4.78E+06
Stratospheric ozone depletion	kg CFC11 eq	1.05E+00	9.79E-01	3.30E+01	3.34E+01	3.35E+01	2.85E+01
Ionizing radiation	kBq Co-60 eq	-6.98E+04	2.90E+04	-6.21E+04	-2.32E+03	-3.05E+03	-8.53E+05
Ozone formation, Human health	kg NOx eq	8.29E+04	8.03E+04	3.66E+05	3.04E+05	3.04E+05	2.84E+05
Fine particulate matter formation	kg PM2.5 eq	2.12E+04	1.24E+04	1.03E+05	6.08E+04	6.09E+04	4.00E+04
Ozone formation, TE*	kg NOx eq	8.30E+04	8.05E+04	3.66E+05	3.04E+05	3.05E+05	2.84E+05
Terrestrial acidification	kg SO2 eq	4.87E+04	3.45E+04	4.45E+05	3.23E+05	3.23E+05	3.00E+05
Freshwater eutrophication	kg P eq	1.84E+03	7.82E+01	8.42E+03	1.82E+02	1.85E+02	-4.41E+03
Marine eutrophication	kg N eq	1.77E+03	1.66E+03	7.28E+03	6.25E+03	6.25E+03	5.94E+03
Terrestrial ecotoxicity	kg 1,4-DCB	3.17E+06	2.14E+06	9.22E+06	9.67E+05	9.95E+05	1.81E+06
Freshwater ecotoxicity	kg 1,4-DCB	5.75E+04	1.19E+04	4.07E+05	2.74E+04	2.84E+04	1.00E+05
Marine ecotoxicity	kg 1,4-DCB	8.18E+04	1.82E+04	5.64E+05	3.83E+04	3.98E+04	1.04E+05
Human carcinogenic toxicity	kg 1,4-DCB	9.29E+04	5.39E+03	5.44E+05	6.65E+03	6.61E+03	-5.26E+04
Human non-carcinogenic toxicity	kg 1,4-DCB	2.58E+06	3.08E+05	2.34E+07	5.92E+05	6.13E+05	-5.10E+06
Land use	m2a crop eq	3.53E+05	1.13E+04	5.47E+04	3.23E+04	3.25E+04	-5.81E+04
Mineral resource scarcity	kg Cu eq	2.59E+03	1.69E+03	5.59E+03	4.04E+03	4.25E+03	3.14E+04
Fossil resource scarcity	kg oil eq	1.32E+06	1.23E+06	4.62E+06	5.38E+06	5.64E+06	-1.58E+06
Water consumption	m3	3.13E+04	8.82E+02	3.70E+04	1.34E+04	1.36E+04	-1.74E+05

* Terrestrial ecosystems

In order to model the six product systems in openLCA, a number of assumptions had to be made. Some of these were tested in perturbation and scenario analyses. From the scenario analyses, two sensitive assumptions were found: the amount of oxygen substituted and the exclusion of NOx abatement technology as they both changed the outcome of the study. Parameter uncertainty and variability was investigated by Monte Carlo simulations. Only four parameters pertaining to Ammonia were tested, as these parameters had known parameter value intervals. Here it was found that in the impact category 'Global warming', all the Ammonia pathways were significantly different. Thus, Green Ammonia had a significantly lower impact than the other pathways.

The following points can be **concluded** from this LCA study.

- Marine Gas Oil (MGO) and Green Ammonia have the lowest impacts in 9 and 8 out of 18 midpoint impact categories, respectively. As for which of the two has the overall better environmental performance, a conclusion cannot be drawn as the impact categories have not been weighted.
- When compared to only the fossil marine fuels, Green Ammonia has the lowest impacts in 9 out of 18 midpoint impact categories including 'Global warming'.
- When compared to VLSFO and MGO, Brown Ammonia has higher impacts in 17 and 16 out of 18 midpoint impact categories, respectively - including 'Global warming'. For both Grey and Blue Ammonia, this number is 8/18, also including 'Global warming'.
- The NOx emissions for Ammonia exceed the IMO Tier II limit and thus NOx abatement technology is necessary for operation in international waters.
- For the impact category 'Global warming', the largest contributions to impacts lie in tank-to-wake for VLSFO and MGO, and in well-to-tank for Ammonia.
- Based on the calculated 95% confidence intervals, constructed through Monte Carlo analyses, it can be concluded that in the impact category 'Global warming', Green Ammonia performs significantly better than Brown, Grey and Blue Ammonia. Oppositely, Brown Ammonia performs significantly worse than Grey, Blue and Green Ammonia.

The three main **limitations** of this LCA study are the following:

- Data could not be located for the production of VLSFO and MGO. Modelling VLSFO as HFO with the addition of a desulfurizing process was deemed as a reasonable approximation. An underestimation of impacts is expected seeing as the Claus Process, a part of the desulfurizing process, could not be modelled due to data not being located. Modelling MGO as diesel was also deemed as a reasonable approximation as only a slight overestimation of impacts occur. Neither of these points are expected to impact the outcome of the study.
- Using life cycle inventory (LCI) data from other LCA studies is not ideal as it can potentially lead to mistakes/problems being replicated. However, it should be noted, that the LCA studies used were all deemed as being credible. Thus, using these LCA studies is not expected to impact the results compared to using data with higher specificity. Complete LCI's were not provided (in these LCA studies) and as a result different sources were often used to model a process - also not ideal as different sources can present different values for the same inputs and outputs in addition to using different methods to produce LCI data. It should be noted that prior to selecting sources to model a specific process, these sources were compared in order to ensure that values and modelling methods are comparable. Consequently, the outcome of this study is not expected to be impacted.
- The DESMO Calculation Tool is geared towards fossil marine fuels and is thus not made to be used for alternative marine fuels such as Ammonia. However, looking into how DESMO calculates the energy demand per nm, the fuel's energy density and total system efficiency are believed to be the only input parameters. Thus, it was deemed as a fair estimation to input Ammonia's energy

density and total system efficiency and then use the estimated energy demand per nm. Based on the current knowledge level regarding DESMO, using this estimate of the energy demand per nm is not expected to impact the outcome of the study. This limitation is further explained in Section E.7 in Appendix E.

The following **recommendations** for further work are given to the study commissioner. Firstly, the following points should be considered:

- Include a NOx abatement technology as otherwise the Ammonia-fuelled two-stroke engine is not allowed to operate in international waters. This is due to NOx regulations (IMO Tier II).
- Include port operations, e.g. berthing and manoeuvring, in order to increase knowledge regarding the well-to-wake environmental impacts of the three investigated fuels.
- Include fuel storage on-board the Panamax bulk carrier in the LCI model, as different storage conditions are expected between the fossil marine fuels and Ammonia - thus relevant to include as this is a comparative LCA study.

Secondly, the following data points should be the focus in order to improve data quality, specificity and consistency:

- Investigate oxygen substitution in more details, including predictions for the future oxygen market's supply and demand.
- Ammonia combustion emissions were not available, and are thus modelled as best estimates. MAN Energy Solutions expects to run its first tests with an Ammonia-fuelled engine in the summer of 2022. Thus, contacting them after this is recommended.
- It is recommended to contact VLSFO, MGO and Ammonia producers in order to get primary production data from representative sites, if possible.

Finally, a critical review of the study is recommended in order to improve its quality and thus its robustness.

Abbreviations

CCS Carbon Capture & Storage

DWT Deadweight Tonnage

GHG Greenhouse Gas
GWP Global Warming Potential

HFO Heavy Fuel Oil

IMO International Maritime Organisation
ISO International Organisation for Standardisation

LCA Life Cycle Assessment
LCI Life Cycle Inventory
LCIA Life Cycle Impact Assessment

MGO Marine Gas Oil

nm Nautical Mile
NSC Normalised sensitivity coefficient

VLSFO Very-Low Sulphur Fuel Oil (max. 0.5% sulphur)

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Introduction

The maritime transport sector is responsible for about 3% of the global greenhouse gas (GHG) emissions. This percentage is projected to increase as the global fleet is increasing [20]. Thus, in 2018, the International Maritime Organisation (IMO) adopted an initial strategy on the reduction of GHG emissions from ships. This initial strategy envisions a reduction of CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2023, pursuing efforts towards 70% by 2050, compared to the 2008 level. In addition, total annual GHG emissions from international shipping should be reduced by at least 50% by 2050 compared to the 2008 level [18]. In order to reach these reduction targets, low carbon or even carbon neutral marine fuels will have to be introduced as alternatives to the currently used fossil fuels. A potential carbon neutral marine fuel is Ammonia - one of the alternative options currently being investigated.

To get the global fleet to change its use of fossil fuels, guidance is needed. This is where an organisation like the Baltic and International Maritime Council (BIMCO) becomes very important. BIMCO is a membership-based non-governmental organisation that provides expert knowledge and practical advice to add value to its members' businesses [4]. As an example of this, BIMCO assists its members with tools on which to base future capital and operational expenditure (CAPED/OPEX) decisions such as choice of fuel. As part of this, BIMCO decided to investigate, through the life cycle assessment (LCA) methodology, possible fuel pathways that will support IMO's reduction targets. That is why BIMCO is commissioning a comparative LCA study of Ammonia and the two fossil marine fuels, Very-Low Sulphur Fuel Oil and Marine Gas Oil.

Ammonia can be produced using different production pathways for hydrogen. Four different production pathways for hydrogen are investigated in this report:

- Brown Ammonia using coal gasification
- Grey Ammonia using methane steam reforming
- Blue Ammonia using methane steam reforming and industrial Carbon Capture and Storage technologies to mitigate the release of CO_2
- Green Ammonia using electrolysis and renewable energy

1 Goal Definition

1.1 Intended Application

This life cycle assessment (LCA) is conducted to compare the environmental impacts of three different marine fuels, Very-Low Sulphur Fuel Oil (VLSFO), Marine Gas Oil (MGO) and Ammonia. Four different production pathways for Ammonia will be investigated. These being Brown, Grey, Blue and Green. In Section E.1 in Appendix E, a description of these different production pathways can be found. The results are intended to be used by BIMCO to assist shipowners (members of BIMCO) with tools on which to base future capital and operational expenditure (CAPEX/OPEX) decisions.

1.2 Method Assumptions and Impact Limitations

In this LCA study, a specific sea route has been chosen by the study commissioner to be from Rotterdam to Singapore, through the Suez Canal. A specific route is modelled to simplify the studied system. Rotterdam and Singapore were selected seeing as production of Ammonia is occurring in or near both locations. In terms of variations in weather and water conditions such as wind and waves, average conditions are assumed to occur during the entire journey.

1.3 Reasons for Carrying Out the LCA Study and Decision Context

The maritime transport sector emits approximately 1.1 billion tonnes of CO_2 annually in addition to being responsible for about 3% of the global greenhouse gas (GHG) emissions, based on the latest IMO GHG study published in 2021 (the Fourth IMO GHG Study). These emissions are projected to increase significantly if mitigation measures are not implemented promptly [20, 12]. Thus, the International Maritime Organisation (IMO) has a rapidly growing desire for the maritime transport sector to become more sustainable and reduce emissions.

In order to reduce GHG emissions, alternative fuels such as Ammonia are being investigated. There are however significantly less studies on the life cycle (well-to-wake) environmental impacts of these alternative marine fuels. Due to this limited number of studies, BIMCO wished to commission this LCA study.

As marine fuels are essential for world trade and transport of goods, a major shift in type of fuel used would cause considerable changes in the background system. In addition, it is anticipated that the results of this LCA study will be disseminated to a large audience as BIMCO is the largest direct entry shipping organisation with over 1,900 members in more than 130 countries. Their membership represents 60% of the world cargo fleet measured by tonnage (the weight of the unloaded ships) [4]. This LCA study is therefore expected to provide a meso/macro-level decision support. According to the 14044 ISO standard, this can be defined as 'Situation B: Macro-Level Decision Support'.

1.4 Target Audience

The target audience is BIMCO. Especially, the department at BIMCO that disseminates the results internally to members of BIMCO/shipowners. BIMCO has limited knowledge of the LCA methodology (this is also expected to be the case for shipowners) and the results will thus be presented with this in mind. In addition to this, to facilitate understanding, an introductory section regarding the LCA methodology has been written, see Appendix C.

1.5 Comparative Assertions to be Disclosed to the Public

This comparative LCA study is not intended to be disclosed to the public and thus does not need to comply with related ISO methodology. If BIMCO decides to make the report public at any point, it should be noted that the study is not ISO 14044 compliant as it has not gone through a critical review.

1.6 Commissioner of the LCA Study and Other Influential Actors

The study commissioner is BIMCO while the team carrying out the LCA study is four master students studying Environmental Engineering at the Technical University of Denmark.

2 Scope Definition

2.1 Deliverables

In compliance with the 14044 ISO standard, the deliverables include: (I) A life cycle inventory (LCI) model of the marine fuels, Very-Low Sulphur Fuel Oil (VLSFO), Marine Gas Oil (MGO) and Ammonia. The four different production pathways for Ammonia (Brown, Grey, Blue and Green) are all included in the LCI model. (II) Life cycle impact assessment (LCIA) results in both characterised and normalised form. (III) An appendix on limitations encountered during the data collection.

2.2 Function, Functional Unit and Reference Flows

The three types of marine fuels are compared in accordance with the main function that they provide. This being the ability to combust, generating kinetic energy. In this life cycle assessment (LCA), the main function is set to occur in a two-stroke engine on an average bulk carrier, which has been defined as a Panamax bulk carrier with a deadweight (DWT) of 75,000 tonnes. In addition, all three marine fuels must comply with relevant regulations. These are obligatory properties. The three maritime fuels will differ in positioning properties as they have different physical properties. Obligatory and positioning properties are stated below in Table 3.

Table 3: Obligatory and positioning properties of marine fuels.

Obligatory Properties	Positioning Properties
Ability to combust, generating kinetic energy	Availability
Comply with relevant regulations	Easy handling (transport and storage)
	Energy density
	Environmental impact
	Multiple production methods and countries
	Need of engine maintenance
	Need of pilot oil
	Cost
	Storage space needed for the fuel

The **Functional Unit** has been defined as: Transport of goods on a fully loaded average Panamax bulk carrier with a two-stroke engine and a deadweight of 75,000 tonnes, from Rotterdam to Singapore in 2022.

The **Reference Flows** specify how much fuel is needed to fulfil the Functional Unit, see Table 4 below. It should be noted that a pilot oil is needed when sailing with an Ammonia-fuelled engine as the flammability of Ammonia is limited - the pilot oil enhances the ignition capability (information provided by MAN Energy Solutions). In this LCA study, the chosen pilot oil is VLSFO with SPOC/SFC = 5% - meaning that 5% of the amount of energy injected into the cylinders at full load and at a given speed is VLSFO. As a result, the reference flow for Ammonia has two components needed to fulfil the functional unit: an amount of Ammonia fuel and an amount of pilot oil (VLSFO).

Table 4: Reference Flows that fulfil the Functional Unit.

Marine Fuel	Fuel Consumption	Total Fuel Consumption: Rotterdam to Singapore
Very-Low Sulphur Fuel Oil	126 kg/nm	1,045,800 kg
Marine Gas Oil	120 kg/nm	996,000 kg
Ammonia	237 kg/nm	1,969,387 kg
Very-Low Sulphur Fuel Oil (Pilot Oil)	6 kg/nm	51,922 kg

The Reference Flows have been calculated using the DESMO Calculation Tool developed by the Technical University of Denmark and the University of Southern Denmark, see Section E.2 in Appendix E for a detailed description of the calculations.

2.3 LCI Modelling Framework

2.3.1 Attributional and Consequential LCA

As the decision context is 'Situation B: Macro-Level Decision Support', this LCA will be conducted as a consequential study in accordance with the ILCD Guidelines (International Life Cycle Data system). The consequential approach entails using a mix of long-term marginal processes/technologies for processes structurally changed while using average processes in all other cases. The potential impacts that the choice of fuel could have on the market will be taken into account in addition to considering general trends in the market e.g. a larger use of renewable energy.

2.3.2 Secondary Functions and Multifunctional Processes

There are four multifunctional processes to consider: Crude oil refining, desulferization, air separation and electrolysis.

Refining of crude oil results in many oil products with varying purity, energy content and economic value. Fuel oil and diesel oil are the products that are used for VLSFO and MGO, respectively. While diesel oil has a lower boiling point and is seen as more valuable, fuel oil is perceived as a residue of the crude oil distillation. The co-production of the remaining oil products is the secondary function of this multifunctional process [2]. The fuel oil fraction is further **desulfurized** in order to reach the allowed sulphur content of VLSFO of maximum 0.5%. MGO is a pure distillate that already has the required sulphur content for an Ultra-Low Sulphur Fuel Oil (ULSFO) of maximum 0.1%. The desulfurization process presents a secondary function as sulphur is produced [2].

Acquisition of nitrogen for Ammonia production consists of **atmospheric air separation**, usually cryogenic [10]. This results in nitrogen, oxygen and argon, each of which are valuable products. Thus, the co-production of oxygen and argon are secondary functions of this process. Hydrogen acquisition for Ammonia production can be done in several ways, of which Green Ammonia is through **electrolysis**. Electrolysis is a multifunctional process, as oxygen is also co-produced in addition to hydrogen [10].

2.3.3 The ISO 14044 Hierarchy to Solving Multifunctionality

Keeping the decision-context and the subsequent choice of conducting a consequential LCA in mind, multifunctionality is handled using the ISO 14044 hierarchy of solutions. Allocation is applied to the co-products stemming from the process of oil distillation as both subdivision and system expansion cannot be performed - there is no alternative production pathway for these products. System expansion (through crediting) is applied with regard to the production of oxygen, argon and sulphur - as there are alternative production pathways for these products.

2.4 System Boundaries and Completeness Requirements

2.4.1 System Boundaries

The product systems include all life cycle stages from cradle (well) to grave (wake). Thus, extraction of raw materials, pre-processing, manufacturing and combustion in the two-stroke engine are all within the system boundaries. Since the marine fuels are combusted during their use phase, the End-of-life phase consists of their exhaust gases being emitted and entering the environment. The system boundaries for all three marine fuels can be seen below in Figure 2.

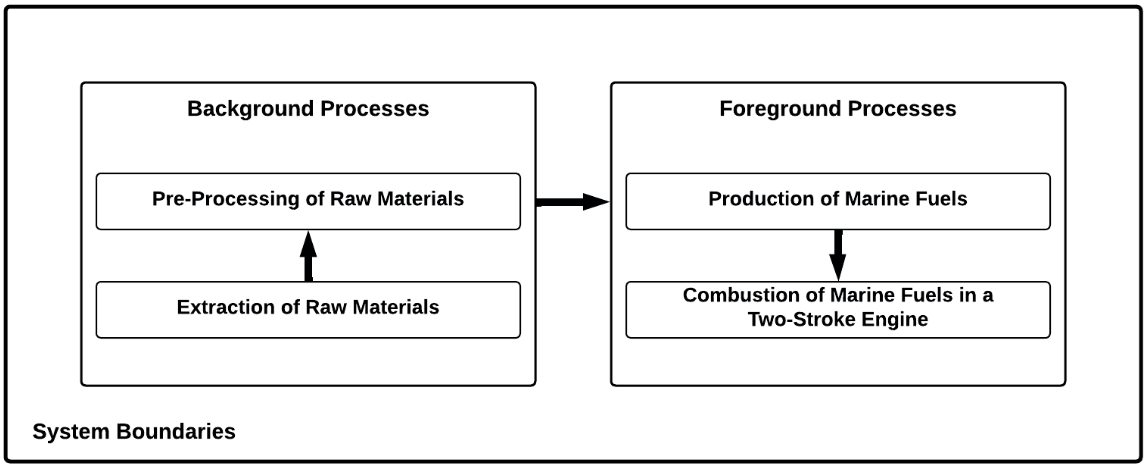

Figure 2: System boundaries for all three marine fuels. To keep the figure simple and readable, emissions such as CO_2 and NOx, as well as inputs such as energy and materials, have been omitted.

2.4.2 Completeness Requirements

As this is a comparative LCA study, processes that are assumed to be the same for all three marine fuels have been excluded from the system boundaries: (I) Production and maintenance of the two-stroke engine. (II) Functional necessities such as lubricating oil.

In addition, other processes/aspects have been excluded from the system boundaries: (I) Capital equipment such as machines and transportation vehicles. This is common practice in a process-based LCA. Additionally, BIMCO and shipowners have no control over the production of such equipment and it is thus not important to include especially with regard to the motivation of this LCA study. (II) Storage both during transport from fuel producer to Rotterdam and on-board the Panamax bulk carrier. Different storage conditions are expected between fossil marine fuels (VLSFO and MGO) and Ammonia. However, as this aspect is viewed as capital equipment it has been excluded from the system boundaries.

(III) Transport from fuel producer to Rotterdam - determining the marginal long-term producers of these three marine fuels could not be done. In addition, it is expected that shipowners buy fuel from producers that are relatively close in proximity to where the fuel will be utilised (in order to minimise costs). Thus, excluding this transport distance from the system boundaries is not expected to impact the results greatly. (IV) Auxiliary engines, as requested by the study commissioner (BIMCO). (V) Berthing, manoeuvring and other port operations, also as requested by the study commissioner.

2.5 Representativeness of LCI Data

Geographical Representativeness

Extraction and pre-processing of raw materials as well as fuel production takes place all over the world.

In addition, in this LCA study, combustion takes place on the route from Rotterdam to Singapore (through the Suez Canal). Therefore, when possible, data used should reflect a global scope. The life cycle inventory (LCI) data is assessed as having high geographical representativeness as global processes or processes deemed to reflect a global scope have been used - applies to all of the investigated marine fuels.

Temporal Representativeness

The functional unit states the current year of 2022. Thus, when possible, the newest data available should be used. The LCI data for the fossil marine fuels is assessed as having moderate temporal representativeness as data used is from 2011 and 2015. It should however be noted that oil refining is a mature technology that is not expected to have changed since 2011/2015, and it is also not expected to change in the coming years. The LCI data for Ammonia, all production pathways, is assessed as having high temporal representativeness as data used is from 2019-2022.

Technological Representativeness

Manufacturing and combustion technologies used should represent the technologies that are currently used on a global scale. Based on research and communication with industry experts, technologies currently used on a global scale, and technologies expected to be used on a global scale (in the case of Green Ammonia), have been identified, see Section 3.1. The LCI data for all fuels is assessed as having high technological representativeness as data used reflects the technologies currently used or expected to be used on a global scale. It should be noted that manufacturing and combustion technologies for the fossil marine fuels are mature technologies. Oppositely, manufacturing and combustion technologies for Ammonia still have room for innovation. Technological improvements could thus be seen in the coming years - if this occurs, this LCA study will then be less representative for Ammonia.

2.6 Basis for Impact Assessment

The impact assessment is carried out using the ReCiPe 2016 Midpoint (H) methodology (version 1.05), see Table 5 below for an overview of the impact categories. As requested by the study commissioner, a greater emphasis is placed on the impact category 'Global warming'.

Table 5: The impact categories included in the ReCiPe 2016 Midpoint (H) Methodology [16].

Impact Category	**Unit**
Global warming	kg CO_2 eq.
Stratospheric ozone depletion	kg CFC11 eq.
Ionizing radiation	kBq Co-60 eq.
Ozone formation, Human health	kg NOx eq.
Fine particulate matter formation	kg PM2.5 eq.
Ozone formation, Terrestrial ecosystems	kg NOx eq.
Terrestrial acidification	kg SO_2 eq.
Freshwater eutrophication	kg P eq.
Marine eutrophication	kg N eq.
Terrestrial ecotoxicity	kg 1,4-DCB eq.
Freshwater ecotoxicity	kg 1,4-DCB eq.
Marine ecotoxicity	kg 1,4-DCB eq.
Human carcinogenic toxicity	kg 1,4-DCB eq.
Human non-carcinogenic toxicity	kg 1,4-DCB eq.
Land use	m^2a crop eq.
Mineral resource scarcity	kg Cu eq.
Fossil resource scarcity	kg oil eq.
Water consumption	m^3 eq.

Global characterisation and normalisation factors are used with the latter having an average person equivalent from 2010 as normalisation point. See Table 19 and 20 in Appendix D for ReCiPe 2016 Midpoint (H)'s characterisation practice and normalisation factors, respectively. The reasoning behind choosing ReCiPe 2016 Midpoint (H) as LCIA methodology is stated in Section E.3 in Appendix E. The endpoint results of ReCiPe will also be calculated i.e. the ReCiPe 2016 Endpoint (H) methodology (version 1.05). Here, three areas of protection are considered, see Table 6 below.

Table 6: The three areas of protection included in the ReCiPe 2016 Endpoint (H) Methodology [16].

Area of Protection	**Unit**	**Concern**
Human health	DALY	Loss of life
Ecosystem quality	Species.year	Loss of species
Resource scarcity	USD2013	Loss of future availability

Modelling impacts at endpoint was done to simplify the midpoint results and make them more understandable. It should however be noted that modelling impacts at endpoint is associated with a higher degree of uncertainty than modelling impacts at midpoint. Thus, a greater focus is placed on the midpoint impact results though also done due to the study commissioner's focus on 'climate change'.

The product systems were modelled in openLCA (using both version 1.10.3 and version 1.11).

2.7 Requirements for Comparative Studies & Critical Review Needs

If the LCA study is to be published in compliance with the 14044 ISO Standard, it must first undergo a critical review by third-party experts. This is required for comparative studies disclosed to the public.

3 Life Cycle Inventory Analysis

3.1 LCI Model at System Level

Below in Figures 3, 4, 5, 6 and 7, the product systems of the investigated marine fuels are illustrated. In order to keep the figures simple, system processes have been grouped into overall steps. The type of energy and/or electricity sources used for the upstream (well-to-tank) processes are indicated.

Figure 3 below illustrates the product system of Very-Low Sulphur Fuel Oil (VLSFO). This marine fuel is produced by extracting and refining crude oil. As stated in Section 2.3.2, VLSFO is produced using the residuals from the refining process with a subsequent desulferization process in order to lower the sulphur content to a maximum of 0.5%, to be in compliance with the 'IMO 2020' maritime regulation [2, 17]. Fossil energy sources are used during crude oil refining as well as during the desulfurization process (production of VLSFO).

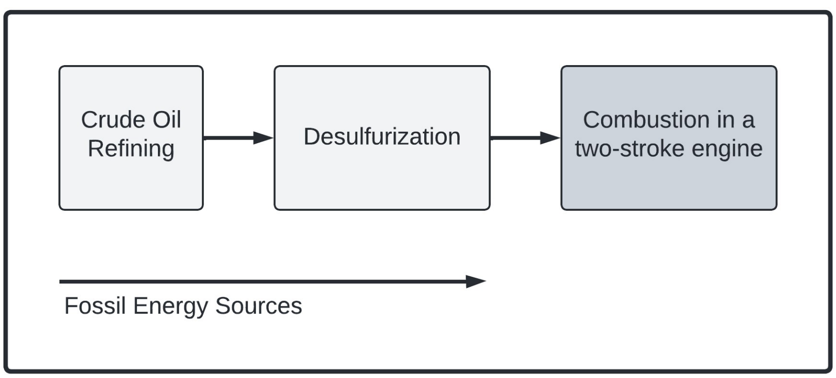

Figure 3: Product system of Very-Low Sulphur Fuel Oil.

Marine Gas Oil (MGO), whose product system is illustrated below in Figure 4, is also produced by extracting and refining crude oil. However, seeing as MGO is a lighter and more pure product of the refining process it does not need to go through a desulferization process. The sulphur content is already in compliance with the 'IMO 2020' maritime regulation [2, 17]. A global energy mix is used during crude oil refining (production of MGO).

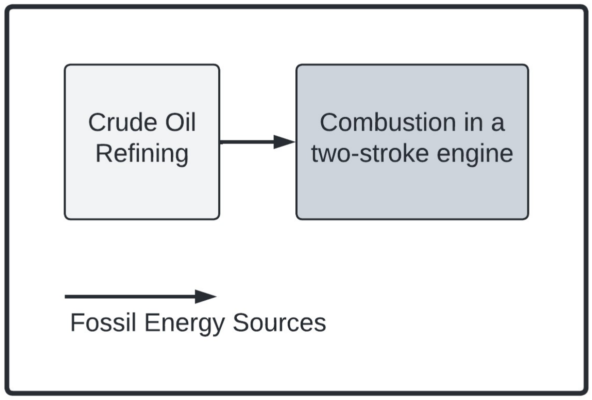

Figure 4: Product system of Marine Gas Oil.

In Figure 5, 6 and 7 below, the product system of Brown, Grey/Blue and Green Ammonia are illustrated, respectively. All Ammonia production pathways investigated in this LCA have the same process for nitrogen production. This is cryogenic air separation, where atmospheric air is separated into its primary components: nitrogen, oxygen and argon [10]. In addition, all Ammonia product systems include the product system of the pilot oil. In this LCA, the pilot oil is VLSFO with SPOC/SFC = 5% - meaning that 5% of the amount of energy injected into the cylinders at full load and at a given speed is VLSFO. Fossil energy sources are used during crude oil refining as well as during the desulfurization process (production of VLSFO).

Ammonia, in all four production pathways, is produced by using the same Haber-Bosch process. With pressures above 10 MPa (100 bar) and temperatures between 400°and 500°Celsius, the gases (nitrogen and hydrogen) are passed over a number of catalyst beds where the conversion to Ammonia occurs. Over each catalyst bed only approximately 10-15% is converted into Ammonia. However, un-reacted gases are recycled and thus ultimately an overall conversion of 97-99% is achieved [31].

The main difference between the four Ammonia production pathways is the production of hydrogen. The Brown production pathway for Ammonia produces hydrogen through coal gasification. In this process, a partial oxidation occurs by letting air react with coal through a traditional combustion. This generates both CO and CO_2 as well as hydrogen and water. CO is afterwards reacted with steam (water), generating both hydrogen and CO_2. This water gas shift reaction is conducted in order to adjust the CO and hydrogen ratio i.e. produce more hydrogen [3]. Cryogenic air separation uses a global electricity mix while coal gasification uses hard coal as energy source which also applies to the Haber-Bosch process.

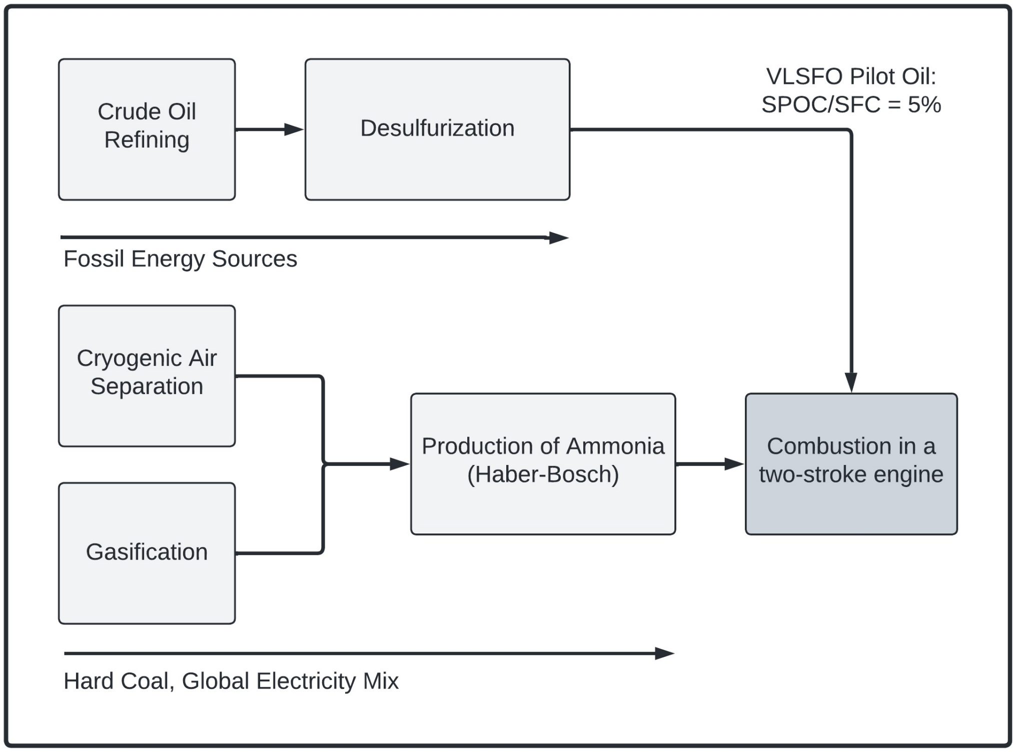

Figure 5: Product system of Brown Ammonia.

The grey production pathway for Ammonia produces hydrogen through methane steam reforming. First, natural gas is desulfurized after which methane reacts with steam (water), generating both CO and hydrogen. The CO is reacted with steam (water) which generates more hydrogen and converts CO into CO_2 [5, 29].

Blue Ammonia has nearly the same production pathway as Grey Ammonia and thus Figure 6 below also illustrates the Blue production pathway. The only difference between the two production pathways (Grey and Blue) is that the aforementioned generated CO_2 is captured and stored using industrial Carbon Capture and Storage (CCS) technologies in the Blue production pathway, see the blue dotted line in Figure 6. Cryogenic air separation uses a global electricity mix while methane steam reforming uses natural gas as energy source which also applies to the Haber-Bosch process.

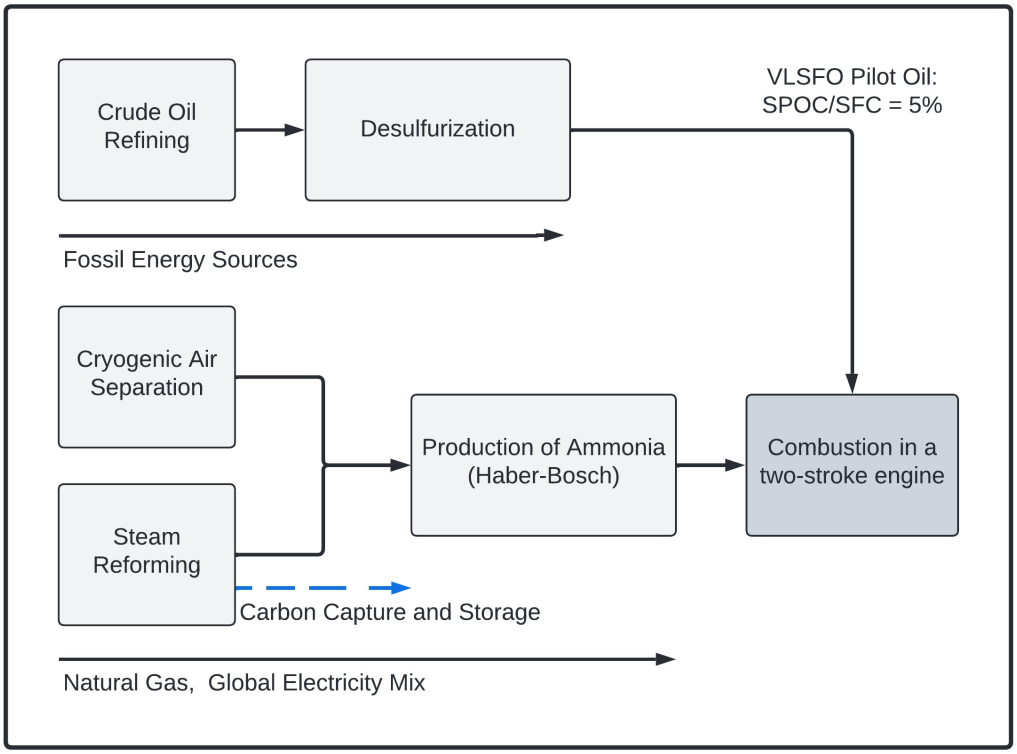

Figure 6: Product system of both Grey and Blue Ammonia.

The Green production pathway for Ammonia produces hydrogen through electrolysis. In this process, water is separated into its primary components, hydrogen and oxygen, by applying electrical energy. The resulting positively charged hydrogen ions (H^+) generate H_2-molecules by reacting with a cathode [25]. Both cryogenic air separation and electrolysis use a global wind electricity mix which also applies to the Haber-Bosch process.

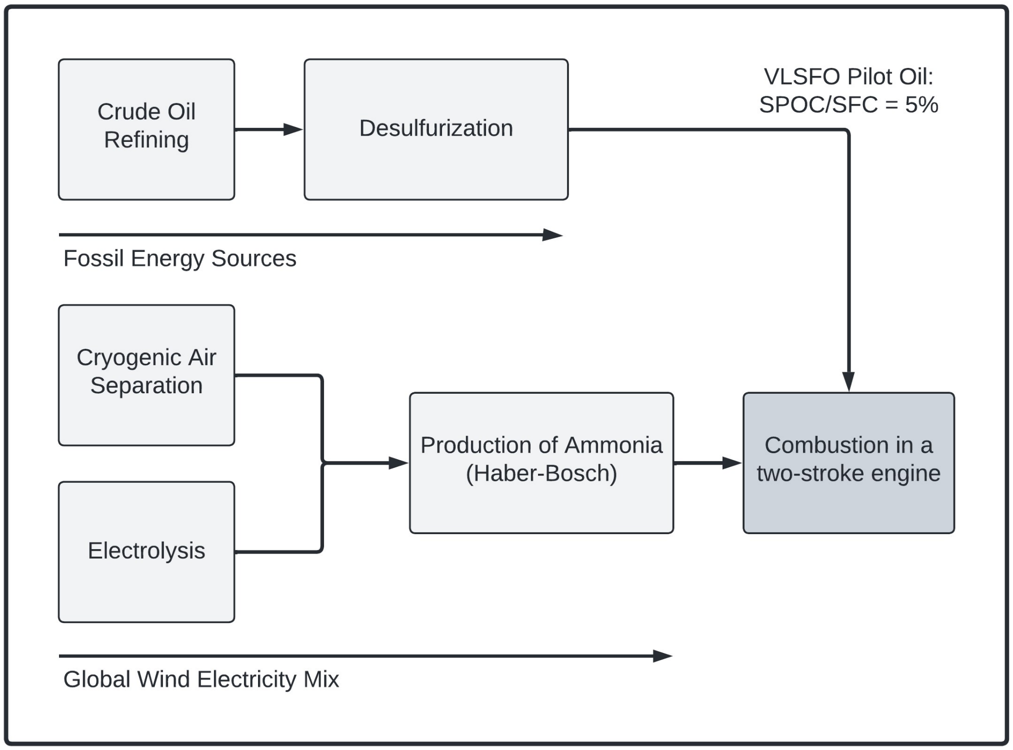

Figure 7: Product system of Green Ammonia.

3.2 Data Collection

Data used to model life cycle inventories for the foreground processes were collected from four different sources: (I) Consulting naval architect; Hans Otto Kristensen, who provided data on fuel consumption and combustion emissions for VLSFO and MGO (through the DESMO Calculation Tool) as well as general knowledge regarding bulk carriers and how they operate. (II) MAN Energy Solutions, who provided data on combustion emissions for Ammonia, physical properties of the exhaust gas (through their online engine calculation tool, CEAS) and amount of pilot oil needed. (III) Previous studies, which provided data on the different hydrogen production pathways (coal gasification, methane steam reforming and electrolysis) and the Haber-Bosch process. (IV) ecoinvent (version 3.7), which provided data for the production of VLSFO, MGO and nitrogen. Modelling the production of VLSFO and MGO using ecoinvent was aided by the knowledge of environmental engineer; Eddy van Bouwel.

Background processes were all modelled using ecoinvent.

3.3 System Modelling Per Life Cycle Stage

3.3.1 Materials Stage

Cryogenic air separation for the production of nitrogen was modelled using the unit process "air separation, cryogenic | oxygen, liquid | Consequential, U" from the consequential ecoinvent database. In this process, the production of nitrogen is a secondary function as the main output is oxygen. According to the process, there is a 1:3.27 ratio between the production of oxygen and nitrogen. Thus, in order to use this process for the production of nitrogen, inputs and outputs are all divided by 3.27.

The four different production pathways for hydrogen are modelled using life cycle inventory (LCI) data from four life cycle assessment (LCA) studies: [27], [35], [24], [9], and one literature review study [11] - all regarding hydrogen production. [27] and [11] were used to model coal gasification (Brown Ammonia) while [27] and [35] were used to model methane steam reforming both with and without CCS(Grey and Blue Ammonia respectively). It is assumed that the CCS technology used has an efficiency of 95% [32].

Electrolysis (Green hydrogen) is modelled using [24] and [9]. In addition to these two sources, a stoichiometric calculation is done in order to estimate the amount of oxygen produced. Theoretically, with a 100% efficiency, 10 kg of de-ionized water would produce approximately 1.1 kg of hydrogen and 8.9 kg of oxygen, see the stoichiometric calculation in Section E.4 in Appendix E. However, [24] states that 10 kg of de-ionized water only produces 1 kg of hydrogen. Thus, with this reduced efficiency, it is expected that 8 kg of oxygen is produced (as the molar mass ratio between hydrogen and oxygen in water is 1:8). The remaining 1 kg is assumed to be un-reacted de-ionized water which is consequently modelled as an output.

3.3.2 Manufacturing Stage

In the manufacturing stage, the three different marine fuels are produced. The production of Ammonia, through the Haber-Bosch process, is modelled using [30], [31] and ecoinvent. In addition, a stoichiometric calculation is done in order to determine the amount of nitrogen and hydrogen needed to produce 1 kg of Ammonia. Theoretically, with 100% conversion, 1 kg of Ammonia requires approximately 0.82 kg of nitrogen and 0.18 kg of hydrogen, see the stoichiometric calculation in Section E.4 in Appendix E. However, as stated in Section 3.1, the Haber-Bosch process has an overall conversion rate of 97-99% thus a bit more nitrogen and hydrogen is required in order to produce 1 kg of Ammonia. This extra amount is however assumed to be negligible and consequently the Haber-Bosch process is modelled with the aforementioned mass values of nitrogen and hydrogen (to produce 1 kg of Ammonia).

Data on the production of both VLSFO and MGO could not be located. Thus, MGO is modelled using the ecoinvent process "market group for diesel, low-sulfur | diesel, low-sulfur | Consequential, U - GLO" - which is deemed as a reasonable approximation as it only results in a slight overestimation of the MGO impacts, as confirmed by Eddy van Bouwel. VLSFO is modelled using the ecoinvent process "market group for heavy fuel oil | heavy fuel oil | Consequential, U - RER".

A desulfurizing process is added in order to model the lower sulphur content in VLSFO compared to heavy fuel oil (HFO). The desulfurization process converts sulphur compounds into hydrogen sulphide (H_2S) by reaction with hydrogen (hydrocracking). After this, elemental sulphide is recovered through the Claus process (information provided by Eddy van Bouwel). The amount of hydrogen needed to convert these sulphide compounds into H_2S is stoichiometrically calculated as being 0.00033 kg H/kg fuel, see the stoichiometric calculation in Section E.4 in Appendix E. The supply of hydrogen is modelled using methane steam reforming, see Section 3.3.1 for how this hydrogen production method is modelled.

Data on the Claus process could not be located and thus only the process of hydrocracking is used to model the desulfurizing process, using [34] and [26]. This is deemed as a reasonable approximation for modelling the production of VLSFO from HFO, as confirmed by Eddy van Bouwel.

3.3.3 Use Stage & End-of-Life Stage

In this LCA study, the marine fuels are combusted during the use stage while the exhaust gases are emitted to the environment as the End-of-Life stage. The use stage is the whole sea route from Rotterdam to Singapore, through the Suez Canal, and it is estimated to be 8300 nm. Combustion emissions for both VLSFO and MGO were provided by the DESMO Calculation Tool whereas Ammonia's combustion emissions were provided by MAN Energy Solutions, see Table 7 below for values.

Table 7: Combustion emissions [kg/nm] for Very-Low Sulphur Fuel Oil (VLSFO), Marine Gas Oil (MGO), Ammonia and Ammonia's pilot fuel (VLSFO). HC stands for hydrocarbons and PM stands for particulate matter. Sections E.5 and E.6 in Appendix E provide further details regarding Ammonia and its pilot oil's combustion emissions.

	VLSFO	**MGO**	**Ammonia**	**Pilot Oil (VLSFO)**
CO	0.25	0.25	-	0.012
CO_2	393	384	-	19.48
NH_3	-	-	12.90	-
N_2O	-	-	0.33	-
NOx	9.40	9.40	34.90	0.47
SOx	1.30	0.30	-	0.066
HC	0.35	0.317	-	0.017
PM	0.23	0.19	-	0.011

As seen above in Table 7, there are no particulate matter emissions for Ammonia. MAN Energy Solutions does not have an estimate as this emission type can only be quantified through measurements taken during engine tests - MAN Energy Solutions expects to run its first tests with an Ammonia-fuelled engine in the summer of 2022. It should be noted that the Ammonia combustion emissions stated in Table 7 are best current estimates, and not based on actual measurements.

The route from Rotterdam to out of the North Sea Emission Control Area is a minor part of the total journey to Singapore. It is therefore assumed that there is no NOx emission abatement technology installed on-board the Panamax bulk carrier. In addition, it is also assumed that there is no scrubber installed to reduce SOx emissions as all three investigated marine fuels already comply with the global sulphur limit.

3.3.4 Transportation

Transport of materials and fuels between processes has not been included in the LCI model.

3.4 Basis for Sensitivity and Uncertainty Analysis

In order to quantify the influence of key values/processes, assumptions and choices on the results and conclusions, both sensitivity and uncertainty analyses will be conducted.

3.4.1 Sensitivity Analysis

Sensitivity analyses is conducted on both continuous parameters (perturbation analysis) and discrete choices (scenario analysis).

Perturbation Analysis

Normalised sensitivity coefficients (NSCs) ($X_{IS,k}$) are calculated using Equation 1 [15].

$$X_{IS,k} = \frac{\Delta IS/IS}{\Delta a_k/a_k} \tag{1}$$

$X_{IS,k}$ is the NSC of an impact score (IS) for a change in parameter k, a_k is the value of parameter k that was used for modelling, Δa_k is the change in the value of parameter k, IS is the calculated impact score for parameter value a_k and ΔIS is the change in the calculated impact score which occurs after the change in a_k [15]. In this LCA study, a parameter is considered to have medium sensitivity if average $|X_{IS,k}| \geq 0.3$ (across all impact categories) and large sensitivity if max $|X_{IS,k}| \geq 0.5$. Medium and large sensitivity equals an important parameter. In Table 8 below, the parameters to which a perturbation analysis is conducted are stated.

Table 8: Parameters to which a perturbation analysis is conducted.

Parameter	**Baseline Scenario**	**Perturbation**
Energy Demand: Haber-Bosch Process	26.0 MJ	+10%
Efficiency: Haber-Bosch Process	100%	-10%
Efficiency: Electrolysis	90.0%	+10%
Efficiency: Carbon Capture and Storage	95.0%	-10%

As seen in Table 8, the four tested parameters are all perturbed by 10%. Taking the actual and/or theoretical parameter value intervals into account, this is deemed as a realistic perturbation. The parameter values used in modelling (Baseline Scenario) for 'Energy Demand: Haber-Bosch Process', 'Efficiency: Haber-Bosch Process' and 'Efficiency: Carbon Capture and Storage' are based on assumptions while the parameter value used in modelling for 'Efficiency: Electrolysis' is based on low data quality. Thus, they were deemed important to test for sensitivity. These four tested parameters all relate to Ammonia. It could be of interest to also test parameters related to VLSFO and MGO. This was however not performed, as these were deemed less relevant to the outcome of this LCA study.

Scenario Analysis

In this LCA study, four scenario analyses and their conclusions are based on the following. The same impact categories across scenarios are compared based on how they rank the six investigated marine fuel pathways. Ranking the six marine fuel pathways in a specific impact category is done with regard to the magnitude of the impact scores. If there is a change in the ranking in five or more comparable impact categories then the parameter is sensitive and thus an important parameter. Oppositely, if there is not a change in ranking in five or more comparable impact categories then the parameter is not considered sensitive. It should be noted that ranking in these scenario analyses refers to ranking the lowest impact score. In Table 9 below, the parameters to which a scenario analysis is conducted are stated.

Table 9: Parameters to which a scenario analysis is conducted. GWP: Global Warming Potential and LCIA: life cycle impact assessment.

Parameter	**Baseline Scenario**	**Scenario 1**	**Scenario 2**
Oxygen Substitution	100%	0%	-
NOx Abatement Technology	Not Installed	Installed	-
GWP, Time Horizon	100 years	20 years	-
LCIA Methodology	ReCiPe 2016 Midpoint (H)	ILCD 2011 Midpoint+	EF 3.0 Method

A scenario analysis is conducted on oxygen substitution as the baseline scenario (used in modelling) is based on the assumption that oxygen produced during the processes of cryogenic air separation and electrolysis is placed on the market and will thus substitute the production of oxygen from other suppliers. Secondly, a scenario analysis is conducted on NOx abatement technology as the baseline scenario is based on the assumption that no NOx abatement technology is installed on-board the Panamax bulk carrier.

A scenario analysis on global warming potential's (GWP) time horizon is requested by the study commissioner to quantify the impact of emissions on a different time scale. This scenario analysis is conducted using two of the cultural perspectives stated in Section E.3 in Appendix E as ReCiPe 2016 Midpoint (H)'s characterisation factor for 'Global warming' is based on IPCC's 100-year GWP time horizon while ReCiPe 2016 Midpoint (I)'s is based on IPCC's 20-year GWP time horizon. In addition, a scenario analysis is conducted on different LCIA methodologies in order to investigate how the use of different LCIA methodologies can impact the results. If the outcome of the study is not affected, the choice of LCIA methodology is deemed suitable for the goal and scope of the study.

3.4.2 Uncertainty Analysis

Parameter uncertainty and variability is investigated by Monte Carlo simulations. For this LCA study's uncertainty analysis, the parameters tested with a perturbation analysis, see Table 8, are considered. Below in Table 10, the four investigated parameters are stated with the parameter value used in the baseline scenario and a realistic and/or theoretical parameter value interval. The uniform distribution is assumed for all the tested parameters as the actual distributions are unknown. Differences in impact scores between the investigated marine fuels are considered to be statistically significant if the calculated 95% confidence intervals of the impact scores from 1,000 iterations do not overlap [6]. A first iteration of Monte Carlo analyses illustrated that after approximately 500-700 iterations, normal distributions were evident. Thus, conducting Monte Carlo analyses with 1,000 iterations is deemed sufficient.

Table 10: Parameters to which an uncertainty analysis is conducted.

Parameter	Baseline Scenario	Parameter Value Interval
Energy Demand: Haber-Bosch Process	26.0 MJ	[20.9 MJ ; 30.0 MJ]
Efficiency: Electrolysis	90.0%	[90.0% ; 100%]
Efficiency: Haber-Bosch Process	100%	[97.0% ; 100%]
Efficiency: Carbon Capture and Storage	95.0%	[95.0% ; 99.0%]

All parameters and flows in the foreground processes are associated with uncertainty and variability. Thus, quantifying parameter value intervals for all parameters and flows in the foreground processes would have supported a more comprehensive uncertainty analysis. However, as realistic and/or theoretical parameter value intervals were difficult to locate/estimate, it was decided that this uncertainty analysis should align with the perturbation analysis. In addition, realistic and/or theoretical parameter value intervals could be located/estimated for these four tested parameters.

Uncertainties in the background processes are not considered as they are unknown. Covariation between processes that occur in some or all of the investigated product systems is also not considered in this uncertainty analysis. If covariation had been taken into account, there is a possibility that more statistically significant differences in impact scores would have been evident - as the uncertainty would have been reduced. In addition, uncertainties related to the characterisation factors are also not considered in this uncertainty analysis.

3.5 Calculated LCI Results

Life cycle inventories are stated in Section D.2.1 (Table 21 - 26), Section D.2.2 (Table 27 - 32), Section D.2.3 (Table 33 - 41) and Section D.2.4 (Table 42 - 44) - all in Appendix D.

4 Life Cycle Impact Assessment

4.1 Characterised Results at Midpoint Level

The environmental impacts of the six fuel pathways are stated below in Table 11 in characterised form. The results are presented in a heat map with graded colours, where green represents the lowest impact and red represents the highest impact in each impact category.

Table 11: Characterised impact scores for the six fuel pathways at midpoint level, calculated using ReCiPe 2016 Midpoint (H) as LCIA methodology. Results are presented in a heat map with graded colours, where green represents the lowest impact and red represents the highest impact in each impact category.

Impact Category	Unit	VLSFO	MGO	Brown Ammonia	Grey Ammonia	Blue Ammonia	Green Ammonia
Global warming	kg CO2 eq	4.67E+06	3.77E+06	2.49E+07	1.32E+07	1.09E+07	-4.78E+06
Stratospheric ozone depletion	kg CFC11 eq	1.05E+00	9.79E-01	3.30E+01	3.34E+01	3.35E+01	2.85E+01
Ionizing radiation	kBq Co-60 eq	-6.98E+04	2.90E+04	-6.21E+04	-2.32E+03	-3.05E+03	-8.53E+05
Ozone formation, Human health	kg NOx eq	8.29E+04	8.03E+04	3.66E+05	3.04E+05	3.04E+05	2.84E+05
Fine particulate matter formation	kg PM2.5 eq	2.12E+04	1.24E+04	1.03E+05	6.08E+04	6.09E+04	4.00E+04
Ozone formation, TE*	kg NOx eq	8.30E+04	8.05E+04	3.66E+05	3.04E+05	3.05E+05	2.84E+05
Terrestrial acidification	kg SO2 eq	4.87E+04	3.45E+04	4.45E+05	3.23E+05	3.23E+05	3.00E+05
Freshwater eutrophication	kg P eq	1.84E+03	7.82E+01	8.42E+03	1.82E+02	1.85E+02	-4.41E+03
Marine eutrophication	kg N eq	1.77E+03	1.66E+03	7.28E+03	6.25E+03	6.25E+03	5.94E+03
Terrestrial ecotoxicity	kg 1,4-DCB	3.17E+06	2.14E+06	9.22E+06	9.67E+05	9.95E+05	1.81E+06
Freshwater ecotoxicity	kg 1,4-DCB	5.75E+04	1.19E+04	4.07E+05	2.74E+04	2.84E+04	1.00E+05
Marine ecotoxicity	kg 1,4-DCB	8.18E+04	1.82E+04	5.64E+05	3.83E+04	3.98E+04	1.04E+05
Human carcinogenic toxicity	kg 1,4-DCB	9.29E+04	5.39E+03	5.44E+05	6.65E+03	6.61E+03	-5.26E+04
Human non-carcinogenic toxicity	kg 1,4-DCB	2.58E+06	3.08E+05	2.34E+07	5.92E+05	6.13E+05	-5.10E+06
Land use	m2a crop eq	3.53E+05	1.13E+04	5.47E+04	3.23E+04	3.25E+04	-5.81E+04
Mineral resource scarcity	kg Cu eq	2.59E+03	1.69E+03	5.59E+03	4.04E+03	4.25E+03	3.14E+04
Fossil resource scarcity	kg oil eq	1.32E+06	1.23E+06	4.62E+06	5.38E+06	5.64E+06	-1.58E+06
Water consumption	m3	3.13E+04	8.82E+02	3.70E+04	1.34E+04	1.36E+04	-1.74E+05

* Terrestrial ecosystems

In 9 of the 18 impact categories, MGO has the lowest impact, while Green Ammonia has the lowest impact in 8 out of the 18 impact categories - including 'Global warming'. Furthermore, Green Ammonia has negative impact scores in the categories where it has the lowest impact, which means that the crediting of the production of secondary functions is higher than the impacts. Brown Ammonia has the highest impact score in 13 out of the 18 impact categories. In addition, Brown Ammonia doesn't have the lowest impact score in any of the categories. Blue and Grey Ammonia have similar impact scores - this was expected seeing as they have very similar product systems, see Figure 6.

In the seven impact categories: 'Stratospheric ozone depletion', 'Ozone formation, Human health', 'Fine particulate matter formation', 'Ozone formation, Terrestrial ecosystems', 'Terrestrial acidification', 'Marine eutrophication' and 'Mineral resource scarcity', VLSFO and MGO have the lowest impact scores. The two impact categories 'Marine eutrophication' and 'Marine ecotoxicity' are considered especially important with regard to the product systems as all emissions related to fuel combustion occur at sea. Here, it is seen that MGO has the lowest impact scores and Brown Ammonia has the highest impact scores.

The results also show that Brown, Grey and Blue Ammonia are the fuels that generally have the highest impact scores, indicating that they are not preferred production pathways for Ammonia as a marine fuel. Of the fossil fuels, MGO has lower impact scores in all impact categories except 'Ionizing radiation'.

Taking a closer look at the impact category 'Global warming', the differences in this category are presented more clearly below in Figure 8.

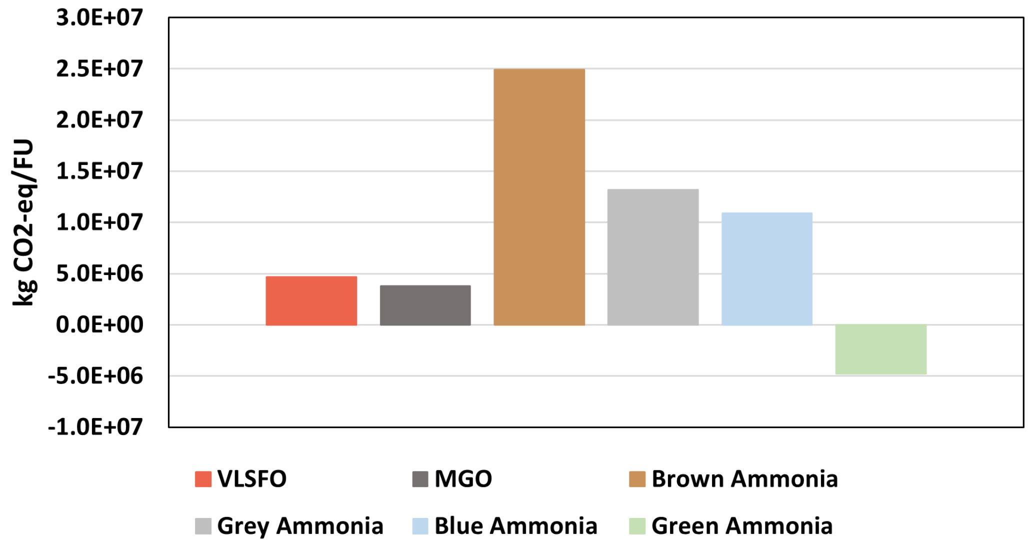

Figure 8: Characterised impact scores for the impact category 'Global warming', calculated using ReCiPe 2016 Midpoint (H) as LCIA methodology.

Switching from the most commonly used marine fuel, VLSFO, to Green Ammonia, will decrease the impact to 'Global warming' with approximately 200%. Furthermore, Green Ammonia has a net negative impact, which means that crediting the production of secondary functions is higher than the impacts. It can moreover be seen that using Carbon Capture and Storage in Blue Ammonia is effective as it lowers the impact score by 17% compared to Grey Ammonia. Brown, Grey and Blue Ammonia all have higher impact scores than VLSFO and MGO. As for the fossil fuels' impact to 'Global warming', it is seen that MGO has a 19% lower impact score than VLSFO.

In general it should be noted that it cannot be concluded that the impact scores are significantly different before an uncertainty analysis has been conducted. In this assessment, a quantitative uncertainty analysis was conducted on the Ammonia pathways, see Section 5.2.3. A clear weighting of importance between the impact categories has not been done and thus 'the best performing' fuel cannot be stated clearly.

4.2 Normalised Results at Midpoint Level

The characterised results shown in Table 11 are normalised using ReCiPe's global normalisation factors. The common unit of person equivalent (PE) corresponds to the annual impact of the average global person in 2010. Figure 9 shows normalised results where impact categories are divided into sub-figures based on the magnitude of their normalised impact score. An important thing to note is that the categories have not been weighted with regards to importance. This means that the different fuel pathways can be compared within each impact category, but not across categories. See Table 45, Section D.3 in Appendix D for numerical results.

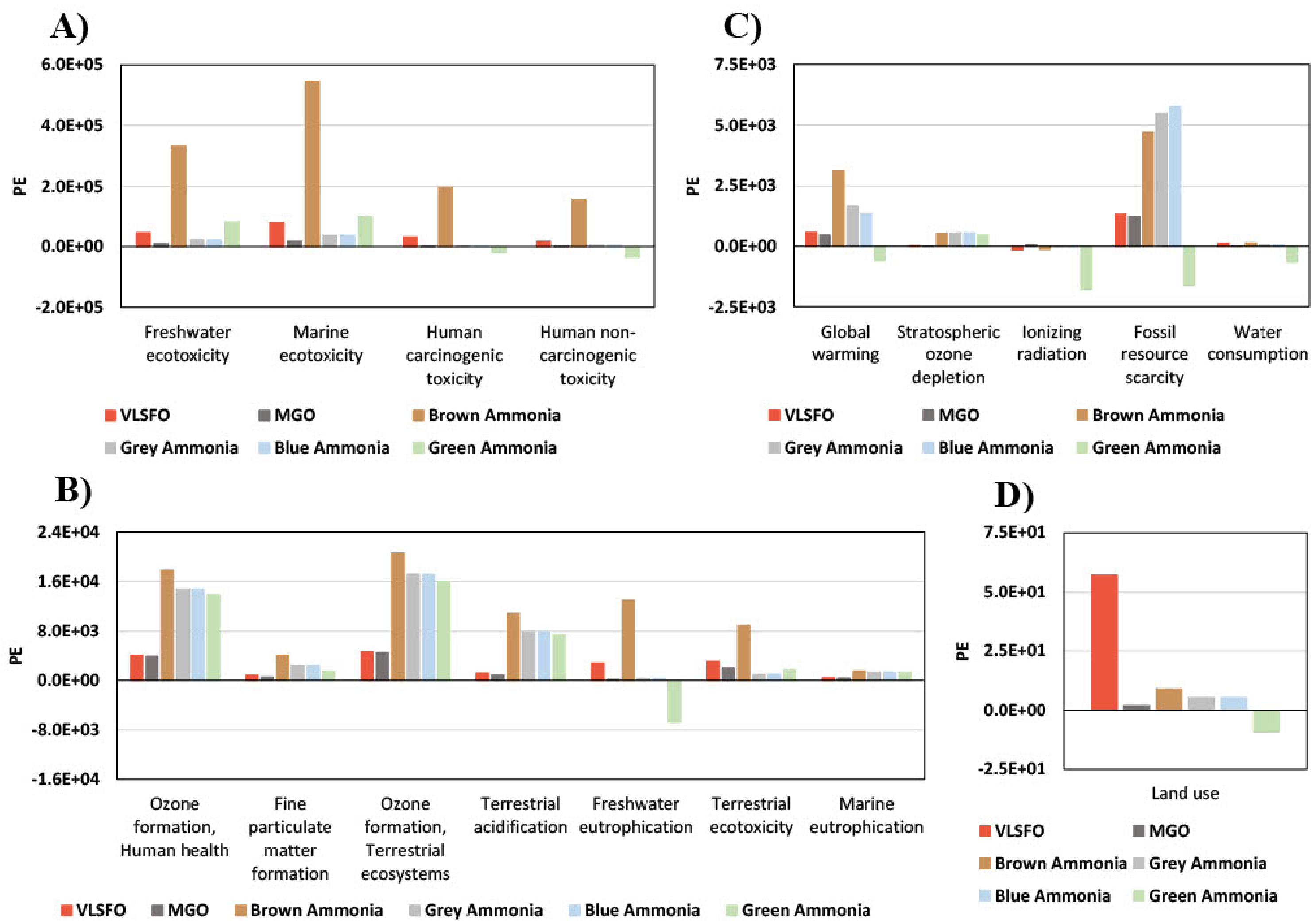

Figure 9: A) Normalised impact scores in the magnitude of E+05 PE, B) Normalised impact scores in the magnitude of E+04 PE, C) Normalised impact scores in the magnitude of E+03 PE, D) Normalised impact scores for 'Land use'. 'Mineral resource scarcity' is not visually depicted. The normalised impact scores have been calculated using ReCiPe 2016 Midpoint (H) as LCIA methodology. All numerical results can be seen in Table 45, Section D.3 in Appendix D.

Figure A) presents the highest normalised impact scores, which are four of the five toxicity impact categories. From Figure A), it is evident that Brown Ammonia has substantially higher impacts than both the fossil marine fuels and the other Ammonia production pathways. As the different production pathways for Ammonia have the same tank-to-wake impacts (combustion emissions), the higher impacts from Brown Ammonia are due to well-to-tank (production) impacts. It is known that the toxicity impact categories have underestimated normalisation factors, which results in overestimated normalised results. This aspect, however, does not affect comparison between the fuel pathways within the toxicity impact categories.

From **Figure B)**, presenting the second highest normalised impact scores, seven impact categories can be seen. On this graph, the two categories for 'Ozone formation', as well as 'Terrestrial acidification', are higher for Ammonia (all production pathways) than the fossil marine fuels. In addition, it is seen that 'Freshwater eutrophication' is the only impact category where crediting the production of secondary functions is higher than the impacts - this pertains to Green Ammonia.

In **Figure C)** it is seen that Green Ammonia has the lowest, as well as a negative, normalised result in 4 out of 5 impact categories. This includes 'Global warming' and 'Fossil resource scarcity', where in the last-mentioned impact category, the other production pathways for Ammonia are substantially higher. This is due to the use of the fossil resources; coal and natural gas in the fuel production.

Figure D) presents only one impact category, 'Land use' for which it can be seen that VLSFO has a substantially higher normalised impact score than the rest.

'Mineral resource scarcity' is not depicted visually in Figure 9, as its largest normalised result is 2.6E-01 PE. This is the result for Green Ammonia, and it is approximately 5 times larger than the second highest, Brown Ammonia. The rest have a similar scale, with MGO being the lowest at 1.4E-02 PE.

4.3 Characterised Result at Endpoint Level

Characterised impact scores at endpoint level are stated below in Table 12 in a heat map with graded colours, where green represents the lowest impact and red represents the highest impact in each area of protection. Here, it is seen that Brown Ammonia has the highest characterised impact score in two out of the three areas of protection. These being 'Human health' and 'Ecosystem quality' with values of 9.56E+01 DALY and 2.19E-01 species.year, respectively. This relates well to what was concluded at midpoint level where Brown Ammonia has the highest impact score in 13 out of 18 impact categories, see Table 11. However, in the last area of protection, 'Resource scarcity', Brown Ammonia has the second lowest characterised impact score, this being 4.13E+05 USD2013. In this area of protection, Blue Ammonia has the highest characterised impact score of 2.02E+06 USD2013 closely followed by Grey Ammonia with an impact score of 1.93E+06 USD2013.

Based on the midpoint results, Green Ammonia was expected to score among the lowest characterised impacts in all three areas of protection. In both 'Human health' and 'Ecosystem quality', it has the third lowest characterised impact score, scoring higher than both VLSFO and MGO, while in 'Resource scarcity' it has the lowest characterised impact score of -2.85E+05 USD2013. Compared to the other fuels' characterised impact score in this area of protection, Green Ammonia's impact score is negative, and compared to the second lowest the difference is 245%. To see which midpoint categories contributed to which area of protection see Table 46, Section D.3 in Appendix D.

Table 12: Characterised impact scores at endpoint level, calculated using ReCiPe 2016 Endpoint (H) as LCIA methodology. Results are presented in a heat map with graded colours, where green represents the lowest impact and red represents the highest impact in each area of protection.

	Unit	**VLSFO**	**MGO**	**Brown Ammonia**	**Grey Ammonia**	**Blue Ammonia**	**Green Ammonia**
Human health	DALY	1.87E+01	1.14E+01	9.56E+01	5.10E+01	4.89E+01	1.93E+01
Ecosystem quality	Species.yr	3.90E-02	2.84E-02	2.19E-01	1.45E-01	1.39E-01	8.12E-02
Resource scarcity	USD2013	4.95E+05	5.52E+05	4.13E+05	1.93E+06	2.02E+06	-2.85E+05

5 Interpretation

5.1 Significant Issues

This section presents and discusses the main processes and substances contributing to impacts. 'Global warming' will be in focus.

5.1.1 Process Contribution

Firstly, the impacts to 'Global warming' are divided into the main life cycle stages well-to-tank (upstream) and tank-to-wake (direct), depicted in Figure 10 as relative contributions. It is evident that there is a clear change in pattern, as the fossil fuels have the majority of their impacts as direct emissions, while the majority of the impact of the Ammonia pathways occur upstream. It can be said that switching from one of the fossil fuels to Ammonia might burden-shift between the life cycle stages, and as the upstream is often not as much in focus as the direct emissions, this is important to remember.

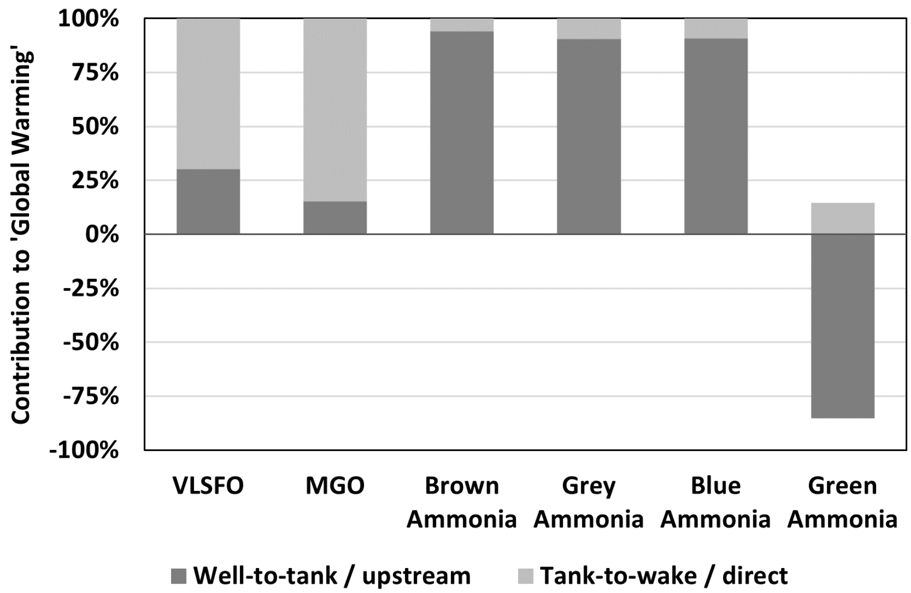

Figure 10: Contributions of processes to the impact category 'Global warming', divided into those occurring well-to-tank (upstream) and tank-to-wake (direct). Contribution is depicted relatively, meaning that differences in magnitude of impacts between the fuels are not depicted.

The direct impacts are simply the combustion emissions, while there is more to explore in the upstream part. In Figure 11, a detailed process contribution is performed. Note that all electricity substitutions are gathered into one process, and thus not included in the processes where they occur. This is done to give a better visual of the division between the impacts of energy use and emissions from these processes, and the substitution occurring. In a similar manner, Hydrogen production is divided into its impacts from Energy use and Emissions to visualise the distribution between these further. This process analysis expands the information on the Ammonia pathways, showing several interesting details:

(I) Electricity makes up most of Ammonia's impacts to 'Global warming'. Electricity use in the Haber-Bosch process dominates all but Green Ammonia - especially Blue Ammonia where the contribution is 80% of the total. Brown Ammonia also shows noticeable impacts for its energy use in the Hydrogen Production and especially Emissions from there, due to the considerable coal input. Impacts from Electricity use in Nitrogen production is identical for all but Green Ammonia, as expected.

(II) Electricity substitution is present for all, occurring in several processes. This substitution is the result of system expansion, which is theoretically introduced in Appendix C. In our case, three different multifunctional processes have either a direct output of electricity, or has an influential by-product. This by-product enters the market and thus, assuming there is a demand, some other producer will not have to produce this anymore to satisfy demands. Thus, the by-product of our system substitutes the production of this same product by other means. **Firstly**, in the Nitrogen production process which they all share, oxygen is a by-product. The market provider of Oxygen in ecoinvent is cryogenic air separation, a process which uses electricity as its energy source. Now, by someone else not having to produce this oxygen through air separation, this total process of air separation to produce the same amount of oxygen does not need to occur, and its impacts on the environment are credited in our system. This impact to 'Global warming' is almost entirely consisting of avoided electricity production, corresponding to 1.00E+06 kgCO_2−eq. **Secondly**, Green Ammonia has the largest energy substitution as its electrolysis process produces a large by-product of oxygen (8:1 molar mass ratio with Hydrogen). And as with the Nitrogen Production, this substitutes the electricity requirements for producing this oxygen by cryogenic air separation and a total of 5.74E+06 CO_2−eq is saved. **Thirdly**, Brown Hydrogen production has an output of electricity from the coal gasification of 6.34E+05 CO_2−eq, which is modelled as entering the market and substituting the global electricity mix.

(III) Emissions from the Hydrogen production vary greatly across the Ammonia pathways, and the contribution from this ranges from less than a percent for Green to 30% for Brown. This is a good example of how the most differing factor between the pathways (the type of Hydrogen production) is reflected in the results.

(IV) Combustion emissions are identical (9.87E+05 CO_2−eq) between the Ammonia pathways, as expected. The contribution to each pathway's total impacts range from 4-11%.

5.1.2 Substance Contribution

In Figure 12, the main substances contributing to the impact category 'Global warming' are presented for each fuel pathway. It should be noted that these substances have been divided into well-to-tank and tank-to-wake referring to the production of the fuels and the combustion emissions, respectively.

As seen in Figure 12, the main substance across fuel pathways that contributes to 'Global warming' is CO_2. The contribution to 'Global warming' from CO_2 is especially substantial for Brown, Grey and Blue Ammonia in well-to-tank. Oppositely, tank-to-wake CO_2 contributions to 'Global warming' are small for all the different Ammonia production pathways and are only due to the use of a pilot oil. As expected, CH_4 is a contributing substance for Brown, Grey and Blue Ammonia - as a result of the use of hard coal and natural gas, respectively. VLSFO and MGO also have CH_4 contributions to 'Global warming' though difficult to view in Figure 12 due to these contributions being small in magnitude. In addition, large crediting values for CO_2 and CH_4 can be seen in Figure 12 for Green Ammonia. These constitute the negative impact score for 'Global warming', seen in Table 11. It should be noted that N_2O also has contributions to 'Global warming' in well-to-tank however too small to visualise, so they are not included in the figure. The values used in Figure 12 are stated in Table 47, Section D.4.1 in Appendix D.

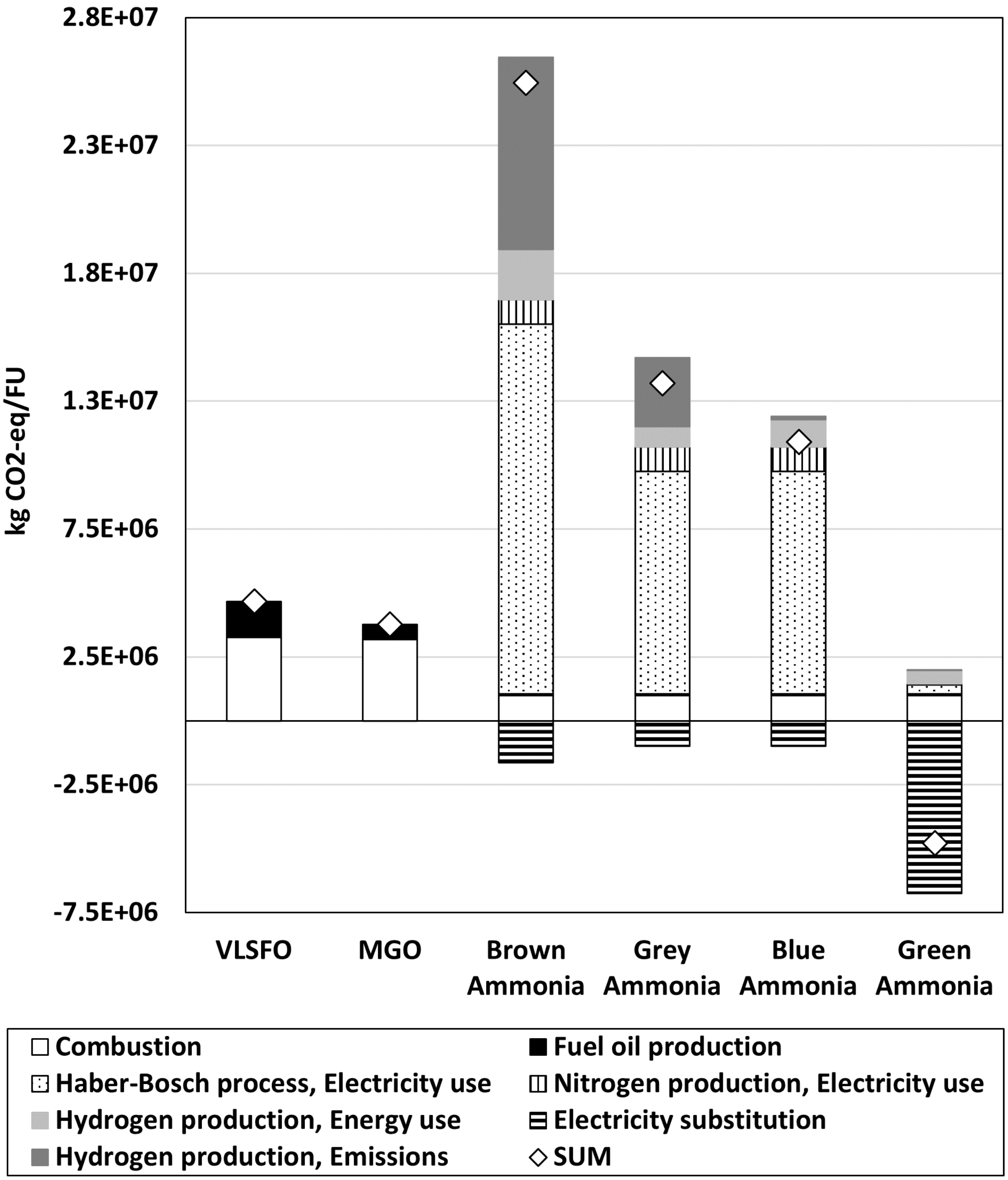

Figure 11: Process contribution to the impact category 'Global warming'. Fuel oil refers to the production of VLSFO and MGO (VLSFO in the cases of Ammonia, as pilot oil). All electricity substitution in any process is joined into one, thus e.g., "Nitrogen production, Electricity" is not a net value. Combustion emissions correspond with the "Tank-to-wake / direct" emissions depicted in Figure 10.

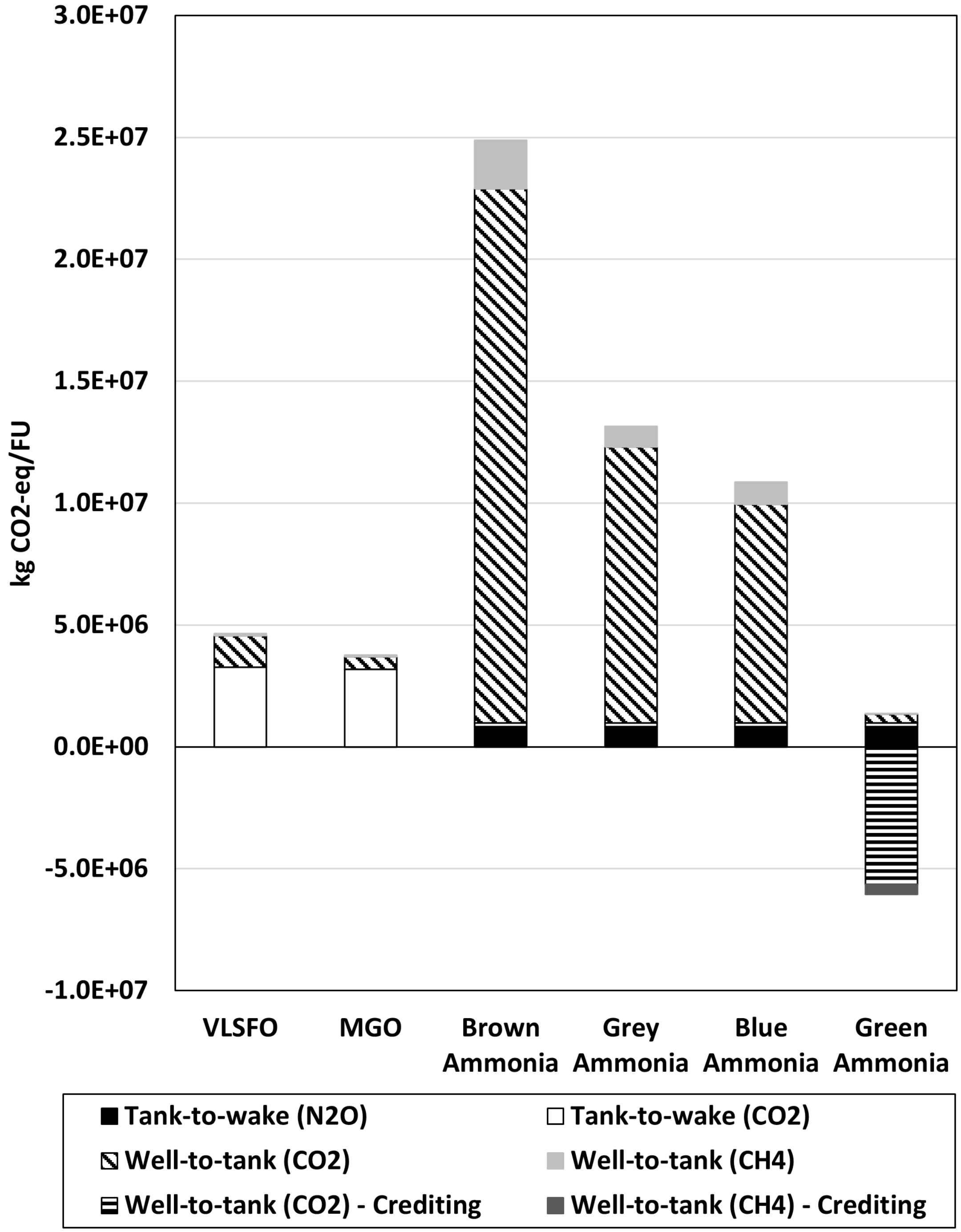

Figure 12: The main substances contributing to the impact category 'Global warming' for each fuel pathway - divided into well-to-tank and tank-to-wake.

If Figure 12 is viewed only with regard to tank-to-wake contributions to 'Global warming', it is evident that Ammonia has a substantially lower contribution than both VLSFO and MGO. However, greenhouse gas emissions are not equal to the full environmental impact of combusting Ammonia as other emissions, especially NOx, are relevant to consider. NOx emissions do not have a global warming potential but will affect the marine environment especially through the impact category 'Marine eutrophication'. When considering this impact category, Ammonia has an approximately 275% higher impact score than both VLSFO and MGO. Eutrophication has negative impacts on marine ecosystems and should therefore be taken into account when deciding whether to use Ammonia as a marine fuel. It should be noted that this LCA study is based on the assumption that no NOx abatement technology is installed on-board the Panamax bulk carrier. If a NOx abatement technology was installed, the NOx emissions would be substantially lower.

5.2 Sensitivity and Uncertainty Analysis

5.2.1 Perturbation Analysis

Perturbation analysis is performed as described in Section 3.4.1.
Table 48-51, Section D.5 in Appendix D includes detailed results of the perturbation analysis. In the following, main outcomes are presented. Table 13 depicts the number of impact categories that for each ammonia pathway and assessed parameter yields a normalised sensitivity coefficient (NSC) higher than or equal to |0.5| ("large" sensitivity). Whether the average NSC is basis for ("medium") sensitivity is included in Table 48-51, Section D.5 in Appendix D.

The parameter **Energy Demand: Haber-Bosch Process** shows large sensitivity across all Ammonia pathways. Brown, Grey and Blue Ammonia each have 11/18 impact categories with large sensitivity, while Green Ammonia has 4/18. While Green Ammonia had the fewest sensitive impact categories, these all had NSCs higher than or equal to any of those of the other Ammonia pathways. For all pathways, the toxicity related impact categories are among the most sensitive. 'Global Warming' is sensitive for all but Green Ammonia, which corresponds well with the contribution analysis, as the Haber-Bosch process did contribute substantially to these three Ammonia pathways.

The parameter **Efficiency: Haber-Bosch Process** shows large sensitivity for Green Ammonia with 10/18 impact categories, including 'Global warming'. This specific perturbation had both the highest average and max NSC across all perturbations made. This is explained primarily by the increased amount of hydrogen input, meaning more oxygen is co-produced resulting in more substitution of electricity production, while yielding the same Ammonia output. As the Electrolysis has net negative characterised impacts to 'Global warming', this perturbation results in an even more net negative impact per FU (See Section 5.1.1). Brown and Blue Ammonia have one sensitive impact category, which is 'Ionizing radiation'. Grey Ammonia shows no sensitivity for this parameter. Specifically, the modelling of Green Ammonia would be improved by increasing data specificity on this parameter, as it shows the highest sensitivity.

The parameter **Efficiency: Electrolysis**, pertaining to Green Ammonia only, shows large sensitivity, occurring in 6/18 impact categories, not including 'Global warming'. The most sensitive impact categories are again the toxicity related (Human carcinogenic, Marine, Freshwater, Terrestrial). As this parameter was modelled with suspected low data quality, it is particularly relevant that it is also sensitive, and the modelling could be improved by gathering better data on this parameter.

The parameter **Efficiency: Carbon Capture and Storage**, pertaining to Blue Ammonia only, showed neither medium nor large sensitivity. The only affected indicator is 'Global warming', as expected, and it only showed a normalised sensitivity coefficient of -0.23. Thus, the assumption on which the parameter is based, is not sensitive.

Table 13: Number of impact categories (out of 18) with large sensitivity for the four assessed parameters. Note that all parameters except for "Efficiency: CCS" have large sensitivity, thus this table depicts the level of large sensitivity, and for which Ammonia pathways they occur. Coloured with light to dark red with increasing number of impact categories with large sensitivity.

	Energy demand: Haber-Bosch	**Efficiency: Haber-Bosch**	**Efficiency: Electrolysis**	**Efficiency: CCS**
Brown Ammonia	11	1	-	-
Grey Ammonia	11	0	-	-
Blue Ammonia	11	1	-	0
Green Ammonia	4	10	6	-

5.2.2 Scenario Analysis

Scenario analysis is performed as described in Section 3.4.1.

Oxygen Substitution

In this scenario analysis, it is assumed that an increase in hydrogen production through electrolysis will result in higher oxygen availability, and thus the market for oxygen is expected to become saturated. As a result, the hydrogen producer has no monetary benefits of supplying the market with oxygen and will thus emit it to the atmosphere instead. The scenario analysis results can be seen below in Table 14 - impact scores are stated in characterised form and presented in a heat map in order for easy comparison with Table 11.

Green Ammonia is now lowest in 2/18 impact categories, including 'Global warming', compared to 8/18 previously. MGO is now lowest in 14/18 impact categories, compared to 9/18 previously. This means that six impact categories have a change in ranking compared to the baseline scenario. Thus oxygen substitution is sensitive for the results of this study, and needs to be investigated further so that a realistic estimate of the oxygen substitution can be used (if further iterations of this LCA study is made).

It should be noted that a scenario of having 0% oxygen substitution is not realistic as oxygen is a very potent and useful chemical substance that is used in many different processes. In addition, it is possible that the large amounts of oxygen available will make the use of oxygen economically viable in processes that currently do not use oxygen. The percentage of oxygen substitution is therefore expected to lie somewhere between 0 and 100%, making this scenario a worst case scenario.

Table 14: Characterised impact scores for the six fuel pathways at midpoint level when 0% oxygen substitution is assumed, calculated using ReCiPe 2016 Midpoint (H) as LCIA methodology. Results are presented in a heat map with graded colours, where green represents the lowest impact and red represents the highest impact in each impact category.

Impact Category	Unit	VLSFO	MGO	Brown Ammonia	Grey Ammonia	Blue Ammonia	Green Ammonia
Global warming	kg CO2 eq	4.67E+06	3.77E+06	2.59E+07	1.42E+07	1.19E+07	1.96E+06
Stratospheric ozone depletion	kg CFC11 eq	1.05E+00	9.79E-01	3.34E+01	3.38E+01	3.39E+01	3.08E+01
Ionizing radiation	kBq Co-60 eq	-6.98E+04	2.90E+04	6.49E+04	1.25E+05	1.24E+05	2.52E+03
Ozone formation, Human health	kg NOx eq	8.29E+04	8.03E+04	3.68E+05	3.06E+05	3.06E+05	2.96E+05
Fine particulate matter formation	kg PM2.5 eq	2.12E+04	1.24E+04	1.06E+05	6.38E+04	6.39E+04	6.02E+04
Ozone formation, TE*	kg NOx eq	8.30E+04	8.05E+04	3.68E+05	3.06E+05	3.06E+05	2.96E+05
Terrestrial acidification	kg SO2 eq	4.87E+04	3.45E+04	4.48E+05	3.26E+05	3.26E+05	3.18E+05
Freshwater eutrophication	kg P eq	1.84E+03	7.82E+01	9.16E+03	9.19E+02	9.22E+02	5.61E+02
Marine eutrophication	kg N eq	1.77E+03	1.66E+03	7.33E+03	6.30E+03	6.30E+03	6.28E+03
Terrestrial ecotoxicity	kg 1,4-DCB	3.17E+06	2.14E+06	9.64E+06	1.38E+06	1.41E+06	4.62E+06
Freshwater ecotoxicity	kg 1,4-DCB	5.75E+04	1.19E+04	4.42E+05	6.26E+04	6.35E+04	3.37E+05
Marine ecotoxicity	kg 1,4-DCB	8.18E+04	1.82E+04	6.10E+05	8.45E+04	8.59E+04	4.15E+05
Human carcinogenic toxicity	kg 1,4-DCB	9.29E+04	5.39E+03	5.87E+05	4.97E+04	4.97E+04	2.38E+05
Human non-carcinogenic toxicity	kg 1,4-DCB	2.58E+06	3.08E+05	2.44E+07	1.63E+06	1.65E+06	1.90E+06
Land use	m2a crop eq	3.53E+05	1.13E+04	7.32E+04	5.08E+04	5.10E+04	6.64E+04
Mineral resource scarcity	kg Cu eq	2.59E+03	1.69E+03	6.04E+03	4.48E+03	4.69E+03	3.44E+04
Fossil resource scarcity	kg oil eq	1.32E+06	1.23E+06	4.90E+06	5.66E+06	5.92E+06	3.10E+05
Water consumption	m3	3.13E+04	8.82E+02	6.61E+04	4.26E+04	4.27E+04	2.22E+04

* Terrestrial ecosystems

NOx Abatement Technology

It is assumed that no NOx abatement technology is installed on-board the Panamax bulk carrier. For Ammonia this results in a NOx emission of 24.16 g/kWh (calculation stated in Section E.5 in Appendix E) which is well above the international limit of 14.40 g/kWh (IMO Tier II). Consequently, Ammonia-fuelled engines are not allowed to operate in international waters without the use of NOx abatement. Thus, a scenario analysis with a NOx abatement technology installed for the Ammonia combustion is conducted. It should be noted that in this scenario analysis only the emissions were changed. This means that capital equipment and a potential change in engine efficiency were not taken into account. MAN Energy Solutions' "engine out emissions" were used in this scenario analysis, see Section E.5 in Appendix E for values. The results can be seen below in Table 15.

Now Green Ammonia is lowest in 13/18 impact categories, and MGO is now only lowest in 4/18 (compared to 8 and 9 in the baseline, respectively). This means that five impact categories have a change in ranking compared to the baseline scenario. This showcases that the inclusion/exclusion of a NOx abatement technology has a substantial influence on the outcome of this study. As a result, it is important to consider how to realistically implement this in potential future iterations of the study, especially with regard to capital equipment and engine efficiency.

Table 15: Characterised impact scores for the six fuel pathways at midpoint level when a NOx abatement technology is installed on-board the Panamax bulk carrier, calculated using ReCiPe 2016 Midpoint (H) as LCIA methodology. Results are presented in a heat map with graded colours, where green represents the lowest impact and red represents the highest impact in each impact category.

Impact category	Unit	VLSFO	MGO	Brown Ammonia	Grey Ammonia	Blue Ammonia	Green Ammonia
Global warming	kg CO2 eq	4.67E+06	3.77E+06	2.49E+07	1.32E+07	1.09E+07	-4.78E+06
Stratospheric ozone depletion	kg CFC11 eq	1.05E+00	9.79E-01	3.31E+01	3.35E+01	3.36E+01	2.86E+01
Ionizing radiation	kBq Co-60 eq	-6.98E+04	2.90E+04	-6.21E+04	-2.32E+03	-3.05E+03	-8.53E+05
Ozone formation, Human health	kg NOx eq	8.29E+04	8.03E+04	1.17E+05	5.50E+04	5.53E+04	3.53E+04
Fine particulate matter formation	kg PM2.5 eq	2.12E+04	1.24E+04	5.03E+04	7.87E+03	7.98E+03	-1.30E+04
Ozone formation, TE*	kg NOx eq	8.30E+04	8.05E+04	1.17E+05	5.54E+04	5.57E+04	3.54E+04
Terrestrial acidification	kg SO2 eq	4.87E+04	3.45E+04	1.46E+05	2.47E+04	2.51E+04	1.18E+03
Freshwater eutrophication	kg P eq	1.84E+03	7.82E+01	8.42E+03	1.82E+02	1.85E+02	-4.41E+03
Marine eutrophication	kg N eq	1.77E+03	1.66E+03	2.04E+03	1.00E+03	1.00E+03	7.01E+02
Terrestrial ecotoxicity	kg 1,4-DCB	3.17E+06	2.14E+06	9.22E+06	9.67E+05	9.95E+05	1.81E+06
Freshwater ecotoxicity	kg 1,4-DCB	5.75E+04	1.19E+04	4.07E+05	2.74E+04	2.84E+04	1.00E+05
Marine ecotoxicity	kg 1,4-DCB	8.18E+04	1.82E+04	5.64E+05	3.83E+04	3.98E+04	1.04E+05
Human carcinogenic toxicity	kg 1,4-DCB	9.29E+04	5.39E+03	5.44E+05	6.65E+03	6.61E+03	-5.26E+04
Human non-carcinogenic toxicity	kg 1,4-DCB	2.58E+06	3.08E+05	2.34E+07	5.92E+05	6.13E+05	-5.10E+06
Land use	m2a crop eq	3.53E+05	1.13E+04	5.47E+04	3.23E+04	3.25E+04	-5.81E+04
Mineral resource scarcity	kg Cu eq	2.59E+03	1.69E+03	5.59E+03	4.04E+03	4.25E+03	3.14E+04
Fossil resource scarcity	kg oil eq	1.32E+06	1.23E+06	4.62E+06	5.38E+06	5.64E+06	-1.58E+06
Water consumption	m3	3.13E+04	8.82E+02	3.70E+04	1.34E+04	1.36E+04	-1.74E+05

* Terrestrial ecosystems

As NOx abatement technology will be needed for operation in international waters, endpoint results were calculated for this scenario, and their characterised scores can be seen in Table 16. Here, Green Ammonia is now the lowest in all three areas of protection, hence the combustion phase is important for the endpoint results. The difference from baseline endpoint results is partly due to the way the impact categories have been weighted from midpoint to endpoint. To see which midpoint impact categories contributed to each area of protection see Table 52, Section D.5 in Appendix D.

Table 16: Characterised impact scores at endpoint level when a NOx abatement technology is installed on-board the Panamax bulk carrier, calculated using ReCiPe 2016 Endpoint (H) as LCIA methodology. Results are presented in a heat map with graded colours, where green represents the lowest impact and red represents the highest impact in each area of protection.

	Unit	VLSFO	MGO	Brown Ammonia	Grey Ammonia	Blue Ammonia	Green Ammonia
Human health	DALY	1.87E+01	1.14E+01	6.21E+01	1.75E+01	1.54E+01	-1.43E+01
Ecosystem health	species.yr	3.90E-02	2.84E-02	1.23E-01	5.00E-02	4.37E-02	-1.43E-02
Resource scarcity	USD2013	4.95E+05	5.52E+05	4.13E+05	1.93E+06	2.02E+06	-2.85E+05

Global Warming Potential, Time Horizon

This scenario analysis' results for 'Global warming' can be seen below in Figure 13. The figure presents the relative change in impact score occurring when using a 20-year time horizon compared to a 100-year time horizon with regard to global warming potential.

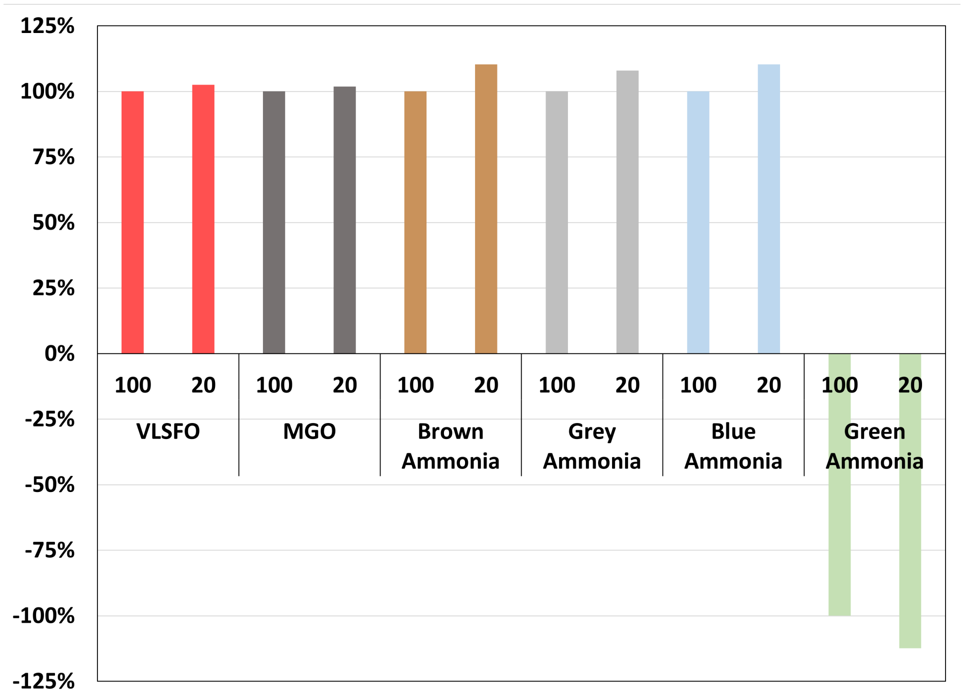

Figure 13: The relative change in impact score occurring when using a 20-year time horizon compared to a 100-year time horizon with regard to global warming potential - done for the impact category 'Global warming', calculated using ReCiPe 2016 Midpoint (H) as LCIA methodology.

Here it can be seen that the change is not substantial and seeing as there is no change in the ranking of the fuel pathways, the choice of GWP time horizon is therefore not considered sensitive.

The Ammonia production pathways have a larger change in results due to methane emissions upstream (well-to-tank) - methane has a substantially higher characterisation factor at a time horizon of 20-year as it is 84 kg CO_2-eq/kg CH_4, compared to 28 CO_2-eq/kg CH_4 with a 100-year time horizon. The fossil marine fuels mostly have CO_2 emissions and CO_2 does not change characterisation factor between a 20- and 100-year time horizon, explaining the smaller changes for these. The other impact categories were also investigated - see Section D.5 in Appendix D.

Life Cycle Impact Assessment Methodology

The results of this scenario analysis are presented below in Table 17. A robustness score of 0 (red) indicates that neither ILCD 2011 Midpoint+ (ILCD) or EF 3.0 has the same ranking as ReCiPe 2016 Midpoint (H) (ReCiPe). A robustness score of 1 (yellow) indicates that either ILCD or EF 3.0 has the same ranking as ReCiPe. Lastly, a robustness score of 2 (green) indicates that both investigated LCIA methodologies have the same ranking as ReCiPe.

Table 17: Comparable impact categories between the LCIA methodologies: ReCiPe 2016 Midpoint (H) (ReCiPe), ILCD 2011 Midpoint+ (ILCD) and EF 3.0. These comparable impact categories often have different names thus R = ReCiPe, I = ILCD and E = EF 3.0. A robustness score of **0** (red) indicates that neither ILCD or EF 3.0 has the same ranking as ReCiPe. A robustness score of **1** (yellow) indicates that either ILCD 2011 Midpoint+ or EF 3.0 has the same ranking as ReCiPe - this is indicated in the table as I = ILCD while E = EF 3.0. A robustness score of **2** (green) indicates that both investigated LCIA methodologies have the same ranking as ReCiPe.

Impact Category	**Robustness Score**
Fine particulate matter formation (R)/ Particulate matter (I, E)	2
Freshwater ecotoxicity	1 (E)
Freshwater eutrophication	2
Global warming (R)/ Climate change (I, E)	2
Human carcinogenic toxicity (R)/ Human toxicity, cancer effects (I)/ Human toxicity, cancer (E)	1 (E)
Human non-carcinogenic toxicity (R)/ Human toxicity, non-cancer effects (I)/ Human toxicity, non-cancer (E)	2
Ionizing radiation	2
Marine eutrophication	2
Stratospheric ozone depletion (R)/ Ozone depletion (I, E)	0
Terrestrial acidification (R)/ Acidification (I, E)	2
Water consumption (R)/ Water resource depletion (I) / Water use (E)	2

As seen in Table 17, the majority of comparable impact categories agree in terms of ranking (robustness score = 2) and thus the choice of LCIA methodology is not a sensitive parameter.

5.2.3 Uncertainty Analysis

Monte Carlo results for the impact category 'Global warming' are presented below in Figure 14 with corresponding 95% confidence intervals depicted as the black boxes. It should be noted that the parameters investigated through this LCA study's uncertainty analysis are only concerning Ammonia. An overview of the tested parameters is stated in Table 10 in Section 3.4.2. Thus, this uncertainty analysis can only conclude significant difference in the four different Ammonia production pathways.

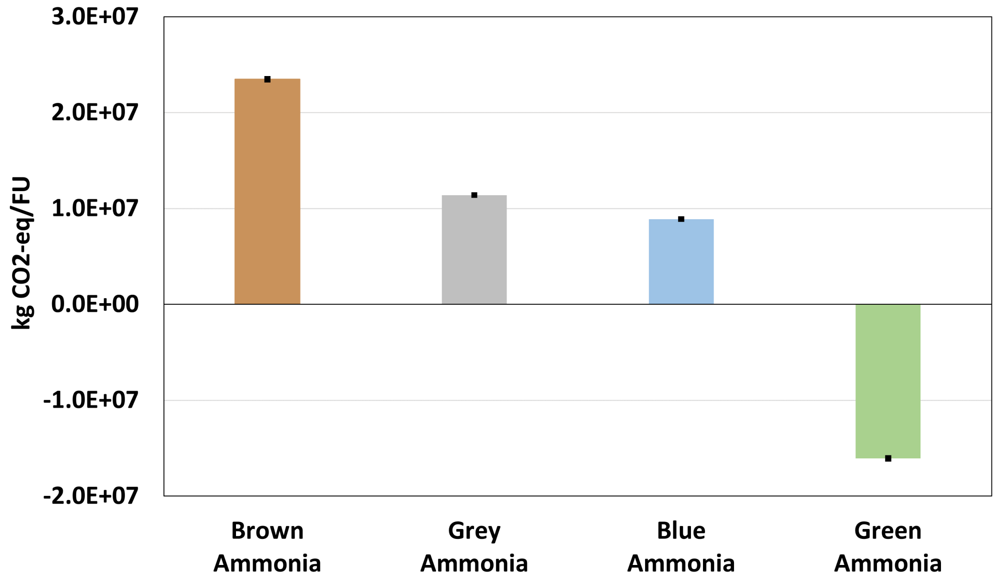

Figure 14: Monte Carlo results for the impact category 'Global warming' with corresponding 95% confidence intervals depicted as the black boxes, calculated using ReCiPe 2016 Midpoint (H) as LCIA methodology.

As seen in Figure 14, the four Ammonia production pathways' confidence intervals do not overlap and thus significantly different impacts to 'Global warming' can be concluded. The best performing production pathway is thereby determined as being Green Ammonia followed by Blue Ammonia, Grey Ammonia and lastly Brown Ammonia. It should be noted that it has not been tested whether Ammonia performs significantly different compared to VLSFO and MGO. It is however at least expected that Green Ammonia performs significantly better than both VLSFO and MGO. This is expected if oxygen substitution is included as done in the Monte Carlo simulations. If not included, it is more difficult to assess per the results presented in Section 5.2.2 (oxygen substitution, scenario analysis) - Monte Carlo analyses would be needed.

Monte Carlo results for the other impact categories are presented in Table 55, 56 and 57, Section D.5.1 in Appendix D. Here, it is worth noting that the only impact category in which all four production pathways are significantly different is 'Global warming'. Grey and Blue Ammonia have overlapping confidence intervals in 15 out of 17 impact categories ('Marine eutrophication' was excluded, see Section D.5.1 in Appendix D). Other than 'Global warming', the two production pathways are significantly different in 'Terrestrial ecotoxicity'. This pattern of insignificant differences was expected as Grey and Blue Ammonia have very similar product systems, see Figure 6 in Section 3.1, with differences only in CO_2 emission and energy use - explaining the significant difference seen in 'Global warming'.

As stated in Section 3.4.2, based on a first iteration of Monte Carlo analyses, running 1,000 iterations was deemed sufficient. However, during this second iteration, normal distributions were less clear even after completing 1,000 iterations. The second iteration included more uncertainty which is expected to be the reasoning for this difference. Thus, if more iterations of this LCA study are conducted, it is recommend that the number of Monte Carlo iterations is increased as this would provide more certain estimates of the means and standard deviations of the impact categories.

5.3 Sensitivity, Completeness and Consistency Checks

5.3.1 Sensitivity Check

In the Significant issues section, key processes and parameters were identified. The process contribution showed that the Haber-Bosch process was important, thus its energy demand and efficiency were relevant to investigate further. As was the efficiency of electrolysis, as it has a substantial electricity substitution, and the CCS efficiency, as it was vital to the difference in impacts between Grey and Blue Ammonia. These four parameters were quantitatively assessed for sensitivity and uncertainty (see Section 5.2), of which all but CCS efficiency showed large sensitivity, and all showed significant difference between the Ammonia pathways in the impact category 'Global Warming'. In addition, four scenarios were investigated for each their reason, see Section 3.4.1. Of these, oxygen substitution and NOx abatement technology inclusion/exclusion showed to have high quantitative significance on the outcome of the study, and for each their reason they were also qualitatively deemed to have uncertainty connected to their modelling. The outcome of the sensitivity analysis is visually summarised in Figure 15 evaluating the parameters or scenarios/modelling choices on relevance, based on both sensitivity/significance and uncertainty. Low, Medium and High refer to the level of relevance, and thus which should be prioritised in possible future iterations of this LCA study. As depicted, the scenarios/modelling choices of oxygen substitution and NOx abatement technology inclusion/exclusion are deemed most relevant.

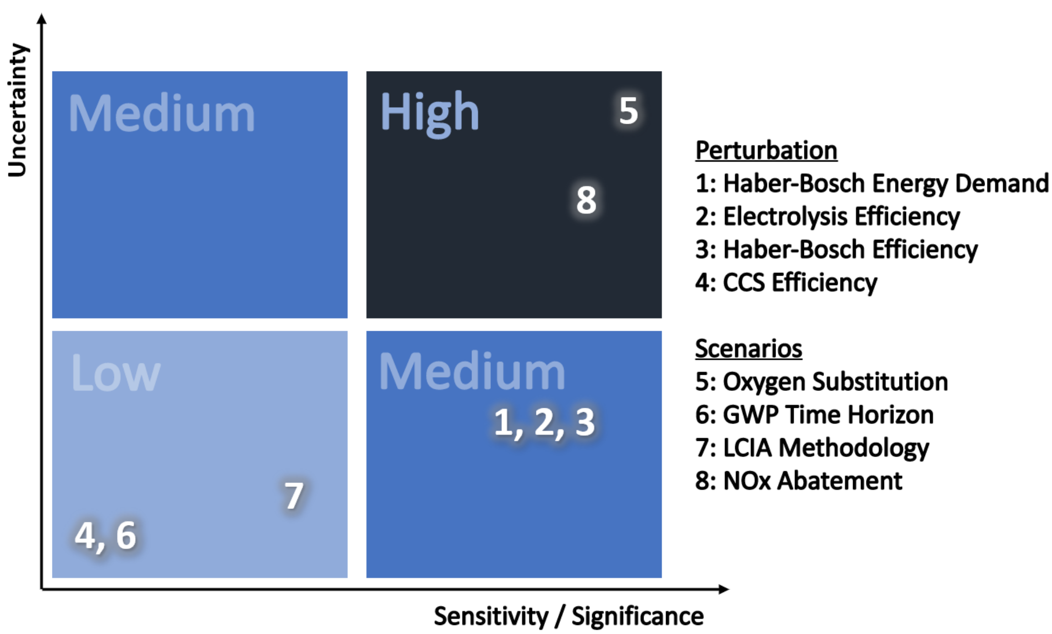

Figure 15: Diagram assessing relevance of four parameters and four scenarios/modelling choices, with regard to their Sensitivity/Significance and Uncertainty. Based on the results of the Sensitivity analysis in Section 5.2

5.3.2 Completeness Check

Capital equipment was excluded from the system boundaries as this is common practice in a process-based LCA. In addition, it was assumed that capital equipment is similar for the six compared product systems with regard to material types and amount used thus delivering identical quantities of service, which is another reason to exclude capital equipment in this comparative LCA study. However, in reality, some capital equipment is not present in all investigated product systems. This includes (I) different storage needs for Ammonia and the fossil fuels, (II) use of CCS technology in Blue Ammonia production and (III) need for NOx abatement technology for Ammonia-fuelled engines to comply with IMO Tier II. Including this capital equipment in the LCI model is expected to result in a higher impact in 'Mineral resource scarcity' especially for Blue Ammonia - as these three capital equipment are all used in this product system. Including NOx abatement is in addition expected to result in lower impacts in impact categories such as 'Marine eutrophication' (in all Ammonia product systems) due to lower NOx emissions. Excluding capital equipment was decided in the scope definition and thus the conclusions stated in Section 6.1 are in accordance with the scope definition.

5.3.3 Consistency Checks

The main source of inconsistency is the lack of primary data for the foreground processes. This is especially evident by how VLSFO and MGO have been modelled compared to how Ammonia has been modelled. VLSFO and MGO are modelled using representative processes in ecoinvent with impacts known to be underestimated and slightly overestimated, respectively. On the other hand, Ammonia is modelled using manually constructed Ammonia production pathways. This inconsistency between using representative processes and actual production pathways is however not expected to impact the outcome of this study and thus the LCI modelling is still in accordance with the goal and scope.

In addition, there is an inconsistency in data quality between Ammonia production and VLSFO/MGO production. The representative processes from ecoinvent use primary data and are thus expected to be complete processes, meaning that the majority of inputs and outputs from oil refining have been included. Oppositely, as the process for Ammonia production was manually constructed, it is unknown whether all inputs and outputs pertaining to the production of Ammonia have been taken into account. However, during data collecting, multiple sources regarding Ammonia production were investigated that all stated similar inputs and outputs as this report's LCI model - applies to all production pathways. Thus, this inconsistency in data quality is not expected to impact the outcome of this study.

It should be noted that even if these aforementioned inconsistencies are improved, a more constant inconsistency in data quality between the fossil marine fuels and Ammonia exists. Using Ammonia as a marine fuel has only recently been introduced and thus data especially on combustion emissions from an Ammonia-fuelled engine are premature. On the other hand, fossil marine fuels are widely used and thus combustion emissions are well-documented. The outcome of this study is not expected to be impacted by this inconsistency as MAN Energy Solutions' estimates are deemed as reasonable approximations. This more constant inconsistency in data quality will be improved once Ammonia-fuelled engines are tested and ultimately put into effect.

Using MAN Energy Solutions' estimates of raw engine emissions for Ammonia creates an inconsistency between this LCA study's system boundaries and the international NOx regulation. In this LCA study, it is assumed that no NOx abatement technology is installed on-board the Panamax bulk carrier and thus data on raw engine emissions is used. This results in a NOx emission of 24.16 g/kWh, calculation stated in Section E.5 in Appendix E, which is well above the international limit of 14.40 g/kWh (IMO Tier II). In order to comply with IMO Tier II and the obligatory properties of marine fuels (stated in Table 3 in Section 2), a NOx abatement technology needs to be installed. Using raw engine emissions for Ammonia also creates an inconsistency between the fossil marine fuels and Ammonia as both VLSFO and MGO are expected to be compliant with IMO Tier II, see the DESMO Calculation Tool.

As stated in Section 2.5, when possible a global scope must be chosen. However, for all six product systems, there were instances where processes in ecoinvent did not have a global scope. For these processes, the broadest geographical scope available was chosen instead which was Rest-of-World. For two specific process, the broadest geographical scope was based on the countries with either the largest market shares or the country with the largest market share. This inconsistency in geographical representativeness is not expected to impact the outcome of the study as global representativeness is deemed as high for the Rest-of-World processes and the processes based on market shares.

6 Conclusions, Limitations and Recommendations

6.1 Conclusions

The following points can be concluded from this LCA study.

- Marine Gas Oil (MGO) and Green Ammonia have the lowest impacts in 9 and 8 out of 18 midpoint impact categories, respectively. As for which of the two has the overall better environmental performance, a conclusion cannot be drawn as the impact categories have not been weighted.
- When compared to only the fossil marine fuels, Green Ammonia has the lowest impacts in 9 out of 18 midpoint impact categories including 'Global warming'.
- When compared to VLSFO and MGO, Brown Ammonia has higher impacts in 17 and 16 out of 18 midpoint impact categories, respectively - including 'Global warming'. For both Grey and Blue Ammonia, this number is 8/18, also including 'Global warming'.
- The NOx emissions for Ammonia exceed the IMO Tier II limit and thus NOx abatement technology is necessary for operation in international waters.
- For the impact category 'Global warming', the largest contributions to impacts lie in tank-to-wake for VLSFO and MGO, and in well-to-tank for Ammonia.
- Based on the calculated 95% confidence intervals, constructed through Monte Carlo analyses, it can be concluded that in the impact category 'Global warming', Green Ammonia performs significantly better than Brown, Grey and Blue Ammonia. Oppositely, Brown Ammonia performs significantly worse than Grey, Blue and Green Ammonia.

6.2 Limitations

The three main limitations of this LCA study are the following:

- Data could not be located for the production of VLSFO and MGO. Modelling VLSFO as HFO with the addition of a desulfurizing process was deemed as a reasonable approximation. An underestimation of impacts is expected seeing as the Claus Process, a part of the desulfurizing process, could not be modelled due to data not being located. Modelling MGO as diesel was also deemed as a reasonable approximation as only a slight overestimation of impacts occur. Neither of these points are expected to impact the outcome of the study.
- Using life cycle inventory (LCI) data from other LCA studies is not ideal as it can potentially lead to mistakes/problems being replicated. However, it should be noted, that the LCA studies used were all deemed as being credible. Thus, using these LCA studies is not expected to impact the results compared to using data with higher specificity. Complete LCI's were not provided (in these LCA studies) and as a result different sources were often used to model a process - also not ideal as different sources can present different values for the same inputs and outputs in addition to

using different methods to produce LCI data. It should be noted that prior to selecting sources to model a specific process, these sources were compared in order to ensure that values and modelling methods are comparable. Consequently, the outcome of this study is not expected to be impacted.

- The DESMO Calculation Tool is geared towards fossil marine fuels and is thus not made to be used for alternative marine fuels such as Ammonia. However, looking into how DESMO calculates the energy demand per nm, the fuel's energy density and total system efficiency are believed to be the only input parameters. Thus, it was deemed as a fair estimation to input Ammonia's energy density and total system efficiency and then use the estimated energy demand per nm. Based on the current knowledge level regarding DESMO, using this estimate of the energy demand per nm is not expected to impact the outcome of the study. This limitation is further explained in Section E.7 in Appendix E.

6.3 Recommendations

The following recommendations for further work are given to the study commissioner. Firstly, the following points should be considered:

- Include a NOx abatement technology as otherwise the Ammonia-fuelled two-stroke engine is not allowed to operate in international waters. This is due to NOx regulations (IMO Tier II).
- Include port operations, e.g. berthing and manoeuvring, in order to increase knowledge regarding the well-to-wake environmental impacts of the three investigated fuels.
- Include fuel storage on-board the Panamax bulk carrier in the LCI model, as different storage conditions are expected between the fossil marine fuels and Ammonia - thus relevant to include as this is a comparative LCA study.

Secondly, the following data points should be the focus in order to improve data quality, specificity and consistency:

- Investigate oxygen substitution in more details, including predictions for the future oxygen market's supply and demand.
- Ammonia combustion emissions were not available, and are thus modelled as best estimates. MAN Energy Solutions expects to run its first tests with an Ammonia-fuelled engine in the summer of 2022. Thus, contacting them after this is recommended.
- It is recommended to contact VLSFO, MGO and Ammonia producers in order to get primary production data from representative sites, if possible.

Finally, a critical review of the study is recommended in order to improve its quality and thus its robustness.

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A Appendix: Assumptions

A.1 Regarding the Bulk Carrier

- A sailing speed of 14.6 knots is assumed for the entire journey from Rotterdam to Singapore.
- Engine maintenance is assumed to be the same for an Ammonia-fuelled and a fossil-fuelled two-stroke engine - data on engine maintenance for an Ammonia-fuelled two-stroke engine is premature as of this LCA study.
- There is no NOx nor SOx emission abatement technology applied to the exhaust gas, e.g. no Selective Catalytic Reduction nor Scrubber is used. Raw emissions from the three assessed fuels are already compliant with the global SOx emission limit. As for NOx, the route from Rotterdam to out of the North Sea Emission Control Area (ECA) is a minor part of the total journey. Thus, the impact of the ECA regulation is assumed to be negligible, and it is not expected to affect the outcome of the study.

A.2 Regarding the Fuels

- The energy sources used in the production of VLSFO and MGO have not been changed in the representative ecoinvent processes used to model them. This is assumed to be representative for the actual production of VLSFO and MGO on a global scale.
- Fuel loss during the desulfurizing process is assumed to be negligible.
- Coal gasification produces more electricity than it consumes. This output of electricity is assumed to be sold on the market where it substitutes the average global electricity grid mix.
- Carbon Capture and Storage (CCS) is assumed for Blue Ammonia, but not including any utilisation of this carbon. The efficiency of CCS is assumed to be 95% [32].
- Regarding Electrolysis Efficiency. Theoretically, with a 100% efficiency, 10 kg of de-ionized water would produce approximately 1.1 kg of hydrogen and 8.9 kg of oxygen, see the stoichiometric calculation in Section E.4 in Appendix E. However, [24] states that 10 kg of de-ionized water only produces 1 kg of hydrogen. Thus, with this reduced efficiency, it is expected that 8 kg of oxygen is produced (as the molar mass ratio between hydrogen and oxygen in water is 1:8). The remaining 1 kg is assumed to be un-reacted de-ionized water which is consequently modelled as an output.
- New Green Ammonia production facilities are assumed to have more than enough renewable energy production to cover their Ammonia production. This assumption means that the facilities are not using any electricity from the local grid, thus the renewable energy market share is not affected. As this is a consequential study, marginals are what is considered, however in this case new capital equipment is made, so the marginal is not relevant.

- It is assumed that oxygen produced during the processes of cryogenic air separation and electrolysis is placed on the market and will thus substitute the production of oxygen from other sources.

- The energy demand for the Haber-Bosh process can vary between 26 and 33 MJ/kg NH_3, where 26 is the current best practice as per 2021 [30]. As this assessment look towards future up-scaling of the Ammonia industry, 26 MJ/kg NH_3 is assumed to be a good indicator of this future energy demand.

- Regarding the Haber-Bosch Process. Theoretically, with 100% conversion, 1 kg of Ammonia requires approximately 0.82 kg of nitrogen and 0.18 kg of hydrogen, see the stoichiometric calculation in Section E.4 in Appendix E. However, as stated in Section 3.1, the Haber-Bosch process has an overall conversion rate of 97-99% thus a bit more nitrogen and hydrogen is required in order to produce 1 kg of Ammonia. This extra amount is however assumed to be negligible and consequently the Haber-Bosch process is modelled with the aforementioned mass values of nitrogen and hydrogen (to produce 1 kg of Ammonia).

- Regarding the geographical scope of fuel production. At times "Global/GLO" processes were not available, and "Rest-of-World/RoW" was used instead. RoW is assumed to be representative for a global scope. This was e.g. the case for the production of VLSFO, where the top 9 residual fuel oil producing countries were a part of the RoW process [1], and thus a good approximation of global conditions.

- As fuel production takes place all over the world, it was deemed reasonable to assume that fuel production would be located close to where the fuel will be utilised. Thus, transport distances are negligible and are thus assumed as zero in this LCA study.

A.3 Other

- Average weather and water conditions are assumed for the entire journey from Rotterdam to Singapore.

- Regarding the Uncertainty Analysis. The uniform distribution is assumed for all the tested parameters as the actual distributions are unknown.

B Appendix: Data Collection - Limitations

Table 18 below lists and describes the limitations that were encountered during the data collection - this table was specifically requested by the study commissioner. Questionnaire refers to mail correspondence.

Table 18: Limitations encountered during the data collection.

Fuel	Process	Sources	Access	Limitations
VLSFO	Production	ecoinvent, [34], [26]	Database & Online Search, Stoichiometric Calculation	Specific data could not be located. Modelling VLSFO as HFO with the addition of a desulfurizing process was deemed as a reasonable approximation. Data on the Claus process could not be located. Thus, only hydrocracking was modelled as the desulfurizing process. See Section 3.3.2 for further details.
	Combustion	DESMO	Questionnaire	-
MGO	Production	ecoinvent	Database Search	Data could not be located. Modelling MGO as diesel was deemed as a reasonable approximation. See Section 3.3.2 for further details.
	Combustion	DESMO	Questionnaire	-
Ammonia	Hydrogen Production	[27], [35], [24], [9], [11]	Online Search, Stoichiometric Calculation	Constructed using life cycle inventory (LCI) data from other LCA studies. Using other LCA studies is not ideal as it can potentially lead to mistakes/problems being replicated. These LCA studies did not provide complete LCI's and as a result different sources were often used to model a process - also not ideal. See Section 6.2 for further details.

Table 18 continued from previous page

	Nitrogen Production	ecoinvent	Database Search	Specific data could not be located. The ecoinvent process "air separation, cryogenic | oxygen, liquid | Consequential, U" was thus used, where all inputs and outputs were divided by 3.27 in order to model nitrogen as the main output. See Section 3.3.1 for further details.
	Haber-Bosch Process	ecoinvent, [30], [31]	Database & Online Search, Stoichiometric Calculation	Different sources were used to model the process which is not ideal. See Section 6.2 for further details.
	Combustion	MAN*	Questionnaire	-
Journey	Fuel Consumption, VLSFO & MGO	DESMO	Questionnaire	-
	Fuel Consumption, Ammonia**	DESMO, MAN*, [5]	Questionnaire, Online Search	Energy demand pr. nautical mile (GJ/nm) was estimated by DESMO. This value is expected to be an estimate as DESMO is geared towards fossil-based marine fuels. See Section E.7 in Appendix E for further details.
-	Wind Electricity	[22]	Online Search	No ecoinvent "electricity production, wind" process reflected the global geographical scope of this LCA study. The constructed wind electricity process is a mix of the top three wind electricity producing countries in the world. See Section D.2.4 in Appendix D for further details.

* MAN Energy Solutions.

** Fuel Consumption, Pilot Oil is based on Ammonia's energy input pr. nautical mile as SPOC/SFC = 5%. See Section E.2 in Appendix E for further details.

C Appendix: Introduction to Life Cycle Assessment

The following section describes the basic theory used when conducting an LCA. The theory is from the book "Life Cycle Assessment Theory and Practice" by Michael Z. Hauschild, Ralph K. Rosenbaum, and Stig Irving Olsen (2018) [14].

C.1 Definition of Life Cycle Assessment

Life Cycle Assessment (LCA) is a methodology that can be used to analyse the life cycle of a product or system - which in this report is done for different marine fuels. LCA covers different impact categories focusing on environmental impacts. The quality of the results of an LCA is strongly dependent on the quality of the data used.

A LCA consists of four different phases; Goal and Scope, Inventory Assessment (LCI), Impact Assessment (LCIA) and Interpretation. LCA is iterative in nature, as can be seen in Figure 16 where common applications are also stated.

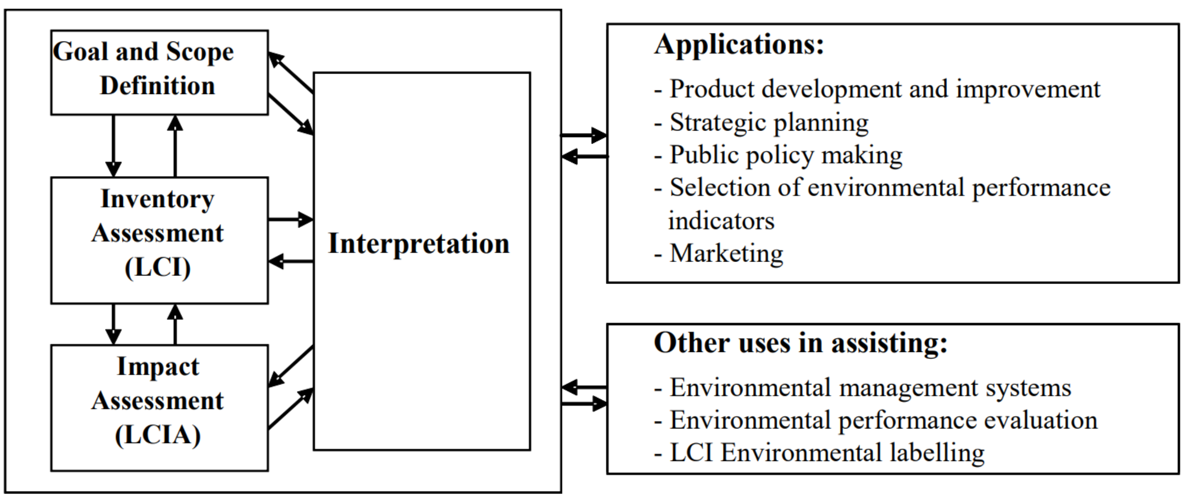

Figure 16: The four phases of conducting a Life Cycle Assessment (LCA) [33]. Common applications are also stated.

C.2 Goal and Scope

The **Goal Definition**, first step, answers questions like: *Why is the study made?* and *To whom is the study made for?* In this phase, the intended application and the target audience are defined and described. The known impact limitations of the study are also identified in order to clearly communicate what limits the conclusions of the studied product or system.

The **Scope Definition** identifies what product systems will be assessed and how this assessment should take place. In this phase, the first step is to define the obligatory and the positioning properties. The **Obligatory properties** are the properties that define the fundamental function of a product/system.

In addition, any legal requirements must also be complied with. **Positioning properties** makes the product or system more attractive to the customer, compared to other products/systems with the same obligatory properties.

The **Functional Unit** defines the qualitative and quantitative aspects of the fundamental function. The functional unit aims to answer the following questions; *"What", "Where", "When", "How much" and "For how long"*. It furthermore has to be formulated so that it can be used in a comparative study.

Other aspects that are described in the Scope Definition are **multifunctionality**, a process that provides more than one product/service, and among these there will be **primary and secondary functions**. Multifunctionality can be handled using different approaches. One approach is **subdivision**. A second approach is **system expansion**, where the secondary functions are integrated in the system, so that they are within the system boundaries. This usually means that the production of secondary functions are credited, resulting in negative impacts. The third and final way of handling secondary functions is **allocation**. This approach is used when there is no alternative production pathway for the secondary function. The flows and impacts are allocated between the primary and secondary function and the part related to the secondary function is then cut off from the system.

System boundaries show what is included and taken into consideration when doing the LCA. The system boundaries delimits the studied product system within the technosphere and ecosphere. Within the system boundaries, there are foreground and background processes. **Foreground processes** are defined as the processes of a product system that are specific to it and that can usually be influenced by the study commissioner. **Background processes** are in contrast defined as the processes of a product system that are not specific to it. This means that the background processes also take part in many other products or systems - an example is society's electricity mix, or the waste management system.

One final aspect that is covered in the scope definition is **representativeness** of the data used. It is used to define how representative the data used is in relation to geography, time and technology with regard to what has been defined in the goal and scope.

C.3 Life Cycle Inventory

The second phase of the LCA is called **Life Cycle Inventory Analysis (LCI)**. This part first consists of identifying all processes within the system boundaries and handling of **multifunctionality**. Then the planning and collection of data can begin. This can be a very time consuming process, as data might be collected from many different sources. With the data, the LCI model can be built, using a software such as openLCA.

C.4 Life Cycle Impact Assessment

The third phase is the **Life Cycle Impact Assessment (LCIA)**. This part aims to translate the information and data collected in the LCI into environmental impact scores. Before calculating any results, a decision on which LCIA methodology to use will be made. This is important and should be consistent with the goal and scope as well as the data used. The selected LCIA methodology should be in compliance with the representativeness of the data used. Next the LCIA results are calculated by the LCA software in characterised form, either at mid- and/or endpoint, where midpoint includes indicators such as 'Global warming', and endpoint is damage modelling to different areas of protection, such as 'Ecosystem quality'. Normalisation of characterised results is optional.

C.5 Interpretation

The final phase of the LCA is **Interpretation**. In this phase the results calculated in the LCIA phase and the assumptions made are discussed. Furthermore a **sensitivity** and **uncertainty** analysis is made, to investigate which parts of the system are most sensitive, and where it is important to have high data quality. This phase is thus an identification of the relevance of modelling aspects in regard to the study outcome. In this phase a sensitivity, completeness and consistency check is also made to address significant issues faced during the previous phases. This phase is finalised with conclusions, limitations and recommendations to the study commissioner with suggestions for further work.

D Appendix: Figures and Tables

D.1 Goal & Scope Definition

Table 19: ReCiPe 2016 Midpoint (H) Methodology's characterisation practice [16].

Midpoint Impact Category	**Indicator**
Global warming	Infrared radiative forcing increase
Stratospheric ozone depletion	Stratospheric ozone decrease
Ionizing radiation	Absorbed dose increase
Ozone formation, Human health	Tropospheric ozone population intake increase (M6M)
Fine particulate matter formation	PM2.5 population intake increase
Ozone formation, Terrestrial ecosystems	Tropospheric ozone increase (AOT40)
Terrestrial acidification	Proton increase in natural soils
Freshwater eutrophication	Phosphorus increase in freshwater
Marine eutrophication	Dissolved inorganic nitrogen increase in marine water
Terrestrial ecotoxicity	Hazard-weighted increase in natural soils
Freshwater ecotoxicity	Hazard-weighted increase in freshwaters
Marine ecotoxicity	Hazard-weighted increase in marine water
Human carcinogenic toxicity	Risk increase of cancer disease incidence
Human non-carcinogenic toxicity	Risk increase of non-cancer disease incidence
Land use	Occupation and time-integrated transformation
Mineral resource scarcity	Ore grade decrease
Fossil resource scarcity	Upper heating value
Water consumption	Increase of water consumed

ReCiPe does not have a characterisation factor for NOx emitted to air in 'Marine eutrophication', both at midpoint and endpoint level. As NOx emissions are a main component of Ammonia combustion, a characterisation factor at midpoint and endpoint level was manually added to openLCA, resulting in an altered LCIA methodology.

At midpoint level, the characterisation factor of 0.021064179 kg N eq/kg was inputted while at endpoint level the characterisation factor of $2.077454642 \cdot 10^{-10}$ Species.year/kg was inputted - both was taken from IMPACT World+ [19]. The latter was stated in the unit of PDF.m^2.yr/kg in IMPACT World+. Thus, the equation stated in line 245 in [7] was used to convert it to Species.year, see calculation below.

$$7.89 \cdot 10^{-10} \, \frac{\text{Species.yr}}{\text{PDF.m}^2\text{.yr}} \cdot 0.263302236 \, \frac{\text{PDF.m}^2\text{.yr}}{\text{kg}} = 2.077454642 \cdot 10^{-10} \, \frac{\text{species.yr}}{\text{kg}}$$

Table 20: The global normalisation factors used in the ReCiPe 2016 Midpoint (H) methodology. Normalisation point is an global average person equivalent from 2010 [28].

ReCiPe Impact Category	**Unit (per person)**	
Human Health		
Global warming	kg CO_2 eq.	7.99E+03
Stratospheric ozone depletion	kg CFC11 eq.	6.00E-02
Ionizing radiation	kBq Co-60 emitted to air eq.	4.80E+02
Fine particulate matter formation	kg PM2.5 eq.	2.56E+01
Photochemical ozone formation	kg NOx eq.	2.06E+01
Toxicity (cancer)	kg 1,4-DCB emitted to urban air eq.	1.03E+01
Toxicity (non-cancer)	kg 1,4-DCB emitted to urban air eq.	3.13E+04
Water consumption	m^3 consumed	2.67E+02
Terrestrial Ecosystems		
Global warming	kg CO_2 eq.	7.99E+03
Photochemical ozone formation	kg NOx eq.	1.77E+01
Acidification	kg SO_2 eq.	4.10E+01
Toxicity	kg 1,4-DBC emitted to industrial soil eq.	1.52E+04
Water consumption	m^3 consumed	2.67E+02
Land use - occupation	m^2 annual crop eq.	6.17E+03
Freshwater Ecosystems		
Global warming	kg CO_2 eq.	7.99E+03
Eutrophication	kg P to freshwater eq.	6.50E-01
Toxicity	kg 1,4-DBC emitted to freshwater eq.	2.52E+01
Water consumption	m^3 consumed	2.67E+02
Marine Ecosystems		
Toxicity	kg 1,4-DBC emitted to sea water eq.	4.34E+01
Eutrophication	kg N to marine water eq.	4.62E+00
Resources		
Mineral resource scarcity	kg Cu eq.	1.20E+05
Fossil resource scarcity		
Crude oil	oil eq.	5.70E+02
Natural gas	oil eq.	4.02E-01
Hard coal	oil eq.	3.82E+02
Brown coal	oil eq.	3.15E+01

D.2 Life Cycle Inventory

D.2.1 Unit Processes: Materials Stage

Table 21: The production of Hydrogen (used in Brown Ammonia).

	Flow	Unit	ecoinvent Process	Source
Outputs: Products				
Hydrogen, liquid	1.00	kg		
Inputs: Materials, Energy				
Electricity, medium voltage	-3.18	kWh	Market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - GLO	[27]
Hard coal	8.51	kg	Market for hard coal | hard coal | Consequential, U - CN	[27]
Water, unspecified natural origin	0.0113	m^3		[27]
Emissions to air				
Carbon dioxide, fossil	22.0	kg		[27]
Dinitrogen monoxide	6.97E-6	kg		[27]
Methane, fossil	0.0266	kg		[27]
Nitrogen oxides	0.0646	kg		[11]
Particulates	0.0891	kg		[11]
Sulfur oxides	0.0323	kg		[11]

Table 22: The production of Hydrogen (used in Grey Ammonia).

	Flow	Unit	ecoinvent Process	Source
Outputs: Products				
Hydrogen, liquid	1.00	kg		
Inputs: Materials, Energy				
Electricity, medium voltage	0.310	kWh	Electricity voltage transformation from high to medium voltage | electricity, medium voltage | Consequential, U GREY - RoW, see Table 43	[27]
Natural gas, high pressure	4.69	m^3	market group for natural gas, high pressure | natural gas, high pressure | Consequential, U - GLO	[27]
Water, unspecified natural origin	0.0219	m^3		[27]
Emissions to air				
Carbon dioxide, fossil	7.58	kg		[35]
Carbon monoxide, fossil	0.00171	kg		[35]
Dinitrogen monoxide	1.79E-5	kg		[35]
Hydrocarbons, aliphatic, alkanes, unspecified	0.00205	kg		[35]
Hydrogen chloride	1.49E-5	kg		[35]
Methane, fossil	8.64E-5	kg		[35]
Nitrogen oxides	0.00321	kg		[35]
Particulates, unspecified	0.0639	kg		[35]
Sulfur dioxide	0.00100	kg		[35]
Emissions to water				
COD, Chemical Oxygen Demand	5.99E-7	kg		[35]
Hydrogen	7.50E-7	kg		[35]

Table 23: The production of Hydrogen (used in Blue Ammonia).

	Flow	Unit	ecoinvent Process	Source
Outputs: Products				
Hydrogen, liquid	1.00	kg		
Inputs: Materials, Energy				
Electricity, medium voltage	1.11	kWh	Electricity voltage transformation from high to medium voltage | electricity, medium voltage | Consequential, U BLUE - RoW, see Table 43	[27]
Natural gas, high pressure	5.24	m^3	market group for natural gas, high pressure | natural gas, high pressure | Consequential, U - GLO	[27]
Water, unspecified natural origin	0.0237	m^3		[27]
Emissions to air				
Carbon dioxide, fossil	0.379	kg		[35]
Carbon monoxide, fossil	0.00171	kg		[35]
Dinitrogen monoxide	1.79E-5	kg		[35]
Hydrocarbons, aliphatic, alkanes, unspecified	0.00205	kg		[35]
Hydrogen chloride	1.49E-5	kg		[35]
Methane, fossil	8.64E-5	kg		[35]
Nitrogen oxides	0.00321	kg		[35]
Particulates, unspecified	0.0639	kg		[35]
Sulfur dioxide	0.00100	kg		[35]
Emissions to water				
COD, Chemical Oxygen Demand	5.99E-7	kg		[35]
Hydrogen	7.50E-7	kg		[35]

Table 24: The production of Hydrogen (used in Green Ammonia).

	Flow	Unit	ecoinvent Process	Source
Outputs: Products				
Hydrogen, liquid	1.00	kg		
Outputs: Avoided Products				
Oxygen, liquid	8.00	kg	market for oxygen, liquid | oxygen, liquid | Consequential, U - RoW	
Inputs: Materials, Energy				
Electricity, medium voltage	57.5	kWh	Electricity voltage transformation from high to medium voltage | electricity, medium voltage | Consequential, U BIMCO - GLO, see Table 44	[24]
Electrolyte, KOH, LiOH additive	1.50	g	Market for electrolyte, KOH, LiOH additive | electrolyte, KOH, LiOH additive | Consequential, U - GLO	[9]
Water, deionised	10.0	kg	Market for water, deionised | water, deionised | Consequential, U - RoW	[24]
Emissions to water				
Water	0.00100	m^3		[24]

Table 25: The production of Nitrogen (used in Brown, Grey and Blue Ammonia).

	Flow	Unit	ecoinvent Process	Source
Outputs: Products				ecoinvent
Nitrogen, liquid	1.00	kg		
Outputs: Avoided Products				
Oxygen, liquid	0.306	kg	Market for oxygen, liquid | oxygen, liquid | Consequential, U - RoW	
Argon, crude, liquid	0.0185	kg	Market for argon, crude, liquid | argon, crude, liquid | Consequential, U - GLO	
Inputs: Materials, Energy				
Nitrogen	1.00	kg		
Oxygen	0.306	kg		
Argon-40	0.0185	kg		
Electricity, medium voltage	1.06	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - GLO	
Water, cooling, unspecified natural origin	0.0403	m3		
Emissions to air				
Water	0.0156	m^3		
Emissions to water				
Water	0.0247	m^3		

Table 26: The production of Nitrogen (used in Green Ammonia).

	Flow	Unit	ecoinvent Process	Source
Outputs: Products				ecoinvent
Nitrogen, liquid	1.00	kg		
Outputs: Avoided Products				
Oxygen, liquid	0.306	kg	Market for oxygen, liquid | oxygen, liquid | Consequential, U - RoW	
Argon, crude, liquid	0.0185	kg	Market for argon, crude, liquid | argon, crude, liquid | Consequential, U - GLO	
Inputs: Materials, Energy				
Nitrogen	1.00	kg		
Oxygen	0.306	kg		
Argon-40	0.0185	kg		
Electricity, medium voltage	1.06	kWh	Electricity voltage transformation from high to medium voltage | electricity, medium voltage | Consequential, U BIMCO - GLO, see Table 44	
Water, cooling, unspecified natural origin	0.0403	m^3		
Emissions to air				
Water	0.0156	m^3		
Emissions to water				
Water	0.0247	m^3		

D.2.2 Unit Processes: Manufacturing Stage

Table 27: Production of Very-Low Sulphur Fuel Oil (VLSFO).

	Flow	Unit	ecoinvent Process	Source
Outputs: Products				
VLSFO	1.00	kg		
Inputs: Materials, Energy				
Electricity, medium voltage	0.648	MJ	Market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - GLO	[34]
Heat, district or industrial, other than natural gas	6.48	MJ	Market group for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Consequential, U - GLO	[34]
Heavy fuel oil	1.00	kg	Market for heavy fuel oil | heavy fuel oil | Consequential, U - RoW	ecoinvent
Hydrogen, liquid	3.33E-4	kg	Hydrogen Production (used in Grey Ammonia), see Table 22	Calculated, see Section E.4
Nickel, class 1	2.51E-4	kg	Market for nickel, class 1 | nickel, class 1 | Consequential, U - GLO	[26]

Table 28: Production of Marine Gas Oil (MGO).

	Flow	Unit	ecoinvent Process	Source
Outputs: Products				
MGO	1.00	kg		
Inputs: Materials, Energy				
Diesel, low-sulfur	1.00	kg	Market group for diesel, low sulfur | diesel, low-sulfur | Consequential, U - GLO	ecoinvent

Table 29: The production of Brown Ammonia.

	Flow	Unit	ecoinvent Process	Source
Outputs: Products				
Ammonia	1.00	kg		
Inputs: Materials, Energy				
Nitrogen, liquid	0.820	kg	Nitrogen Production (Brown, Grey, Blue), see Table 25	Calculated, see Section E.4
Hydrogen, liquid	0.180	kg	Hydrogen Production (Brown), see Table 21	Calculated, see Section E.4
Electricity, medium voltage	26.0	MJ	Electricity voltage transformation from high to medium voltage | electricity, medium voltage | Consequential, U BROWN - RoW, see Table 42	[30]
Iron pellet	3.50E-4	kg	Market for iron pellet | iron pellet | Consequential, U - GLO	[31] & ecoinvent

Table 30: The production of Grey Ammonia.

	Flow	Unit	ecoinvent Process	Source
Outputs: Products				
Ammonia	1.00	kg		
Inputs: Materials, Energy				
Nitrogen, liquid	0.820	kg	Nitrogen Production (Brown, Grey, Blue), see Table 25	Calculated, see Section E.4
Hydrogen, liquid	0.180	kg	Hydrogen Production (Grey), see Table 22	Calculated, see Section E.4
Electricity, medium voltage	26.0	MJ	Electricity voltage transformation from high to medium voltage | electricity, medium voltage | Consequential, U GREY - RoW, see Table 43	[30]
Iron pellet	3.50E-4	kg	Market for iron pellet | iron pellet | Consequential, U - GLO	[31] & ecoinvent

Table 31: The production of Blue Ammonia.

	Flow	Unit	ecoinvent Process	Source
Outputs: Products				
Ammonia	1.00	kg		
Inputs: Materials, Energy				
Nitrogen, liquid	0.820	kg	Nitrogen Production (Brown, Grey, Blue), see Table 25	Calculated, see Section E.4
Hydrogen, liquid	0.180	kg	Hydrogen Production (Blue), see Table 23	Calculated, see Section E.4
Electricity, medium voltage	26.0	MJ	Electricity voltage transformation from high to medium voltage | electricity, medium voltage | Consequential, U BLUE - RoW, see Table 43	[30]
Iron pellet	3.50E-4	kg	Market for iron pellet | iron pellet | Consequential, U - GLO	[31] & ecoinvent

Table 32: The production of Green Ammonia.

	Flow	Unit	ecoinvent Process	Source
Outputs: Products				
Ammonia	1.00	kg		
Inputs: Materials, Energy				
Nitrogen, liquid	0.820	kg	Nitrogen Production (Green), see Table 26	Calculated, see Section E.4
Hydrogen, liquid	0.180	kg	Hydrogen Production (Green), see Table 24	Calculated, see Section E.4
Electricity, medium voltage	26.0	MJ	Electricity voltage transformation from high to medium voltage | electricity, medium voltage | Consequential, U BIMCO - GLO, see Table 44	[30]
Iron pellet	3.50E-4	kg	Market for iron pellet | iron pellet | Consequential, U - GLO	[31] & ecoinvent

D.2.3 Unit Processes: Use Stage & End-of-Life Stage

Table 33: Combustion of Very-Low Sulphur Fuel Oil (VLSFO).

	Flow	**Unit**	**Source**
Outputs: Products			DESMO
Combustion, VLSFO	1.00	km	
Emissions to air			
Carbon dioxide, fossil	212	kg	
Carbon monoxide, fossil	0.135	kg	
Hydrocarbons, aliphatic, alkanes, unspecified	0.189	kg	
Nitrogen oxides	5.08	kg	
Particulates, <2.5 um	0.124	kg	
Sulfur oxides	0.702	kg	

Table 34: Combustion of Marine Gas Oil (MGO).

	Flow	**Unit**	**Source**
Outputs: Products			DESMO
Combustion, MGO	1.00	km	
Emissions to air			
Carbon dioxide, fossil	207	kg	
Carbon monoxide, fossil	0.135	kg	
Hydrocarbons, aliphatic, alkanes, unspecified	0.171	kg	
Nitrogen oxides	5.08	kg	
Particulates, <2.5 um	0.103	kg	
Sulfur oxides	0.162	kg	

Table 35: Combustion of Ammonia and its pilot oil, Very-Low Sulphur Fuel Oil (VLSFO).

	Flow	Unit	Emission Source	Source
Outputs: Products				
Combustion, Ammonia	1.00	km		
Inputs: Materials, Energy				
VLSFO	3.24	kg		
Emissions to air				
Carbon dioxide, fossil	10.5	kg	Pilot Oil	DESMO
Carbon monoxide, fossil	0.00659	kg	Pilot Oil	DESMO
Hydrocarbons, aliphatic, alkanes, unspecified	0.00942	kg	Pilot Oil	DESMO
Nitrogen oxides	0.256	kg	Pilot Oil	DESMO
Particulates, <2.5 um	0.00608	kg	Pilot Oil	DESMO
Sulfur oxides	0.0355	kg	Pilot Oil	DESMO
Ammonia	6.96	kg	Ammonia	MAN Energy
Dinitrogen monoxide	0.180	kg	Ammonia	MAN Energy
Nitrogen oxides	18.8	kg	Ammonia (only NO_2)	MAN Energy

Table 36: The journey from Rotterdam to Singapore with Very-Low Sulphur Fuel Oil (VLSFO).

	Flow	Unit	ecoinvent Process
Outputs: Products			
Journey from Rotterdam to Singapore	1.00	item	
Inputs: Materials, Energy			
VLSFO	1.05E6	kg	Production of VLSFO, see Table 27
Combustion of VLSFO	1.54E4	km	Combustion of VLSFO, see Table 33

Table 37: The journey from Rotterdam to Singapore with Marine Gas Oil (MGO).

	Flow	Unit	ecoinvent Process
Outputs: Products			
Journey from Rotterdam to Singapore	1.00	item	
Inputs: Materials, Energy			
MGO	9.96E5	kg	Production of MGO, see Table 28
Combustion of MGO	1.54E4	km	Combustion of MGO, see Table 34

Table 38: The journey from Rotterdam to Singapore with Brown Ammonia.

	Flow	Unit	ecoinvent Process
Outputs: Products			
Journey from Rotterdam to Singapore	1.00	item	
Inputs: Materials, Energy			
Ammonia	1.97E6	kg	Production of Brown Ammonia, see Table 29
Combustion of Ammonia	1.54E4	km	Combustion of Ammonia, see Table 35

Table 39: The journey from Rotterdam to Singapore with Grey Ammonia.

	Flow	Unit	ecoinvent Process
Outputs: Products			
Journey from Rotterdam to Singapore	1.00	item	
Inputs: Materials, Energy			
Ammonia	1.97E6	kg	Production of Grey Ammonia, see Table 30
Combustion of Ammonia	1.54E4	km	Combustion of Ammonia, see Table 35

Table 40: The journey from Rotterdam to Singapore with Blue Ammonia.

	Flow	Unit	ecoinvent Process
Outputs: Products			
Journey from Rotterdam to Singapore	1.00	item	
Inputs: Materials, Energy			
Ammonia	1.97E6	kg	Production of Blue Ammonia, see Table 31
Combustion of Ammonia	1.54E4	km	Combustion of Ammonia, see Table 35

Table 41: The journey from Rotterdam to Singapore with Green Ammonia.

	Flow	Unit	ecoinvent Process
Outputs: Products			
Journey from Rotterdam to Singapore	1.00	item	
Inputs: Materials, Energy			
Ammonia	1.97E6	kg	Production of Green Ammonia, see Table 32
Combustion of Ammonia	1.54E4	km	Combustion of Ammonia, see Table 35

D.2.4 Unit Processes: Electricity Voltage Transformation

Table 42: Electricity voltage transformation (for Brown - coal).

	Flow	Unit	ecoinvent Process
Outputs: Products			
Electricity, medium voltage	1.00	kWh	
Inputs: Materials, Energy			
Electricity, high voltage	1.01	kWh	Electricity production, hard coal | electricity, high voltage | Consequential, U - RoW

Table 43: Electricity voltage transformation (for Grey and Blue - natural gas).

	Flow	Unit	ecoinvent Process
Outputs: Products			
Electricity, medium voltage	1.00	kWh	
Inputs: Materials, Energy			
Electricity, high voltage	1.01	kWh	Electricity production, natural gas, conventional power plant | electricity, high voltage | Consequential, U - RoW

Table 44: Electricity voltage transformation (for Green - wind power).

	Flow	Unit	ecoinvent Process
Outputs: Products			
Electricity, medium voltage	1.00	kWh	
Inputs: Materials, Energy			
Electricity, high voltage	0.613	kWh	Electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | Consequential, U - CN-HB (**China**)
Electricity, high voltage	0.126	kWh	Electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | Consequential, U - DE (**Germany**)
Electricity, high voltage	0.266	kWh	Electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | Consequential, U - US-TRE (**USA**)

The wind electricity process was constructed by the LCA practitioners performing this LCA study as no ecoinvent 'electricity production, wind' process reflected the global geographical scope desired. The constructed wind electricity process, stated in Table 44, is a mix of the top three wind electricity producing countries in the world. These being China, The United States and Germany who combined produced 62% of the world's electricity generated from wind turbines in 2020 [23]. Their different percentage contributions to the total global amount of electricity generated from wind are accounted for in Table 44 by the following. Note that all values have been multiplied with 1.0046 in the LCI to account for losses during electricity voltage transformation from high to medium.

Information needed [23]:

China: 276 GW installed wind power capacity.

The United States: 120 GW installed wind power capacity.

Germany: 56.6 GW installed wind power capacity.

China:

$$\frac{276\,\text{GW}}{(276\,\text{GW} + 120\,\text{GW} + 56.6\,\text{GW})} = 0.61$$

The United States:

$$\frac{120\,\text{GW}}{(276\,\text{GW} + 120\,\text{GW} + 56.6\,\text{GW})} = 0.266$$

Germany:

$$\frac{56.6\,\text{GW}}{(276\,\text{GW} + 120\,\text{GW} + 56.6\,\text{GW})} = 0.126$$

D.3 Life Cycle Impact Assessment

D.3.1 Normalised Results at Midpoint Level.

Table 45: Normalised impact scores for the six fuel options at midpoint level. Calculated using ReCiPe 2016 Midpoint (H) as LCIA methodology. The unit is PE.

Impact Category	VLSFO	MGO	Brown Ammonia	Grey Ammonia	Green Ammonia	Blue Ammonia
Freshwater ecotoxicity	4.7E+04	9.7E+03	3.3E+05	2.2E+04	2.3E+04	8.2E+04
Marine ecotoxicity	7.9E+04	1.8E+04	5.5E+05	3.7E+04	3.9E+04	1.0E+05
Human carcinogenic toxicity	3.4E+04	1.9E+03	2.0E+05	2.4E+03	2.4E+03	-1.9E+04
Human non-carcinogenic toxicity	1.7E+04	2.1E+03	1.6E+05	4.0E+03	4.1E+03	-3.4E+04
Global warming	5.8E+02	4.7E+02	3.1E+03	1.7E+03	1.4E+03	-6.0E+02
Stratospheric ozone depletion	1.8E+01	1.6E+01	5.5E+02	5.6E+02	5.6E+02	4.8E+02
Ionizing radiation	-1.5E+02	6.0E+01	-1.3E+02	-4.8E+00	-6.3E+00	-1.8E+03
Fossil resource scarcity	1.3E+03	1.3E+03	4.7E+03	5.5E+03	5.8E+03	-1.6E+03
Water consumption	1.2E+02	3.3E+00	1.4E+02	5.0E+01	5.1E+01	-6.5E+02
Ozone formation, Human health	4.0E+03	3.9E+03	1.8E+04	1.5E+04	1.5E+04	1.4E+04
Fine particulate matter formation	8.3E+02	4.8E+02	4.0E+03	2.4E+03	2.4E+03	1.6E+03
Ozone formation, TE*	4.7E+03	4.5E+03	2.1E+04	1.7E+04	1.7E+04	1.6E+04
Terrestrial acidification	1.2E+03	8.4E+02	1.1E+04	7.9E+03	7.9E+03	7.3E+03
Freshwater eutrophication	2.8E+03	1.2E+02	1.3E+04	2.8E+02	2.8E+02	-6.8E+03
Terrestrial ecotoxicity	3.1E+03	2.1E+03	8.9E+03	9.3E+02	9.6E+02	1.8E+03
Marine eutrophication	3.8E+02	3.6E+02	1.6E+03	1.4E+03	1.4E+03	1.3E+03
Land use	5.7E+01	1.8E+00	8.9E+00	5.2E+00	5.3E+00	-9.4E+00
Mineral resource scarcity	2.2E-02	0.01407	4.7E-02	3.4E-02	3.5E-02	2.6E-01

* Terrestrial ecosystems

D.3.2 Characterised Results at Endpoint Level

Table 46: Characterised impact scores at endpoint level, calculated using ReCiPe 2016 Endpoint (H) as LCIA methodology. Results are presented in a heat map with graded colours, where green represents the lowest impact and red represents the highest impact in each area of protection

Indicator	Unit	VLSFO	MGO	Brown Ammonia	Grey Ammonia	Blue Ammonia	Green Ammonia
Global warming, Human health	DALY	4.33E+00	3.49E+00	2.31E+01	1.23E+01	1.01E+01	-4.43E+00
Global warming, Terrestrial ecosystems	species.yr	1.31E-02	1.05E-02	6.98E-02	3.70E-02	3.05E-02	-1.34E-02
Global warming, Freshwater ecosystems	species.yr	3.57E-07	2.88E-07	1.91E-06	1.01E-06	8.34E-07	-3.65E-07
Stratospheric ozone depletion	DALY	5.56E-04	5.19E-04	1.75E-02	1.78E-02	1.78E-02	1.52E-02
Ionizing radiation	DALY	-5.92E-04	2.46E-04	-5.27E-04	-1.96E-05	-2.58E-05	-7.24E-03
Ozone formation, Human health	DALY	7.54E-02	7.31E-02	3.33E-01	2.77E-01	2.77E-01	2.59E-01
Fine particulate matter formation	DALY	1.33E+01	7.77E+00	6.49E+01	3.83E+01	3.83E+01	2.52E+01
Ozone formation, Terrestrial ecosystems	species.yr	1.07E-02	1.04E-02	4.72E-02	3.93E-02	3.93E-02	3.67E-02
Terrestrial acidification	species.yr	1.03E-02	7.31E-03	9.43E-02	6.85E-02	6.86E-02	6.36E-02
Freshwater eutrophication	species.yr	1.23E-03	5.24E-05	5.64E-03	1.22E-04	1.24E-04	-2.95E-03
Marine eutrophication	species.yr	1.65E-05	1.63E-05	6.74E-05	6.14E-05	6.14E-05	6.07E-05
Terrestrial ecotoxicity	species.yr	3.62E-05	2.44E-05	1.05E-04	1.10E-05	1.13E-05	2.07E-05
Freshwater ecotoxicity	species.yr	3.98E-05	8.26E-06	2.82E-04	1.90E-05	1.97E-05	6.93E-05
Marine ecotoxicity	species.yr	8.59E-06	1.91E-06	5.93E-05	4.03E-06	4.18E-06	1.10E-05
Human carcinogenic toxicity	DALY	3.09E-01	1.79E-02	1.81E+00	2.21E-02	2.20E-02	-1.75E-01
Human non-carcinogenic toxicity	DALY	5.89E-01	7.03E-02	5.33E+00	1.35E-01	1.40E-01	-1.16E+00
Land use	species.yr	3.13E-03	1.00E-04	4.85E-04	2.86E-04	2.89E-04	-5.15E-04
Mineral resource scarcity	USD2013	5.99E+02	3.90E+02	1.29E+03	9.33E+02	9.81E+02	7.25E+03
Fossil resource scarcity	USD2013	4.94E+05	5.52E+05	4.12E+05	1.93E+06	2.02E+06	-2.92E+05
Water consumption, Aquatic ecosystems	species.yr	1.89E-08	5.33E-10	2.23E-08	8.11E-09	8.20E-09	-1.05E-07
Water consumption, Human health	DALY	6.96E-02	1.96E-03	8.21E-02	2.98E-02	3.01E-02	-3.87E-01
Water consumption, Terrestrial ecosystem	species.yr	4.23E-04	1.19E-05	4.99E-04	1.81E-04	1.83E-04	-2.35E-03

D.4 Interpretation

D.4.1 Significant Issues

Table 47: The main substances contributing to the impact category 'Global warming', divided into well-to-tank and tank-to-wake and stated in the unit of kg CO_2 eq. Calculated using ReCiPe 2016 Midpoint (H) as LCIA methodology.

	VLSFO	MGO	Brown Ammonia	Grey Ammonia	Blue Ammonia	Green Ammonia
Tank-to-wake (N2O)	-	-	8.26E+05	8.26E+05	8.26E+05	8.26E+05
Tank-to-wake (CO2)	3.26E+06	3.19E+06	1.62E+05	1.62E+05	1.62E+05	1.62E+05
Well-to-tank (CO2)	1.31E+06	5.21E+05	2.19E+07	1.13E+07	8.97E+06	3.65E+05
Well-to-tank (CH4)	8.62E+04	5.15E+04	1.97E+06	8.42E+05	8.97E+05	1.69E+04
Well-to-tank (CO2) - Crediting	-	-	-	-	-	-5.65E+06
Well-to-tank (CH4) - Crediting	-	-	-	-	-	-3.92E+05

D.5 Sensitivity Analysis

Table 48: Normalised sensitivity coefficients pertaining to a perturbation of +10% in the parameter Energy Demand: Haber-Bosch process, stated for all Ammonia pathways. Marked in bold red are instances where the impact categories are sensitive, as well as |Max|≥ 0.5 and |Average| ≥ 0.3.

	Brown Ammonia	**Grey Ammonia**	**Blue Ammonia**	**Green Ammonia**
Fine particulate matter formation	-0.36	-0.02	-0.02	-0.02
Fossil resource scarcity	**-0.69**	**-0.69**	**-0.66**	0.06
Freshwater ecotoxicity	**-0.92**	**-0.73**	**-0.70**	**-1.31**
Freshwater eutrophication	**-0.87**	**-0.67**	**-0.66**	0.04
Global warming	**-0.58**	**-0.66**	**-0.80**	0.07
Human carcinogenic toxicity	**-0.85**	**-0.76**	**-0.76**	**1.74**
Human non-carcinogenic toxicity	**-0.93**	**-0.67**	**-0.64**	0.14
Ionizing radiation	0.18	**0.86**	**0.65**	0.00
Land use	**-0.53**	-0.35	-0.34	0.32
Marine ecotoxicity	**-0.91**	**-0.70**	**-0.67**	**-1.55**
Marine eutrophication	-0.07	0.00	0.00	-0.01
Mineral resource scarcity	**-0.66**	**-0.64**	**-0.61**	-0.43
Ozone formation, Human health	-0.13	-0.02	-0.02	0.00
Ozone formation, Terrestrial ecosystems	-0.13	-0.03	-0.03	0.00
Stratospheric ozone depletion	-0.08	-0.07	-0.07	0.00
Terrestrial acidification	-0.24	-0.01	-0.01	0.00
Terrestrial ecotoxicity	**-0.94**	**-0.66**	**-0.64**	**-0.96**
Water consumption	**-0.69**	**-0.96**	**-0.95**	-0.02
|Max|	**0.94**	**0.96**	**0.95**	**1.74**
|Average|	**0.54**	**0.47**	**0.46**	**0.37**

Table 49: Normalised sensitivity coefficients pertaining to a perturbation of -10% in the parameter Efficiency: Haber-Bosch process, stated for all Ammonia pathways. Marked in bold red are instances where the impact categories are sensitive, as well as |Max|≥ 0.5 and |Average| ≥ 0.3.

	Brown Ammonia	**Grey Ammonia**	**Blue Ammonia**	**Green Ammonia**
Fine particulate matter formation	-0.07	-0.01	-0.02	0.48
Fossil resource scarcity	-0.29	-0.30	-0.33	**-1.10**
Freshwater ecotoxicity	-0.08	-0.17	-0.20	0.34
Freshwater eutrophication	-0.11	0.16	0.14	**-1.06**
Global warming	-0.38	-0.26	-0.11	**-1.30**
Human carcinogenic toxicity	-0.14	0.42	0.43	**-2.82**
Human non-carcinogenic toxicity	-0.06	-0.13	-0.16	**-1.16**
Ionizing radiation	**-1.13**	-0.43	**-0.57**	**-1.00**
Land use	-0.17	-0.13	-0.14	**-1.61**
Marine ecotoxicity	-0.08	-0.20	-0.23	**0.59**
Marine eutrophication	-0.08	-0.01	-0.01	0.05
Mineral resource scarcity	-0.31	-0.32	-0.35	**-0.57**
Ozone formation, Human health	-0.07	-0.01	-0.01	0.04
Ozone formation, Terrestrial ecosystems	-0.07	-0.01	-0.01	0.04
Stratospheric ozone depletion	0.00	-0.02	-0.02	0.07
Terrestrial acidification	-0.05	-0.01	-0.01	0.06
Terrestrial ecotoxicity	-0.04	-0.18	-0.21	0.05
Water consumption	-0.27	0.07	0.06	**-0.99**
|Max|	**1.13**	0.43	**0.57**	**2.82**
|Average|	0.19	0.16	0.17	**0.74**

Table 50: Normalised sensitivity coefficients pertaining to a perturbation of +10% in the parameter Efficiency: Electrolysis, stated for all Ammonia pathways. Marked in bold red are instances where the impact categories are sensitive, as well as |Max|≥ 0.5 and |Average| ≥ 0.3.

	Green Ammonia
Fine particulate matter formation	0.06
Fossil resource scarcity	-0.17
Freshwater ecotoxicity	**1.72**
Freshwater eutrophication	-0.14
Global warming	-0.20
Human carcinogenic toxicity	**-2.48**
Human non-carcinogenic toxicity	-0.27
Ionizing radiation	-0.08
Land use	**-0.57**
Marine ecotoxicity	**2.05**
Marine eutrophication	0.01
Mineral resource scarcity	**0.51**
Ozone formation, Human health	0.01
Ozone formation, Terrestrial ecosystems	0.01
Stratospheric ozone depletion	0.01
Terrestrial acidification	0.01
Terrestrial ecotoxicity	**1.26**
Water consumption	-0.07
|Max|	**2.48**
|Average|	0.09

Table 51: Normalised sensitivity coefficients pertaining to a perturbation of -10% in the parameter Efficiency: Carbon Capture and Storage, stated for all Ammonia pathways. Marked in bold red are instances where the impact categories are sensitive, as well as |Max|≥ 0.5 and |Average| ≥ 0.3.

	Blue Ammonia
Fine particulate matter formation	0.00
Fossil resource scarcity	0.00
Freshwater ecotoxicity	0.00
Freshwater eutrophication	0.00
Global warming	-0.23
Human carcinogenic toxicity	0.00
Human non-carcinogenic toxicity	0.00
Ionizing radiation	0.00
Land use	0.00
Marine ecotoxicity	0.00
Marine eutrophication	0.00
Mineral resource scarcity	0.00
Ozone formation, Human health	0.00
Ozone formation, Terrestrial ecosystems	0.00
Stratospheric ozone depletion	0.00
Terrestrial acidification	0.00
Terrestrial ecotoxicity	0.00
Water consumption	0.00
|Max|	0.23
|Average|	0.01

Scenario: NOx abatement technology

Table 52: Characterised impact scores at endpoint level, calculated using ReCiPe 2016 Endpoint (H) as LCIA methodology. Results are presented in a heat map with graded colours, where green represents the lowest impact and red represents the highest impact in each area of protection

Impact Category	Unit	VLSFO	MGO	Brown Ammonia	Grey Ammonia	Blue Ammonia	Green Ammonia
Global warming, Human health	DALY	4.33E+00	3.49E+00	2.31E+01	1.23E+01	1.01E+01	-4.43E+00
Global warming, Terrestrial ecosystems	species.yr	1.31E-02	1.05E-02	6.98E-02	3.70E-02	3.05E-02	-1.34E-02
Global warming, Freshwater ecosystems	species.yr	3.57E-07	2.88E-07	1.91E-06	1.01E-06	8.34E-07	-3.65E-07
Stratospheric ozone depletion	DALY	5.56E-04	5.19E-04	1.75E-02	1.78E-02	1.78E-02	1.52E-02
Ionizing radiation	DALY	-5.92E-04	2.46E-04	-5.27E-04	-1.96E-05	-2.58E-05	-7.24E-03
Ozone formation, Human health	DALY	7.54E-02	7.31E-02	1.06E-01	5.01E-02	5.04E-02	3.21E-02
Fine particulate matter formation	DALY	1.33E+01	7.77E+00	3.16E+01	4.95E+00	5.02E+00	-8.15E+00
Ozone formation, Terrestrial ecosystems	species.yr	1.07E-02	1.04E-02	1.51E-02	7.14E-03	7.19E-03	4.56E-03
Terrestrial acidification	species.yr	1.03E-02	7.31E-03	3.10E-02	5.24E-03	5.31E-03	2.49E-04
Freshwater eutrophication	species.yr	1.23E-03	5.24E-05	5.64E-03	1.22E-04	1.24E-04	-2.95E-03
Marine eutrophication	species.yr	1.65E-05	1.63E-05	1.57E-05	9.68E-06	9.69E-06	8.95E-06
Terrestrial ecotoxicity	species.yr	3.62E-05	2.44E-05	1.05E-04	1.10E-05	1.13E-05	2.07E-05
Freshwater ecotoxicity	species.yr	3.98E-05	8.26E-06	2.82E-04	1.90E-05	1.97E-05	6.93E-05
Marine ecotoxicity	species.yr	8.59E-06	1.91E-06	5.93E-05	4.03E-06	4.18E-06	1.10E-05
Human carcinogenic toxicity	DALY	3.09E-01	1.79E-02	1.81E+00	2.21E-02	2.20E-02	-1.75E-01
Human non-carcinogenic toxicity	DALY	5.89E-01	7.03E-02	5.33E+00	1.35E-01	1.40E-01	-1.16E+00
Land use	species.yr	3.13E-03	1.00E-04	4.85E-04	2.86E-04	2.89E-04	-5.15E-04
Mineral resource scarcity	USD2013	5.99E+02	3.90E+02	1.29E+03	9.33E+02	9.81E+02	7.25E+03
Fossil resource scarcity	USD2013	4.94E+05	5.52E+05	4.12E+05	1.93E+06	2.02E+06	-2.92E+05
Water consumption, Aquatic ecosystems	species.yr	1.89E-08	5.33E-10	2.23E-08	8.11E-09	8.20E-09	-1.05E-07
Water consumption, Human health	DALY	6.96E-02	1.96E-03	8.21E-02	2.98E-02	3.01E-02	-3.87E-01
Water consumption, Terrestrial ecosystem	species.yr	4.23E-04	1.19E-05	4.99E-04	1.81E-04	1.83E-04	-2.35E-03

Scenario: GWP Time Horizon

Table 53: Characterised impact scores for the six fuel pathways at midpoint level. Calculated with the two cultural perspectives, Hierarchist (H) equal to using ReCiPe 2016 Midpoint (H) as LCIA methodology and Individualist (I) equal to using ReCiPe 2016 Midpoint (I) as LCIA methodology. Results are presented in a heat map with graded colours, where green represents the lowest impact and red represents the highest impact in each impact category.

		Global warming [kg CO2 eq]	Stratospheric ozone depletion [kg CFC11 eq]	Ionizing radiation [kBq Co-60 eq]	Fine particulate matter formation [kg PM2.5 eq]	Terrestrial ecotoxicity [kg 1,4-DCB]
VLSFO	**H**	4.67E+06	1.05E+00	-6.98E+04	2.12E+04	3.17E+06
	I	4.79E+06	7.97E-01	-7.96E+04	6.62E+03	1.35E+06
MGO	**H**	3.77E+06	9.79E-01	2.90E+04	1.24E+04	2.14E+06
	I	3.84E+06	7.87E-01	1.67E+04	1.91E+03	9.18E+05
BROWN	**H**	2.49E+07	3.31E+01	-6.21E+04	1.03E+05	9.22E+06
	I	2.75E+07	2.11E+01	-6.34E+04	7.46E+03	3.81E+06
GREY	**H**	1.32E+07	3.35E+01	-2.32E+03	6.08E+04	9.67E+05
	I	1.43E+07	2.24E+01	-3.27E+03	5.82E+02	4.05E+05
BLUE	**H**	1.09E+07	3.36E+01	-3.05E+03	6.09E+04	9.95E+05
	I	1.20E+07	2.25E+01	-4.03E+03	5.90E+02	4.17E+05
GREEN	**H**	-4.78E+06	2.86E+01	-8.53E+05	4.00E+04	1.81E+06
	I	-5.37E+06	1.81E+01	-8.41E+05	-1.34E+04	7.38E+05

Table 54: Characterised impact scores for the six fuel pathways at midpoint level. Calculated with the two cultural perspectives, Hierarchist (H) equal to using ReCiPe 2016 Midpoint (H) as LCIA methodology and Individualist (I) equal to using ReCiPe 2016 Midpoint (I) as LCIA methodology. Results are presented in a heat map with graded colours, where green represents the lowest impact and red represents the highest impact in each impact category.

		Freshwater ecotoxicity [kg 1,4-DCB]	Marine ecotoxicity [kg 1,4-DCB]	Human carcinogenic toxicity [kg 1,4-DCB]	Human non-carcinogenic toxicity [kg 1,4-DCB]	Mineral resource scarcity [kg Cu eq]
VLSFO	**H**	5.75E+04	8.18E+04	9.29E+04	2.58E+06	2.59E+03
	I	5.57E+04	1.92E+04	9.36E+02	4.63E+04	1.90E+03
MGO	**H**	1.19E+04	1.82E+04	5.39E+03	3.08E+05	1.69E+03
	I	1.11E+04	3.96E+03	2.46E+02	1.36E+04	1.47E+03
BROWN	**H**	4.07E+05	5.64E+05	5.44E+05	2.34E+07	5.59E+03
	I	3.96E+05	1.33E+05	5.01E+03	5.23E+05	3.90E+03
GREY	**H**	2.74E+04	3.83E+04	6.65E+03	5.92E+05	4.04E+03
	I	2.54E+04	8.30E+03	3.17E+02	3.64E+04	2.41E+03
BLUE	**H**	2.84E+04	3.98E+04	6.61E+03	6.13E+05	4.25E+03
	I	2.63E+04	8.63E+03	3.34E+02	3.84E+04	2.54E+03
GREEN	**H**	1.00E+05	1.04E+05	-5.26E+04	-5.10E+06	3.14E+04
	I	8.16E+04	1.01E+04	-1.30E+03	-9.28E+04	2.59E+04

The rest of the impact categories were also investigated and they showed a different pattern than 'Global warming', where their impact scores either stayed the same or became lower with the use of the Individualist perspective. To see the values that changed, see Tables 53 and 54 above. These changes in results are most likely due to different requirements for evidence as the Individualist perspective only considers proven effects, whereas the Hierarchist perspective includes effects based on consensus. The two cultural perspectives also have different time perspectives, where Individualist considers short term, and Hierarchist has a balance between short and long term, with regard to environmental impacts, which might also have caused the difference in results. As only one impact category changed in regards to which fuel was the lowest, the change in LCIA perspective is not considered sensitive.

D.5.1 Uncertainty Analysis

Table 55: Monte Carlo results (1,000 iterations). Lower and Upper refer to the lower and upper bound of the 95% confidence interval. Marked in bold red are instances where confidence intervals overlap. Calculated using ReCiPe 2016 Midpoint (H) as LCIA methodology

	Mean	Margin of Error	Lower	Upper
Global warming				
Brown	2.35E+07	1.27E+05	2.34E+07	2.36E+07
Grey	1.14E+07	7.15E+04	1.13E+07	1.15E+07
Blue	8.89E+06	7.50E+04	8.81E+06	8.96E+06
Green	-1.61E+07	1.30E+05	-1.62E+07	-1.59E+07
Stratospheric ozone depletion				
Brown	32.0	0.0462	32.0	32.1
Grey	32.6	0.0725	**32.6**	**32.7**
Blue	32.6	0.0691	**32.5**	**32.7**
Green	20.6	0.120	20.5	20.7
Ionizing radiation				
Brown	-1.73E+05	1.80E+04	-1.91E+05	-1.55E+05
Grey	-6.11E+04	4.66E+03	**-6.57E+04**	**-5.64E+04**
Blue	-6.51E+04	5.31E+03	**-7.05E+04**	**-5.98E+04**
Green	-1.83E+06	1.55E+05	-1.98E+06	-1.67E+06
Ozone formation, Human health				
Brown	3.58E+05	4.16E+02	3.58E+05	3.59E+05
Grey	2.96E+05	2.63E+02	**2.96E+05**	**2.96E+05**
Blue	2.96E+05	3.80E+02	**2.96E+05**	**2.97E+05**
Green	2.29E+05	7.19E+02	2.28E+05	2.30E+05
Ozone formation, Terrestrial ecosystems				
Brown	3.58E+05	4.16E+02	3.58E+05	3.59E+05
Grey	2.96E+05	2.65E+02	**2.96E+05**	**2.96E+05**
Blue	2.96E+05	3.82E+02	**2.96E+05**	**2.97E+05**
Green	2.27E+05	7.35E+02	2.27E+05	2.28E+05

Table 56: Monte Carlo results (1,000 iterations). Lower and Upper refer to the lower and upper bound of the 95% confidence interval. Marked in bold red are instances where confidence intervals overlap. Calculated using ReCiPe 2016 Midpoint (H) as LCIA methodology

	Mean	Margin of Error	Lower	Higher
Human carcinogenic toxicity				
Brown	2.44E+06	3.84E+05	2.05E+06	2.82E+06
Grey	-6.09E+04	5.25E+03	**-6.62E+04**	**-5.57E+04**
Blue	-6.88E+04	9.79E+03	**-7.86E+04**	**-5.90E+04**
Green	-1.42E+06	2.99E+05	-1.72E+06	-1.12E+06
Human non-carcinogenic toxicity				
Brown	9.02E+07	2.28E+07	6.74E+07	1.13E+08
Grey	-2.23E+06	1.23E+05	**-2.36E+06**	**-2.11E+06**
Blue	-2.36E+06	1.62E+05	**-2.52E+06**	**-2.20E+06**
Green	-4.01E+07	1.36E+07	-5.37E+07	-2.65E+07
Terrestrial ecotoxicity				
Brown	-1.20E+07	4.91E+05	-1.25E+07	-1.15E+07
Grey	-2.63E+07	4.75E+05	-2.67E+07	-2.58E+07
Blue	-2.76E+07	4.90E+05	-2.81E+07	-2.71E+07
Green	-1.53E+08	2.06E+06	-1.55E+08	-1.50E+08
Freshwater ecotoxicity				
Brown	8.77E+05	6.57E+04	8.11E+05	9.42E+05
Grey	-5.62E+04	2.48E+03	**-5.86E+04**	**-5.37E+04**
Blue	-5.74E+04	2.23E+03	**-5.96E+04**	**-5.52E+04**
Green	-3.05E+05	2.77E+04	-3.33E+05	-2.78E+05
Marine ecotoxicity				
Brown	1.22E+06	9.29E+04	1.12E+06	1.31E+06
Grey	-8.61E+04	3.50E+03	**-8.96E+04**	**-8.26E+04**
Blue	-8.80E+04	3.14E+03	**-9.11E+04**	**-8.48E+04**
Green	-5.58E+05	3.91E+04	-5.97E+05	-5.19E+05

Table 57: Monte Carlo results (1000 iterations). Lower and Upper refer to the lower and upper bound of the 95% confidence interval. Marked in bold red are instances where confidence intervals overlap. Calculated using ReCiPe 2016 Midpoint (H) as LCIA methodology

	Mean	Margin of Error	Lower	Higher
Freshwater eutrophication				
Brown	1.21E+04	8.09E+02	1.12E+04	1.29E+04
Grey	-1.49E+02	9.41E+00	**-1.59E+02**	**-1.40E+02**
Blue	-1.64E+02	9.46E+00	**-1.73E+02**	**-1.54E+02**
Green	-7.79E+03	3.04E+02	-8.09E+03	-7.48E+03
Terrestrial acidification				
Brown	4.41E+05	9.41E+02	4.40E+05	4.42E+05
Grey	3.18E+05	1.21E+02	**3.18E+05**	**3.18E+05**
Blue	3.18E+05	1.59E+02	**3.18E+05**	**3.18E+05**
Green	2.65E+05	4.28E+02	2.64E+05	2.65E+05
Fine particulate matter formation				
Brown	1.01E+05	3.44E+02	1.01E+05	1.02E+05
Grey	5.80E+04	5.35E+01	**5.79E+04**	**5.80E+04**
Blue	5.80E+04	6.56E+01	**5.79E+04**	**5.81E+04**
Green	2.19E+04	2.36E+02	2.16E+04	2.21E+04
Land use				
Brown	-3.60E+04	7.45E+03	-4.34E+04	-2.85E+04
Grey	-8.36E+04	1.28E+04	**-9.65E+04**	**-7.08E+04**
Blue	-9.62E+04	2.54E+03	**-9.88E+04**	**-9.37E+04**
Green	-9.20E+05	3.37E+04	-9.54E+05	-8.86E+05
Mineral resource scarcity				
Brown	1.59E+02	4.54E+01	1.13E+02	2.04E+02
Grey	-2.72E+03	7.69E+01	**-2.80E+03**	**-2.65E+03**
Blue	-2.87E+03	7.85E+01	**-2.95E+03**	**-2.79E+03**
Green	1.92E+04	4.97E+02	1.87E+04	1.97E+04
Fossil resource scarcity				
Brown	4.07E+06	3.22E+04	4.04E+06	4.11E+06
Grey	4.81E+06	3.90E+04	4.77E+06	4.85E+06
Blue	5.02E+06	4.05E+04	4.98E+06	5.06E+06
Green	-5.47E+06	4.55E+04	-5.51E+06	-5.42E+06
Water consumption				
Brown	1.92E+05	4.72E+04	**1.45E+05**	**2.40E+05**
Grey	1.22E+05	2.42E+04	**9.80E+04**	**1.46E+05**
Blue	1.26E+05	2.20E+04	**1.04E+05**	**1.48E+05**
Green	9.27E+05	4.95E+05	4.33E+05	1.42E+06

E Appendix: Additional Information

E.1 Alternative Fuel Terminology

The alternative fuel terminology seen below has been provided by BIMCO.

Brown/Grey Ammonia is produced using traditional fossil fuels. The shade refers to the fossil fuel feedstock that is used in the production, brown for coal and grey for natural gas. Carbon dioxide (CO_2) and any carbon monoxide generated during the process of fuel production are not captured.

Blue Ammonia is produced using traditional fossil fuels. However, during the hydrogen production, CO_2 is captured and stored using industrial carbon capture and storage (CCS) technologies. In this LCA, Blue ammonia is produced using natural gas.

Green Ammonia is produced using electrolysis - the separation of hydrogen and oxygen molecules by applying electrical energy to water. Renewable energy sources are used to generate the electricity for the separation process. In addition, renewable energy sources are also used to separate nitrogen from air. In this LCA study, Green Ammonia is produced using electricity generated from wind.

E.2 Fuel Consumption

Fuel consumption in the unit of kg/nm was provided by DESMO for both Very-Low Sulphur Fuel Oil (VLSFO) and Marine Gas Oil (MGO) whereas the following calculations had to be done in order to obtain the fuel consumption for Ammonia and its pilot oil (VLSFO).

Information needed:

Ammonia Energy Demand per nm: 5.2 GJ/nm, provided by DESMO.

Ammonia Energy Density: 12.7 MJ/L, provided by MAN Energy Solutions.

Ammonia Density: 0.61 t/m^3, provided by [5].

VLSFO Energy Density: 39.9 MJ/L, provided by MAN Energy Solutions.

VLSFO Density: 960 kg/m^3, provided by MAN Energy Solutions.

It should be noted that SPOC/SFC = 5% - meaning that 5% of the amount of energy injected into the cylinders at full load and at a given speed is pilot oil (VLSFO). Thus, the remaining 95% is Ammonia fuel.

Ammonia Fuel Consumption:

$$5.2 \text{ GJ/nm} \cdot 0.95 = 4.940 \text{ GJ/nm}$$

$$\frac{4.940 \text{ GJ/nm}}{12.7 \text{ MJ/L}} \cdot 1000 \text{ MJ/GJ} = 388.98 \text{ L/nm}$$

$$388.98 \text{ L/nm} \cdot 0.61 \text{ t/m}^3 \cdot 0.001 \text{ m}^3\text{/L} \cdot 1000 \text{ kg/t} = 237.28 \text{ kg/nm}$$

Pilot Oil Fuel Consumption:

$$5.2\ \text{GJ/nm} \cdot 0.05 = 0.260\ \text{GJ/nm}$$

$$\frac{0.260\ \text{GJ/nm}}{39.9\ \text{MJ/L}} \cdot 1000\ \text{MJ/GJ} \cdot 0.001\ \text{m}^3/\text{L} = 0.0065\ \text{m}^3/\text{nm}$$

$$0.0065\ \text{m}^3/\text{nm} \cdot 960\ \text{kg/m}^3 = 6.26\ \text{kg/nm}$$

Specific fuel consumption from Rotterdam to Singapore was calculated by multiplying the fuel consumption (kg/nm) with 8300 nm. A detailed description of the DESMO Calculation Tool is stated in Section E.7 in Appendix E.

E.3 ReCiPe 2016 (H)

ReCiPe 2016 Midpoint (H) was chosen as the midpoint life cycle impact assessment (LCIA) methodology as it uses global characterisation factors which fits with the geographical scope of this LCA study. In addition, ReCiPe is a fairly recent LCIA methodology as it was published in 2016 with improvements/changes made in ultimo 2017 thus making it one of the most recent LCIA methodologies that is suited for a global perspective [16].

The H stands for Hierarchist which is one of three cultural perspectives used in ReCiPe LCIA methodologies to model impact categories. These three perspectives are social-science-based, not representing the choices of specific individuals but regrouping typical combinations of ethical values and preferences that are present in society. The hierarchist perspective is an intermediate approach to the impact categories' time perspective, manageability and required level of evidence. By using the hierarchist perspective, the impact categories are balanced between a short and long term time perspective while it is assumed that many problems can be avoided by implementing proper policies. Regarding the required level of evidence, effects should be included (in the impact categories) based on consensus [13]. The hierarchist perspective was chosen as it is often considered to be the default perspective. In Table 58 below, the three cultural perspectives are presented.

Table 58: The three cultural perspectives used in ReCiPe life cycle impact assessment methodologies [13].

	Time Perspective	**Manageability**	**Required Level of Evidence**
H (Hierarchist)	Balance between short and long term	Proper policy can avoid many problems	Inclusion based on consensus
I (Individualist)	Short term	Technology can avoid many problems	Only proven effects
E (Egalitarian)	Very long term	Problems can lead to catastrophe	All possible effects

E.4 Stoichiometric Calculations

Electrolysis

	$2H_2$	+	O_2	$\longrightarrow$	$2H_2O$
Mass [g]	1111.1		8888.9		10000
Molar Mass [g/mole]	2		32		18
Number of Moles	555.56		277.78		555.56

Haber-Bosch Process

	N_2	+	$3H_2$	$\longrightarrow$	$2NH_3$
Mass [g]	823.53		176.47		1000
Molar Mass [g/mole]	28		2		17
Number of Moles	29.41		88.24		58.82

Desulfurization Process

Amount of S in Heavy Fuel Oil (HFO) is 1.03% equal to 0.0103 kg S/kg fuel. Amount of S allowed in VLSFO is 0.5% equal to 0.005 kg S/kg fuel. Thus, 0.0103 kg S/kg fuel - 0.005 kg S/kg fuel = 0.0053 kg S/kg fuel must be removed.

	H_2	+	S	$\longrightarrow$	H_2S
Mass [g]	0.333		5.3		5.633
Molar Mass [g/mole]	2.016		32.06		34.076
Number of Moles	0.165		0.165		0.165

E.5 Ammonia Combustion Emissions

The following Ammonia combustion emissions were provided by MAN Energy Solutions (MAN Energy). It should be noted that these emissions are so-called raw emissions. That is emissions directly from the combustion of Ammonia, prior to any NOx abatement technology. Raw emissions are used in this LCA as it is assumed that there is no NOx abatement technology installed on-board the Panamax bulk carrier.

- **N_2O:** 20 ppm in the exhaust gas (by volume)
- **NH_3:** 2000 ppm in the exhaust gas (by volume)
- **NOx:** 2000 ppm in the exhaust gas (by volume)

It should be noted that the emission of NOx only covers nitrogen dioxide (NO_2). MAN Energy provided the following formula in order to convert the combustion emissions from the unit of ppm into the unit of g/kWh.

$$m_X = \frac{m_{\text{exhaust gas}}}{M_{\text{exhaust gas}}} \cdot C_X \cdot M_X \tag{2}$$

Where m_X is the mass of exhaust gas component X in the unit of g/kWh, $m_{\text{exhaust gas}}$ is the mass of the exhaust gas in the unit of kg/kWh, $M_{\text{exhaust gas}}$ is the molar mass of the exhaust gas in the unit of kg/kmol, C_X is the concentration of exhaust gas component X in the unit of ppm and M_X is the molar mass of exhaust gas component X in the unit of kg/kmol. In order to obtain the unit of g/kWh for the mass of exhaust gas component X, Equation 2 is multiplied by two unit conversions; 10^{-6} ppm and 10^{3} g/kg. Equation 2 is stated below in units.

$$\text{g/kWh} = \frac{\text{kg/kWh}}{\text{kg/kmol}} \cdot \text{ppm} \cdot \text{ppm}^{-1} \cdot \text{kg/kmol} \cdot \text{g/kg}$$

In this LCA study, the molar mass of the exhaust gas is assumed to be 29 kg/kmol (information provided by MAN Energy) while the mass of the exhaust gas is estimated to be 7.62 kg/kWh, based on the following calculation.

$$\frac{72360 \text{ kg/h}}{9500 \text{ kW}} = 7.62 \text{ kg/kWh}$$

Where 72360 kg/h is the mass of the exhaust gas and 9500 kW is the power at full load (100% SMCR). These two values were obtained through MAN Energy's online engine calculation tool; CEAS. The following calculation is done in order to obtain the mass of exhaust gas component X (m_X) in the unit of kg/nm.

$$\text{kg/nm} = \text{g/kWh} \cdot \text{GJ/nm} \cdot \text{kWh/GJ} \cdot \text{kg/g}$$

Where GJ/nm is the energy demand per nm for Ammonia and kWh/GJ as well as kg/g are two unit conversions.

Nitrous Oxide (N_2O):

$$\frac{7.62 \text{ kg/kWh}}{29 \text{ kg/kmol}} \cdot 20 \text{ ppm} \cdot 10^{-6} \text{ ppm}^{-1} \cdot 44 \text{ kg/kmol} \cdot 10^{3} \text{ g/kg} = 0.23 \text{ g/kWh}$$

$$0.23 \text{ g/kWh} \cdot 5.2 \text{ GJ/nm} \cdot 278 \text{ kWh/GJ} \cdot 0.001 \text{ kg/g} = 0.33 \text{ kg/nm}$$

Ammonia (NH_3):

$$\frac{7.62 \text{ kg/kWh}}{29 \text{ kg/kmol}} \cdot 2000 \text{ ppm} \cdot 10^{-6} \text{ ppm}^{-1} \cdot 17 \text{ kg/kmol} \cdot 10^{3} \text{ g/kg} = 8.93 \text{ g/kWh}$$

$$8.93 \text{ g/kWh} \cdot 5.2 \text{ GJ/nm} \cdot 278 \text{ kWh/GJ} \cdot 0.001 \text{ kg/g} = 12.90 \text{ kg/nm}$$

NOx (NO_2):

$$\frac{7.62\ \text{kg/kWh}}{29\ \text{kg/kmol}} \cdot 2000\ \text{ppm} \cdot 10^{-6}\ \text{ppm}^{-1} \cdot 46\ \text{kg/kmol} \cdot 10^{3}\text{g/kg} = 24.16\ \text{g/kWh}$$

$$24.16\ \text{g/kWh} \cdot 5.2\ \text{GJ/nm} \cdot 278\ \text{kWh/GJ} \cdot 0.001\ \text{kg/g} = 34.90\ \text{kg/nm}$$

Engine Out Emissions (after a Selective Catalytic Reduction) were also provided by Man Energy, which are used in the NOx abatement scenario.

- **N_2O:** Maximum 20 ppm in the exhaust gas (by volume)
- **NH_3:** Maximum 10 ppm in the exhaust gas (by volume)
- **NOx:** Compliant with IMO Tier III

It should be noted that in the final stages of preparing this report, a second iteration of using the CEAS calculation tool was conducted. This gave a more precise value of 7.73 kg/kWh for the mass of the exhaust gas as opposed to the used value of 7.62 kg/kWh. The combustion emissions only have a small increase in magnitude (as a result of using this more precise value compared to the used one) and thus including this more precise value is not expected to change the outcome of this study. Consequently, and due to time constraints, it was decided that the value of 7.62 kg/kWh would remain.

E.6 Pilot Oil (VLSFO) Combustion Emissions

Combustion emissions for the pilot oil (VSLFO) are calculated by the following. The emission factors (g/kg) are provided by DESMO.

Carbon Monoxide (CO):

$$6.26\ \text{kg/nm} \cdot 1.95\ \text{g/kg} \cdot 0.001\ \text{kg/g} = 0.012\ \text{kg/nm}$$

Carbon Dioxide (CO_2):

$$6.26\ \text{kg/nm} \cdot 3114\ \text{g/kg} \cdot 0.001\ \text{kg/g} = 19.48\ \text{kg/nm}$$

NOx:

$$6.26\ \text{kg/nm} \cdot 75.9\ \text{g/kg} \cdot 0.001\ \text{kg/g} = 0.47\ \text{kg/nm}$$

SOx:

$$6.26\ \text{kg/nm} \cdot 10.5\ \text{g/kg} \cdot 0.001\ \text{kg/g} = 0.066\ \text{kg/nm}$$

Hydrocarbons (HC):

$$6.26\ \text{kg/nm} \cdot 2.79\ \text{g/kg} \cdot 0.001\ \text{kg/g} = 0.017\ \text{kg/nm}$$

Particulate Matter (PM):

$$6.26\ \text{kg/nm} \cdot 1.8\ \text{g/kg} \cdot 0.001\ \text{kg/g} = 0.011\ \text{kg/nm}$$

E.7 DESMO Calculation Tool

The Ship-Desmo Calculation Tool (DESMO) is an Excel package predicting energy demand and exhaust gas emissions from ships using empirical and semi-empirical methods based only on ship type and bulk parameters (description stated in the sheet 'LICENSE AGREEMENT' in DESMO). It was developed by the Technical University of Denmark and the University of Southern Denmark [8]. The latest version from 2020 is used in this LCA study which has been provided by naval architect Hans Otto Kristensen, who is one of the main contributors to the development of DESMO. After an introductory meeting with Hans Otto Kristensen, the following parameters were modified in the sheet 'Ship data' in order to model the specifics of this LCA study such as engine and fuel type - this was done in collaboration with BIMCO. It should be noted that these rows are highlighted in green in the DESMO Calculation Tool.

- **Row 3:** The maximum deadweight is set to 75,000 tonnes for both VLSFO and MGO.
- **Row 37 & 97:** The service allowance on resistance is set to 0% for both VLSFO and MGO.
- **Row 41 & 98:** Weather condition. A Beaufort number of 4.5 is used for both VLSFO and MGO.
- **Row 78:** The main engine service rating is set to 100% for both VLSFO and MGO.
- **Row 79:** Fuel type 1 (heavy fuel oil) is chosen for VLSFO while Fuel type 2 (gas oil) is chosen for MGO.
- **Row 82:** The sulphur content in heavy fuel (HFO) is set to 0.5%. This row is only used to model VLSFO.
- **Row 83:** The sulphur content in gas oil (GO) is set to 0.1%. This row is only used to model MGO.
- **Row 86:** TIER 2 is chosen for both VLSFO and MGO.
- **Row 88:** The use of scrubbers if oil is used is set to 0 for both VLSFO and MGO, indicating that there is no use of scrubbers.
- **Row 90:** The capacity utilization is set to 100% for both VLSFO and MGO.
- **Row 96:** The service speed at actual draught is set to 14.6 knots for both VLSFO and MGO.

The DESMO Calculation Tool was mainly used to model data regarding VLSFO and MGO - as seen above when listing the modifications. The only information drawn from DESMO with regard to Ammonia is the energy demand per nm of 5.2 GJ/nm, see the sheet 'Emissions at sea' in DESMO, cell E14 (highlighted in yellow). This value is expected to be an estimate of the energy demand per nm for Ammonia as DESMO is geared towards fossil marine fuels. In order to model the energy demand per nm, the specific fuel consumption (SFC) for Ammonia was defined in the sheet 'Emission factors', cell F5 (also highlighted in yellow). This value is based on Equation 4 in [21]. However, as the total system efficiency (η) is unknown (100% is assumed), the calculated SFC value is expected to also be a rough estimate. [21] assumes a total system efficiency of 96% for Ammonia. The SFC calculation can be seen below where multiplication with the density of Ammonia is done in order to obtain the correct unit.

$$\frac{1}{12.7\ \text{MJ/L}} \cdot 0.61\ \text{t/m}^3 \cdot 0.001\ \text{m}^3\text{/L} \cdot 3.6\ \text{MJ/kWh} \cdot 10^6\ \text{g/t} = 172.9\ \text{g/kWh}$$

Where 12.7 MJ/L is the energy density of Ammonia (provided by MAN Energy Solutions) and 0.61 t/m^3 is the density of Ammonia (provided by [5]). The rest are unit conversions.