Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Simon Agasøster Botnen

Comparison study of alternative energy carriers for a low-emission purse seiner/pelagic trawler

Master's thesis in Marine Technology
Supervisor: Harald Ellingsen
Co-supervisor: Svein Aanond Aanondsen and Trym Sandvik Steinshamn

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Preface

This Master Thesis is the result of a comparative study exploring different alternative energy carriers for a low-emission fishing vessel. The thesis has been conducted during the spring semester of 2021 at the Department of Marine Technology at NTNU Trondheim as a part of my Master of Science. The workload corresponds to 30 credits. It is written in cooperation with Salt Ship Design.

The thesis description has been developed through conversations with both Salt Ship Design and my supervisors at NTNU. My motivation for this thesis is to gain knowledge concerning low- and zero-emission technology in the maritime industry and how it can be applied to the fishing industry. Even though alternative energy carriers are highly relevant today, it has been challenging to collect information covering some topics. Support from Salt has reduced this information gap, and it would be challenging to write about this topic without their assistance.

I would like to thank my supervisor Harald Ellingsen and co-supervisor Svein Aanond Aanondsen at NTNU for continuous guidance and support throughout the semester. In addition, I would also like to thank Trym Sandvik Steinshamn at Salt Ship Design for being available and supplying relevant data and good input when questions have occurred.

Trondheim, 10th of June 2021

Simon A. Botnen

Simon Agasøster Botnen

NTNU Trondheim
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MASTER THESIS DESCRIPTION SHEET

Name of the candidate: Simon Agasøster Botnen

Field of study: Marine Systems Design

Thesis title (Norwegian): Komparativ studie av alternative energiberarar for ein lågutslepps snurper/pelagisk trålar

Thesis title (English): Comparative study of alternative energy carriers for a low emission purse seiner/pelagic trawler

Overall aim and focus
The overall aim of the project is to investigate the possibilities of alternative energy carriers in a low emission fishing vessel through a comparison study and to further assess a safe and efficient implementation of the most relevant fuels.

Work description
Write a list with abbreviations and definitions of terms, explaining relevant concepts related to the literature study and project assignment.

1. Perform a background and literature review to provide information and relevant references on:
   - Fisheries
   - Alternative energy carriers
   - Energy converters
   - Regulations
   - Emissions and LCA

2. Perform a comparative study of the different fuels utilized in a purse seiner/pelagic trawler and rank them based on weighting of the different criteria:
   - Environmental performance – based on emission values from existing LCAs and a general operation of the vessel
   - Technical maturity – The commercial availability, infrastructure, experience, political commitments.
   - Economy – The change in CAPEX, OPEX and VOYEX due to the implementation of the fuels.
   - Safety **-** Identify risks associated with the use of the fuels.

3. Further assess the best performing fuel/fuels regarding safe and efficient implementation in a purse seiner/pelagic trawler
   - Identify what consequences the implementation of the fuel will have on the design based on regulations, systems and safety.
   - Provide simple sketches of arrangements, showing how the different systems work.

Specifications
The thesis is written in cooperation with Salt Ship Design.

The scope of work may prove to be larger than initially anticipated. By the approval from the supervisor, described topics may be deleted or reduced in extent without consequences with regard to grading.

The candidate shall present personal contribution to the resolution of problems within the scope of work. Theories and conclusions should be based on mathematical derivations and logic reasoning identifying the various steps in the deduction.

The report shall be organized in a logical structure to give a clear exposition of background, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Rigorous mathematical deductions and illustrating figures are preferred over lengthy textual descriptions. It shall be written in English (preferably US) and contain the following elements: Title page, abstract, project specification, list of symbols and acronyms, table of contents, introduction and background, problem formulations, scope and delimitations, main body with derivations/developments and results, conclusions with recommendations for further work, references, and optional appendices. All figures, tables, and equations shall be numerated. The original contribution of the candidate and material taken from other sources shall be clearly identified. Work from other sources shall be properly acknowledged using quotations and a Harvard citation style (e.g. *natbib* Latex package). The work is expected to be conducted in an honest and ethical manner, without any sort of plagiarism and misconduct. Such practice is taken very seriously by the university and will have consequences. NTNU has according to the present rules ownership of the thesis report. Any use of the report has to be approved by NTNU (or external parties when this applies). NTNU can use the results freely in research and teaching by proper referencing, unless otherwise agreed upon.

The thesis shall be submitted with an electronic copy to the main supervisor, signed by the candidate. The final revised version of this thesis description must be included after title page. The report must be submitted according to NTNU procedures. Computer code, pictures, videos, data series, and a PDF version of the report shall be included electronically with all submitted versions.

Start date: 15 January, 2021 **Due date:** 10 June, 2021

Supervisors: Harald Ellingsen and Svein Aanond Aanondsen (co-supervisor)

Trondheim, _________________

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Harald Ellingsen
Supervisor

____
Svein Aanond Aanondsen
Co-supervisor

Abstract

Global warming is on the agenda worldwide. As an attempt to tackle this, Authorities and international organizations are introducing regulations and incentives to improve the performance of green solutions. Despite the uncertainty, the situation drives innovation for greener solutions, with both the Norwegian Government and IMO setting ambitious reduction goals for the future. Fisheries is an important export industry in Norway and a segment with a considerable reduction potential for Norway's total emission of Greenhouse Gases (GHGs). Based on the relative environmental impact of different steps in the value chain for fish products, fuel use is one of the more significant contributors, making it a good source of reduction potential for the value chain.

This thesis investigates the implementation of alternative energy carriers in a purse seiner/pelagic trawler through a comparison study and further assesses a safe implementation of the best-performing alternative solution. The alternative energy carriers assessed are hydrogen, ammonia, and methanol. LNG and MDO are included as a benchmark. Based on the argument of maintaining flexibility concerning bunkering for the vessel, all three alternative fuels are assumed combusted in dual-fuel engines. This requires an amount of pilot fuel, making the solutions low-emission and not zero-emission.

Through a Case Study, the implementation of the alternative energy carriers in a reference vessel is assessed with a focus on the technical, environmental, and financial aspects. Purse seiners/pelagic trawlers have a high endurance range- and power requirement. Based on a lower energy density, this makes the implementation of alternative energy carriers more challenging. The technical assessment reveals that incorporating the fuels requiring a type C tank for storage, would lead to a required extension of the ship length if an equivalent fish storage capacity is kept. This is the case for LNG, liquid hydrogen, and ammonia, while methanol is capable of meeting the endurance range requirement through storage in the reference vessel's standard tanks.

The environmental assessment is conducted through the Life Cycle Impact Assessment, ReCiPe2016H. Emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), nitrogen oxide (NO_x), sulfur oxide (SO_x), and particulate matter (PM) to the atmosphere are included, for both the production of the fuels and the operation of the vessel. The performance is assessed for Midpoint and Endpoint. Hydrogen, ammonia, and methanol all perform well at Endpoint when produced in a renewable way, with methanol performing the best. From the assessment, it is also evident that there is no point in implementing natural gas-based alternative fuels when using LNG as a benchmark. This ranking is based on the fuels implemented in the vessel with a general annual operation.

For the financial performance, a Life Cycle Cost Analysis (LCCA) is used. Through the definition of the CAPEX, OPEX, and VOYEX for the different fuel solutions implemented in the reference vessel, a Life Cycle Cost (LCC) is estimated for two scenarios:

- Scenario 1: A more present scenario with today's taxation and 2020 fuel costs
- Scenario 2: A future scenario with 2030 taxation and 2030 fuel costs

Both scenarios reveal significantly higher LCCs for the alternative fuels compared to LNG and MDO, with the main difference being found in the fuel cost. The combination of higher CO_2- and NO_x-tax and future green fuel prices used in this thesis does not improve the financial performance of alternative solutions sufficiently compared to the performance of the more traditional ones.

Based on a set of criteria covering environmental performance, technical maturity, economy, and safety, a multi-criteria decision analysis is conducted. The importance of the different criteria is weighted for a shipowner as the stakeholder, revealing the traditional fuels to perform better than the alternative, with green ammonia performing the best of the alternative. Because shipowners heavily weigh the financial aspect of the solutions, a sensitivity analysis is conducted where the case of the Government as the stakeholder is assessed. This results in an opposite ranking, with the alternative solutions outperforming the traditional, and green ammonia performing the best.

Based on the results from the multi-criteria decision analysis, the thesis further assesses different ammonia concepts defined based on the fuel mix ratio. An ammonia ratio of 70%, 90%, and 95% is assessed, revealing the concepts are capable of reducing the emissions of GHGs by their respective ammonia ratio. An improved environmental performance does, however, increase the LCC due to a higher ammonia consumption. A design assessment with a focus on safety is also conducted for ammonia. The main concern when implementing ammonia is to avoid leakages of ammonia and to minimize consequences should leakage occur. To ensure the safe implementation of ammonia as a fuel, many of the same safety principles used for LNG can be applied. The main difference is the toxicity of ammonia, imposing stricter regulations for ventilation and the definition of toxic zones on deck to ensure a safe operation for personnel.

The study concludes that ammonia performs the best of the green alternatives included but is not financially viable today. Thus one solution is to design the vessel ammonia-ready, meaning for LNG with ammonia regulations and requirements accounted for in the design. Operating on LNG would reduce emissions to some extent shortly while maintaining a good financial operation. The vessel would also be capable of using ammonia as a drop-in fuel, having the opportunity of achieving emission reductions complying with the Government's goal for 2030, should the price drop to a sufficiently low level. This alternative solution would lower the investment risk compared to a traditional LNG vessel while only slightly increasing the extra investment cost. One challenge is the vessel's reduced endurance range by changing a specific volume of LNG with ammonia.

Samandrag

Global oppvarming og det grøne skiftet er på agendaen verda over. Myndighetar og internasjonale organisasjonar introduserer ulike reguleringar og insentiv for å betre prestasjonen til grøne løysingar. Trass usikkerheita så er situasjonen ein pådrivar for innovasjon av grøne løysingar, med både dei Norske Myndighetane og IMO som sett ambisiøse reduksjonsmål for framtida. Fiskeri er ein viktig eksportindustri i Noreg med eit betydeleg reduseringpotensial for Noregs totale CO_2-utslepp. Basert på den relative miljøpåverkinga ulike steg i verdikjeda for fiskeprodukt har, så er bruken av drivstoff ein av dei større bidragsytarane som igjen gjer det til ei god kjelde for reduksjonspotensiale.

Denne oppgåve undersøker implementering av alternative energiberarar i ein snurpar/pelagisk trålar gjennom eit komparativ studie og vidare undersøking av den beste alternative løsyinga. Dei alternative energiberarane bedømt er hydrogen, ammoniakk og metanol. LNG og MDO er inkludert som ein referanseindeks. Basert på argumentet om å behalde fleksibilitet med tanke på fylling av drivstoff så er alle dei tre alternative drivstoffa antatt forbrent i ein forbrenningsmotor dreven med kombinert drivstoff. Desse motorane treng ein viss mengde pilotdrivstoff avhengig av drivstoffet, noko som gjer løysingane låg-utslepp og ikkje null-utslepp.

Oppgåva undersøker implementeringa av dei alternative energiberarane i eit referansefartøy gjennom eit komparativ studie, med eit fokus på det tekniske, miljømessige og finansielle. Snurparar/pelagiske trålarar har høge krav for rekkevidde og kraft. Implementeringa av dei alternative energiberarane er derfor meir utfordrande grunna lågare energitettleik. Den tekniske delen av tilfellestudiet avdekka at ei forlenging er naudsynt for drivstoffa som krevjar lagring i ein trykksett tank (type C), om den same lagringskapasiteten for fisk skal behaldast. Dette gjeld for LNG, flytande hydrogen og ammoniakk, medan metanol er i stand til å lagrast i dei konvensjonelle tankane til referansefartøyet og samtidig møte kravet for rekkevidde.

Miljøprestasjonen blir undersøkt gjennom ein konverteringsmetode for livsløpseffektvurdering med namn ReCiPe2016H. Utslepp av karbondioksid (CO_2), metan (CH_4), lystgass (N_2O), nitrogenoksid (NO_x), svoveloksid (SO_x) og partikkelmaterie (PM) til atmosfæren er inkludert, både for produksjon og operasjon. Prestasjonen blir vurdert for Midpoint og Endpoint. Flytande hydrogen, ammoniakk og metanol er drivstoffa med lågast total potensiell miljøeffekt ved Endpoint når dei er produsert på ein fornybar måte, med metanol som presterer best. Det er og tydeleg at det ikkje noko miljømessig gevinst ved å innføre naturgassbaserte alternative drivstoff med LNG som referanseindikator. Rangeringa baserast på dei ulike drivstoffa implementert i referansefartøyet med ein generell årleg operasjon.

For å gjennomføre den økonomiske vurderinga blir ein analyse av livsløpskostnadar tatt i bruk. Ved å definere CAPEX, OPEX og VOYEX for dei ulike drivstoffløysingane implementert i referansefartøyet, blir ein livsløpskostnad (LCC) estimert for to ulike tilfeller:

- Tilfelle 1: Eit notidsscenario med dagens skatting av utslepp og drivstoffprisar for 2020
- Tilfelle 2: Eit framtidsscenario med auka skatting av utslepp og drivstoffprisar for 2030

Begge tilfella avdekkjer signifikante livsløpskostnadar for dei alternative drivstoffa samanlikna med LNG og MDO, grunna ein stor differanse i drivstoffkostnad. Den planlagde auken i utsleppsskatt og framtidige estimerte prisar for grøne drivstoff er ikkje nok til auke konkurransekrafta for alternative drivstoff til eit naudsynt nivå nivå samanlikna med dei tradisjonelle.

Ei fleirkriteriebasert avgjerdsanalyse er gjennomførd basert på eit sett med kriterium som dekkjer miljøeffekt, teknisk modning, økonomi og sikkerheit. Dei ulike kriteria er vekta basert på ein redar som interessent. Det resulterer i at tradisjonelle drivstoff presterer betre enn alternative, medan grønn ammoniakk presterer best av dei alternative. Ein sensitivitetsanalyse blei gjennomførd med blant anna Myndigheitene som ein interessent, grunna redarar si høge vektlegging av det økonomiske aspektet. Dette resulterer i ei motsett rangering, med dei alternative drivstoffa som betre enn dei tradisjonelle og grønn ammoniakk på topp.

Basert på resultata frå avgjerdsanalysa, undersøkjer oppgåva vidare ulike ammoiakk-konsept basert på drivstoffmiksen. Konsepta har ein ammoniakkandel i drivstoffmiksen på høvesvis 70%, 90% og 95%. Tilfellestudiet avdekkjer at dei forskjellige konsepta er i stand til å kutte utsleppet av drivhusgassar med deira respektive ammoniakkandel. Ein forbetra miljøprestasjon vil derimot auke livssykluskostnaden grunna eit høgare forbruk av ammoniakk. Ei designvurdering med fokus på sikkerheit blir også gjennomførd for ammoniakk. Hovudfokuset når ein implementerer ammoniakk er å unngå lekkasjar av ammoniakk og minimisere potensielle konsekvensar av ein potensiell lekkasje. For å sikre ein trygg implementering av ammoniakk som drivstoff kan mange av dei same sikkerheitsprinsippa for LNG bli brukt. Den største skilnaden er giftigheita til ammoniakk som fører til strengare reguleringar for ventilering og krav om å definere giftsonar på dekk, alt for å sikre trygg operasjon for personell.

Oppgåva konkluderar med at ammoniakk presterer best av dei grøne alternativa, men ikkje er realistisk basert på økonomi. Ei løysing er derfor å designe nye fartøy ammoniakk-tilrettelagd. Dette betyr at fartøyet er designa for LNG, men det er tatt høgde for framtidige krav og reguleringar for ammoniakk i designprosessen. Å operere på LNG vil redusere utslepp til ein viss grad i nær framtid, medan ein opprettheld ein god økonomisk operasjon. Fartøyet er også i stand til å skifte til ammoniakk ved relativt små modifiseringar og dermed oppnå større utsleppsreduksjon som oppfyll Myndigheitene sitt mål for 2030, skulle drivstoffprisen søkke til eit tilstrekkeleg lågt nivå. Denne alternative løysinga vil senke investeringsrisikoen samanlikna med eit vanleg LNG-fartøy og krev berre ein liten ekstra investeringskostnad. Ei utfording er då den reduserte rekkevidda ein får ved å bytte ut eit gitt volum LNG med ammoniakk.

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Abbreviations

AEGL = Acute Exposure Guideline Levels
AHP = Analytic Hierarchy Process
AIS = Automatic Identification System
CcH_2 = Cold and Cryo-Compressed Hydrogen
CCS = Carbon Capture and Storage
CCU = Carbon Capture and Utilization
CGH_2 = Compressed Gaseous Hydrogen
CH_4 = Methane
CH_3OH = Methanol
CI = Consistency Index
CNG = Compressed Natural Gas
CO_2 = Carbon Dioxide
CR = Consistency Ratio
DALY = Disability-Adjusted Life Years
DF = Discounting Factor
ECA = Emission Control Area
E-fuels = Electro-fuels (Green Fuels)
EEDI = Energy Efficiency Index
EOFP = Ecosystem Ozone Formation Potential
EQV. = Equivalents
EUR = Euro
FC = Fuel Cell
FPR = Fuel Preparation Room
GHG = Greenhouse Gasses
GHS = Globally Harmonized System of Classification and Labelling of Chemicals
GWP = Global Warming Potential
HFO = Heavy Fuel Oil
Hh_H = Hull Man-Hours
HOFP = Human Health Ozone Formation Potential
HPLSDF = High Pressure Low Speed Dual Fuel
HPMSDF = High Pressure Medium Speed Dual Fuel
HT-PEMFC = High Temperature Proton Exchange Membrane Fuel Cell
IBC Code = The International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk
ICE = Internal Combustion Engine
IGC Code = The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code = International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels

IMO = International Maritime Organization
kEUR = Thousand Euro
LBSI = Lean Burning Spark Ignited
LCA = Life Cycle Assessment
LCCA = Life Cycle Cost Analysis
LCI = Life Cycle Inventory
LCIA = Life Cycle Impact Assessment
$\mathrm{LH_2}$ = Liquefied Hydrogen
LNG = Liquefied Natural Gas
$\mathrm{L\text{-}NH_3}$ = Liquefied Ammonia
LOA = Length Overall
LPDF = Low-Pressure Dual Fuel
LPLSDF = Low-Pressure Low Speed Dual Fuel
$\mathrm{m_H}$ = Unit Cost of Structural Steel
$\mathrm{m_{HhH}}$ = Unit Cost of One Man-Hour
MARPOL = International Convention for the Prevention of Pollution from Ships
MCDA = Multi-Criteria Decision Analysis
MCR = Maximum Continous Rating
MDO = Marine Diesel Oil
ME-LGIM = Electronically Controlled Liquid Gas Injection Dual-Fuel Two-Stroke for Low-Flashpoint-Liquid Fuels
ME-LGIP = Electronically Controlled Liquid Gas Injection Dual-Fuel Two-Stroke Engine
MeOH = Methanol
MGO = Marine Gas Oil
$\mathrm{N_2O}$ = Nitrous Oxide
$\mathrm{NH_3}$ = Ammonia
NO_x = Nitrogen Oxide
NSS Herring = Norwegian Spring Spawning Herring
OPEX = Operational Expenditure
p’ = Real Interest Rate
$\mathrm{P_0}$ = Design Vapor Pressure
P_r = Productivity Factor
PCM = Pairwise Comparison Matrix
PEMFC = Proton Exchange Membrane Fuel Cell
PM = Particulate Matter
PMFP = Particulate Matter Formation Potential
PPM = Parts Per Million
Pt = Potential Environmental Impact
PV = Present Value
$\mathrm{Q_{HV}}$ = Heating Value
R&D = Research and Development
RI_n = Random Consistency Index
RSW = Refrigerated Sea Water
RV = Residual Value
SCR = Selective Catalytic Reactor

SDS = Safety Data Sheet
SEEMP = Ship Energy Efficiency Managment Plan
SFC = Specific Fuel Consumption
SH_2 = Slush Hydrogen
SMR = Steam Methane Reforming
SOFC = Solide Oxide Fuel Cell
SOLAS = Safety of Life at Sea
SO_x = Sulfur Oxides
TA = Terrestrial Acidification
TCS = Tank Connection System
TtP = Tank-to-Propeller
UREA = Reactant for the SCR system
VOYEX = Voyage Related Expenditures
W_H = Hull Weight

Chapter 1

Introduction

1.1 Background

Global warming is on the political agenda worldwide. In order to tackle the present and coming challenges, the world's visionary leaders and industries must cooperate. The situation requires and drives for innovative and greener solutions in all segments. IMO has set a goal of reducing greenhouse gas emissions by at least 50% by 2050 compared to emission levels in 2008. To reach its goals, IMO has launched a strategy that provides candidates of short-term, mid-term, and long-term measures illustrated in Figure 1.1.

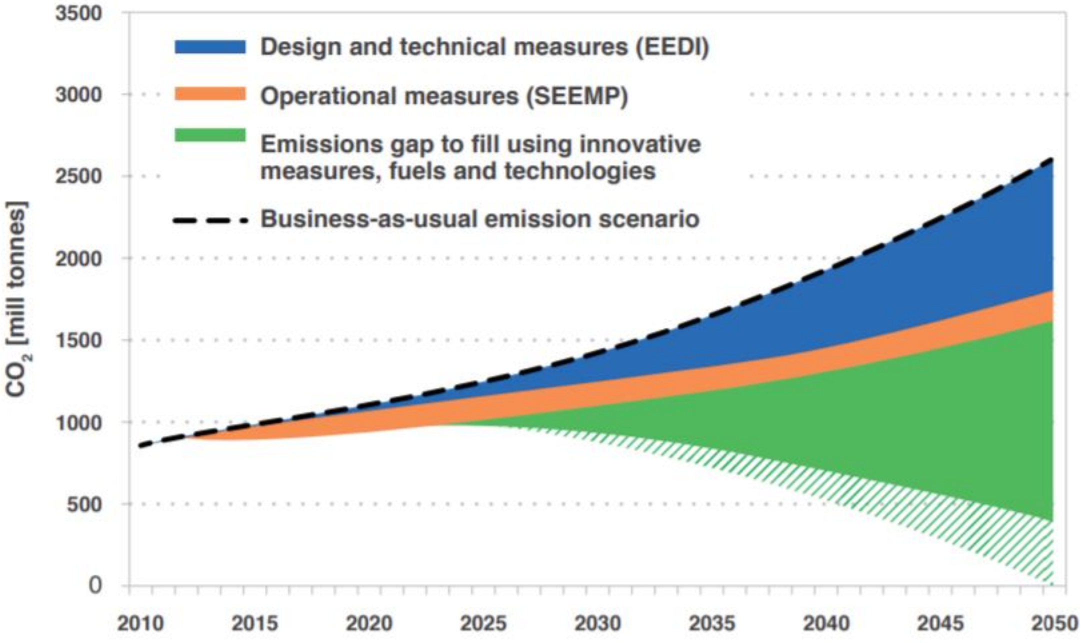

Figure 1.1: IMO's proposed strategy (IMO (N.D.b))

IMO have already reviewed requirements that cover some of these candidates. The previous fall, a proposed draft amendment was developed. If ratified, it would add stricter requirements to the energy efficiency measures in MARPOL Annex VI Chapter 4 (IMO (N.D.a)). This covers the Energy Efficiency Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). Through regulations, IMO will make it progressively tougher to meet the requirements needed to meet the reduction goal.

From Figure 1.1, it is possible to conclude that alternative fuels and technologies can make a major impact on the reduction. Based on several studies assessing the relative environmental impact at different value chain steps for fish products, it is found that fuel use during fishing operations is one of the main contributors to the environmental impact (Ziegler et al. (2013), Avadí and Fréon (2013)). By this, it is important to assess the fuel system in the fishing vessel if the environmental performance of the value chain is to be improved. IMO's goals have resulted in many emerging potential fuels and solutions. All with varying levels of maturity concerning both technology and infrastructure. Some of these are categorized as temporary solutions with lower emissions than today's traditional fuels, and some are seen as possible long-term zero-emission fuels.

In addition, Norway has committed to reducing emissions based on the Paris Agreement, setting strong guidelines for emissions in the maritime sector. Domestic shipping is responsible for 9% of Norway's total CO_2 emissions, meaning it has a great reduction potential for Norway's total climate footprint. Even though society is to undergo a major and fundamental change to reduce emissions, the process provides possibilities for both the development and innovation of new technology. Norway, as a global advanced maritime nation, has a great opportunity to take the first steps and thus create increased opportunities for export, economic growth, and jobs.

1.2 Objective and Scope

The overall aim of the project is to investigate the possibilities of alternative energy carriers in a low emission fishing vessel through a comparison study and to further assess a safe and efficient implementation of the most relevant fuels.

The objective will be achieved through the following methods:

- Background and literature review: Provide information and relevant references on related topics
- Comparative study: Compare the performance of the different alternative marine fuel solutions implemented in a purse seiner/pelagic trawler. This study is to cover the aspects; environmental performance, technical maturity, economy and safety.
- Design assessment: Assess a safe and efficient implementation of the most relevant solution based on the results from the comparative study.

1.3 Limitations

The project is limited to four different fuels; LNG, Hydrogen, Ammonia, and Methanol. Based on conversations with Salt Ship Design during the definition of the thesis description, these were deemed the most prominent candidates to further assess. LNG is included as a benchmark because an LNG fishing vessel has already been designed by Salt. The technical details for the different solutions are defined by a conceptual and preliminary approach. The Life Cycle Inventory will be based on existing Life Cycle Assessments. Emissions to air are the only emissions considered. Pollution to soil and water will not be assessed.

Chapter 2

Methodology

2.1 Information and Data Collection

The focus for this thesis is of high current interest but is still only somewhat covered by relevant literature. Salt Ship Design has a long experience with ship design, and they are especially skilled in the area of fishing vessels. Because they already have designed a fishing vessel capable of running on LNG, in addition to investigating other alternative fuels, they sit on relevant information and data, reducing the gap in the existing literature. Information and data have been retrieved through both literature review and conversations with people at Salt. It could be expected that the thesis would be somewhat more limited if not written on behalf of a dissertation affiliation like Salt Ship Design.

2.2 Case Study

A Case study is a research method with the goal and desire of deriving an in-depth understanding of one or several complex cases set in the real world (Yin (2011)). Because it represents a real or hypothetical situation, it must cover a broad range of topics resulting in multiple sources of data, e.g. literature review, interviews with stakeholders, or experiments.

To effectively perform a case study, the boundaries and goal of the case study must be defined. This makes it easier to define the parameters to be explored and to set up a time frame for the work to be performed.

There are several different types of case study approaches. According to Stake (1995), an instrumental case study is performed to understand more than a specific case and an intrinsic case study to understand a specific case or situation. What is somewhat challenging is when the case study is somewhere in between. This can be defined as an instrumental single case study where the outcome is for a specific case but can be generalized and seen in context to other cases.

2.3 Life Cycle Assessment

EC-JRC (2010) defines Life Cycle Assessment as a “structured, comprehensive and internationally standardized method. It quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services (“products”).”

All relevant emissions and resources consumed covers the product's lifetime from cradle to grave. An LCA is a good way of comparing the environmental impact of different products, but it does not tell you if the performance is "good enough" for the environment. The LCAs used in this thesis consider different alternative marine energy carriers from well-to-tank (production) and tank-to-propeller (operation), i.e. cradle-to-grave or well-to-propeller specifically for this thesis.

There exist different Life Cycle Impact Assessments (LCIA) methods to better interpret the LCA studies. These methods translate emissions and resource extraction into a limited number of environmental impact scores (Huijbregts et al. (2016)). This applies especially if the LCA only provides a Life Cycle Inventory containing e.g. emissions per kg produced of a product. The LCIA method used in this thesis is ReCiPe2016, developed by the National Institute for Public Health and the Environment (RIVM) in the Netherlands. This method translates emissions and resource extraction into environmental impact scores through characterization factors, indicating the environmental impact per unit of a stressor (Huijbregts et al. (2016)). These characterization factors can be derived at either Midpoint or Endpoint. The following information is adapted from Huijbregts et al. (2016). At Midpoint, the characterization factor is a dimensionless number that expresses the strength of a substance relative to that of the reference substance, e.g. kg CO_2-eqv./kg. This makes it possible to gather different environmental flows in one environmental mechanism. The advantage at Midpoint is that the characterization has a high degree of relation to the emission flows with low uncertainty, e.g. kg of SO_x-eqv. emitted. The characterization factors at Endpoint cover three categories; human health, natural environment, and resource scarcity. The environmental mechanisms at Midpoint are translated into these three categories, which are then weighted compared to each other and normalized to create a total potential environmental effect score. The advantage at Endpoint is that it provides information on the relevant environmental effect the different environmental mechanisms have, e.g. fine particulate matter formation could have a bigger impact on the environment compared to terrestrial acidification. It does, however, come with a higher degree of uncertainty compared to that of Midpoint.

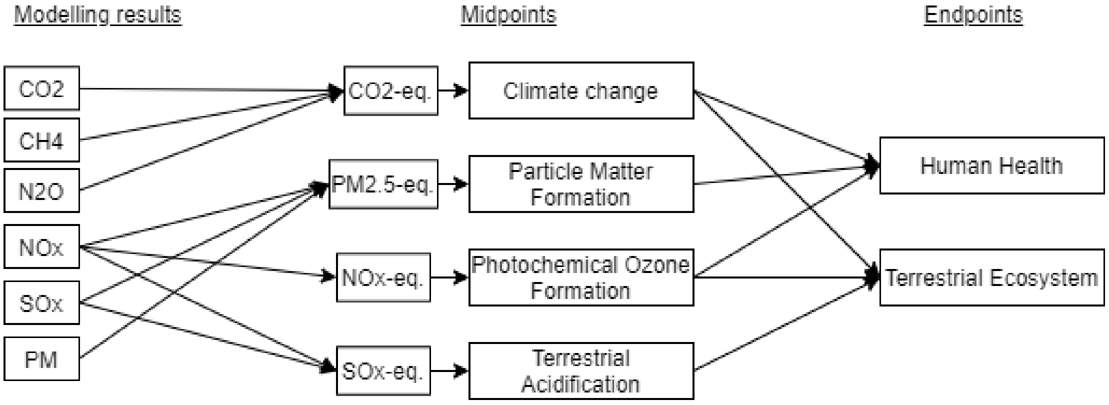

Figure 2.1: Flowchart of the ReCiPe2016 method, with the impact categories and protection areas relevant for this thesis included. (adapted from Huijbregts et al. (2016) and Bengtsson (2011))

For the impact category climate change, the Midpoint characterization factor is Global Warming Potential (GWP), expressing the increased amount of additional radiative forcing by the release of one kg GHG compared to that of one kg of CO_2, i.e. kg CO_2-eqv./kg GHG. Because the different GHGs have different atmospheric lifetimes, the GWP values are dependent on the defined value choice for the time horizon. The three choices are; Individualist, Hierarchist, and Egalitarian.

Table 2.1: Value choices for GWP (Huijbregts et al. (2016))

Choice category	Individualist	Hierarchist	Egalitarian
Time horizon	20 years	100 years	1000 years
Future socio-economic developments	Optimistic	Baseline	Pessimistic
Adaption potential	Adaptive	Controlling	Comprehensive

For the Midpoint to Endpoint conversion, endpoint characterization factors are used. In this thesis, climate change is defined as causing human health damage and terrestrial ecosystem damage. According to Huijbregts et al. (2016), human health damage due to climate change is measured in Disability-Adjusted Life Years (DALY) per CO_2-eqv., i.e. DALY/kg CO_2-eqv., and terrestrial ecosystem damage defined as Species.year/kg CO_2-eq. Both have to be defined for one of the time horizons.

For the impact category Particulate Matter Formation Potential (PMFP), the Midpoint characterization factor is defined as $PM_{2.5}$-eqv./kg of emitted substance x. The value for the particulate matter formation is thus defined as kg of $PM_{2.5}$-eqv. Based on the value choice, it is different what emissions are defined as contributing to this impact category at Midpoint. The time horizon is not relevant here because only short-living substances are involved (Huijbregts et al. (2016)).

Table 2.2: Value choices for fine particulate matter formation (Huijbregts et al. (2016))

Choice category	Individualist	Hierarchist	Egalitarian
Included effects	Primary aerosols	Primary aerosols, secondary aerosols from SO_2	Primary aerosols, secondary aerosols from SO_2, NH_3 and NO_x

For the conversion from Midpoint to Endpoint, particulate matter formation potential is only affecting human health. The Midpoint to Endpoint conversion factor is defined as yr/kg $PM_{2.5}$-eqv. with different values for the different value choices.

Another impact category is Photochemical Ozone Formation caused by the emission of NO_x. This can harm both human health and vegetation. At Midpoint, the characterization factor is defined as NO_x-eqv./kg of emitted substance x. Only the emission of NO_x is relevant for this thesis. Different from the other impact categories is that it is divided into human health damage and terrestrial ecosystem damage already at Midpoint. Thus photochemical ozone formation is defined as Human Health Ozone Formation Potential (HOFP) and Ecosystem Ozone Formation Potential (EOFP). Neither are impacted by value choices due to only involving short-living substances.

For the conversion from Midpoint to Endpoint, HOFP affects human health and the conversion factor is defined as yr/kg NO_x-eqv. EOFP affects terrestrial ecosystems and has a conversion factor defined as species.year/kg NO_x-eqv. Both are defined differently for the three value choices.

The last impact category defined for this thesis is Terrestrial Acidification (TA). The emissions of sulfates, nitrates, and phosphates, in particular, cause a change in the acidity in the soil which again affects the plant species. The Midpoint characterization factor is defined as SO_2-eqv./kg of emitted substance X. The emission of NO_x, NH_3, and SO_2 is particularly contributing to this phenomenon.

The change of the acidity level in the soil affects only the terrestrial ecosystem, thus the conversion factor from Midpoint to Endpoint is defined as species.year/kg SO_2-eqv.

After converting the different impact categories to Endpoint values, the final environmental performance can be calculated by weighting and normalizing the different Endpoint categories.

2.4 Life-Cycle Cost Analysis

Life-cycle cost analysis (LCCA) is a method for assessing the total cost of owning a product, a ship in this case, all the way from acquiring to disposing of. This covers everything from initial purchasing costs and financial charges to fuel costs, operation costs, and resale values or disposal costs. In general, the costs can be divided into Capital Expenditures (CAPEX), Operational Expenditures (OPEX), and Voyage Related Expenditures (VOYEX) in addition to residual value and financial costs. LCCA is a useful tool when comparing different project alternatives with different costs, as it helps to assess the relevant economical performance for the alternatives over a given period.

A discount rate must be defined to compare cash flows from different times during the life cycle of the ship. What this means is that they have to be made time-equivalent. This is done by converting them to present values (PV) through discounting to the base date of the purchase. The discount rate represents the shipowner's opportunity cost of money over time, i.e. the minimum acceptable rate of return. The LCCA can be performed both in constant- and current currency. The main difference is that constant-currency analysis does not include inflation. For this thesis, the current-currency method is chosen, and the discount rate, also called the real interest rate, is calculated with the following equation:

$$p' = \frac{1+p}{1+f} - 1 \tag{2.1}$$

where p is the market rate and f is the rate of inflation. Following the discounting factor can be calculated:

$$DF = \frac{(1+p')^n - 1}{p' \cdot (1+p')^n} \tag{2.2}$$

where p' is the discount rate and n the duration of the assessment. Finally the Life-Cycle Cost (LCC) can be calculated:

$$\text{LCC} = \text{CAPEX} + (\text{OPEX} + \text{VOYEX}) \cdot \text{DF} - \text{RV} \tag{2.3}$$

The LCC analysis can be altered to find the maximum cost an input must not exceed for a project to still break even after n number of years. This is done by setting the income equal to the expenses and solve for the unknown cost algebraically. The unknown cost of interest for this thesis is the fuel cost. By extracting the fuel cost from the VOYEX and defining the LCC for n years to be equal to the income over n years, the discounted fuel cost over n number of years can be calculated as follows:

$$\text{FUEL COST} \cdot \text{DF} = \text{INCOME} \cdot \text{DF} + \text{RV} - \text{CAPEX} - (\text{OPEX} + \text{VOYEX}) \cdot \text{DF} \tag{2.4}$$

2.5 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process often referred to as the Saaty method, can be applied to help in decision-making analyses. The decision to be made in this thesis is to find the alternative fuel ranking highest when considering its performance in different criteria and the weighting of those criteria. AHP is a way of calculating this weighting through a pairwise comparison of the different criteria. To make comparisons, a scale of numbers indicating the relative importance of one criterion compared to another is defined in Table 2.4. These comparisons are carried out in Pairwise Comparisons Matrices (PCM) where aij, from Saaty's rating scale, represents the degree of preference of xi compared to xj.

$$\text{PCM} = (a_{ij})_{\text{nxn}}\text{PCM} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \tag{2.5}$$

Table 2.3: Example of a Pairwise Comparison Matrix

	Criterion 1	Criterion 2
Criterion 1	1	Numerical Rating
Criterion 2	1/Numerical Rating (Reciprocal)	1
	$a_{11} + a_{21}$ = SUM1	$a_{12} + a_{22}$ = SUM2

Table 2.4: The Saaty rating scale (Saaty (2008))

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgement slightly favour one over the other
5	Much more important	Experience and judgement strongly favour one over the other
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity
2,4,6,8	Intermediate values	When compromise is needed

After assigning the relative importance in the PCM, each criterion is given a relative weight through normalization. This is done by dividing each value in PCM by the respective total column sum, see Table 2.5.

Table 2.5: Example of normalizing a PCM

	Criterion 1	Criterion 2
Criterion 1	1/SUM1 = a	Numerical Rating/SUM2 = b
Criterion 2	(1/Numerical Rating)/SUM1 = c	1/SUM2 = d

Further, the criterion weights, also called eigenvectors, can be estimated by taking each total row sum and dividing them by the number of criteria, see Table 2.6. These criteria weights provide the relative importance of the different criteria assessed.

Table 2.6: Example of deriving the criteria weights from the normalized PCM

	Criterion 1	Criterion 2	Criteria weights
Criterion 1	a	b	(a+b)/2
Criterion 2	c	d	(c+d)/2

The next step is to check if the PCM created is consistent. To check this λ_{max} must be calculated first. First, each value of a row in the original PCM is multiplied with the respective criterion weight before each row is summarized to a single value. These values are called the weighted sum values. By dividing these weighted sum values by the criterion weight, we get a number of estimates for λ_{max} equal to the number of criteria defined for the PCM. The mean of these values gives the final estimate of λ_{max} used in the consistency check. For a perfectly consistent PCM, $\lambda_{\text{max}} = n$, this is however very rare. Normally, the λ_{max} should be higher than n. The Consistency Index is calculated by the following formula:

$$\text{CI}(\text{PCM}) = \frac{\lambda_{\text{max}} - n}{n - 1} \tag{2.6}$$

where n is the number of criteria. This Consistency Index is again used to find the Consistency Ratio:

$$\text{CR}(\text{PCM}) = \frac{\text{CI}(\text{PCM})}{\text{RI}_n} \tag{2.7}$$

here RI_n is the random Consistency Index for the corresponding number of criterion from a large sample of matrices of purely random judgments. Saaty defined these random CI values found in Table 2.7. A CR(PCM) < 0.1 is seen as a sufficiently consistent PCM.

Table 2.7: Random index value for calculating the consistency ratio (Hansson et al. (2019))

n	3	4	5	6	7	8	9	10
RIn	0.5247	0.8816	1.1086	1.2476	1.3417	1.4057	1.4499	1.4854

More specifically for the thesis, the AHP method can be used to define how a specific stakeholder would weigh different performance criteria for a solution. By defining the fuels relative performance for the criteria and using the weights retrieved through the AHP method, the different fuels implemented in the reference vessel can be ranked.

2.6 Sensitivity Analysis

In order to improve the robustness and to assess uncertainties in the ranking of the different fuels implemented in the reference vessel, a sensitivity analysis is to be conducted. Through the definition of different cases where one or several parameters are altered, the change in ranking can be noted, thus providing insight into how different assumptions have affected the results.

Chapter 3

Fisheries

Fisheries is one of the greater export industries in Norway and plays an important role in the Norwegian economy, particularly along the coast. Fishing vessels released right above one million tonnes of CO_2 in Norwegian waters during 2013 (Green Shipping Programme (2016)). This makes it a segment capable of making a considerable cut in the release of CO_2 in Norway.

There exist many different fisheries and fishing methods. The two methods focused on in this thesis are pelagic trawling and purse seining. It is not uncommon with vessels that can perform both of these operations. The vessels are then often defined as pelagic trawlers with purse seine capabilities. This is because the required engine power is much higher for trawling than for purse seining. The two fishing methods are among the most fuel-efficient fishing methods in the Norwegian fleet, according to Schau et al. (2009).

Figure 3.1: An example of a purse seiner/pelagic trawler designed by SALT Ship Design

Figure 3.2 illustrates how big the operational area can be for some fishing vessels. This example is most relevant for bigger fishing vessels with several different quotas. The operational pattern can vary from year to year for several reasons. One reason is the fish both in regards to fish population and location. The population affects the quota sizes. During delivery of the caught fish, the boat often puts the fish out on auction and delivers to the fish delivery offering the highest price.

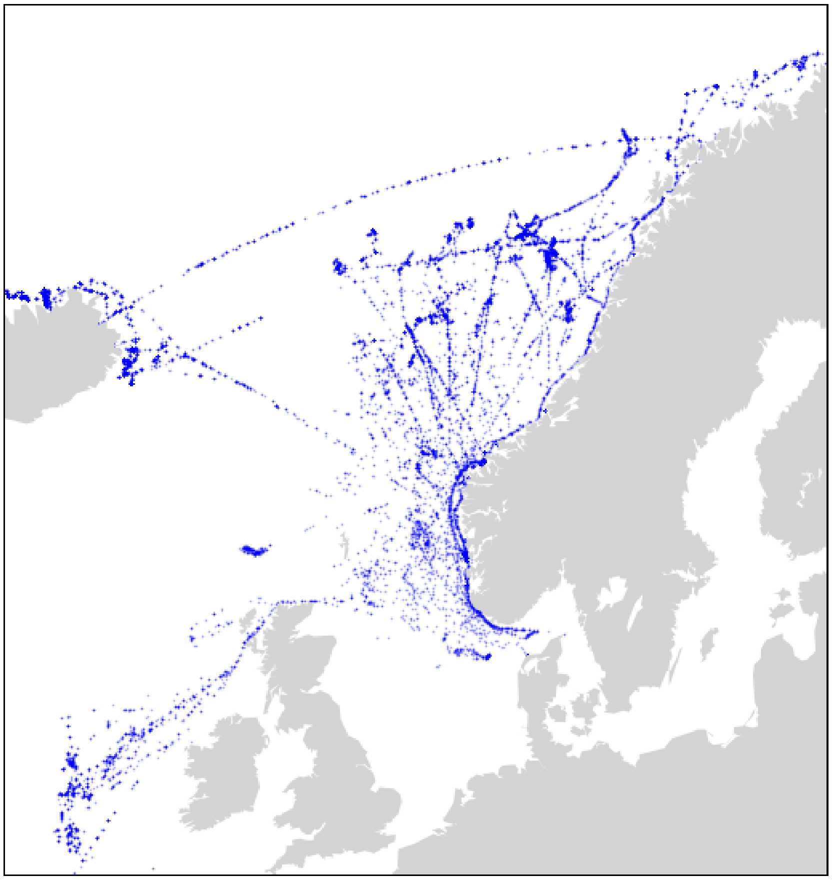

Figure 3.2: AIS-plot of all activity for a single purse seiner/pelagic trawler during 2018 (Botnen (2020))

3.1 Purse Seine

A purse seine is a big net that is shot in a circle around a shoal of fish trapping the fish in the horizontal direction. The net is fitted with rings on the bottom where a winch passes through. When this winch is hauled the net will be pursed in the bottom, enclosing the fish from the bottom as well. The fish is then trapped in a bowl-like shape and the hauling of the net can begin. The part of the net lastly shot is the part that is hauled first. This is because the first section of the seine, called the 'bunt', often is strengthened and intended to contain the fish while it is pumped on board. The process of fishing with a purse seine can be summarized as follows.

1. Search and positioning - a big part of the time is used for fish searching and positioning with the help of instruments and experience. Important parameters are depth location, shoal size, behavior, and size if possible.
2. Setting the seine - the setting is adjusted by the skipper depending on the fish behavior, current, etc.
3. Pursing of the seine - depending on the depth of the fish, the pursing phase can be delayed to let the net sink properly.
4. Retrieval of the seine

5. Handling of the catch

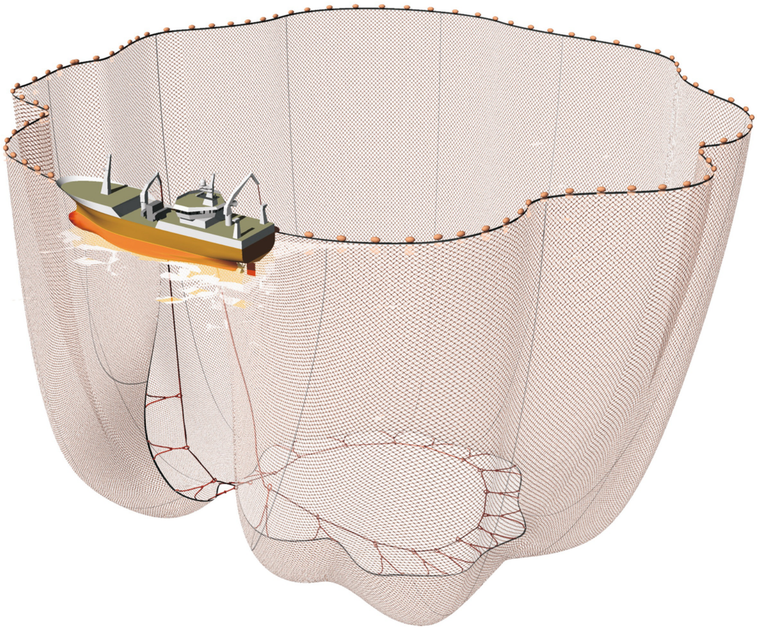

Figure 3.3: Illustration of a purse seine operation (Galbraith et al. (2004))

3.2 Pelagic Trawl

Pelagic trawl is a mid-water trawl designed to target fish in mid- and higher water columns. Compared to demersal trawls they are much bigger and more energy-efficient (Schau et al. (2009)). By the use of trawl doors, the opening of the trawl can be 200 meter wide and the depth 150 meter. The meshes at the entrance are very large, around 8-12 meters. This makes it possible to tow, despite the big size. By using both sonar and echo sounder the position and depth of the fish can be found and the trawling path adjusted accordingly.

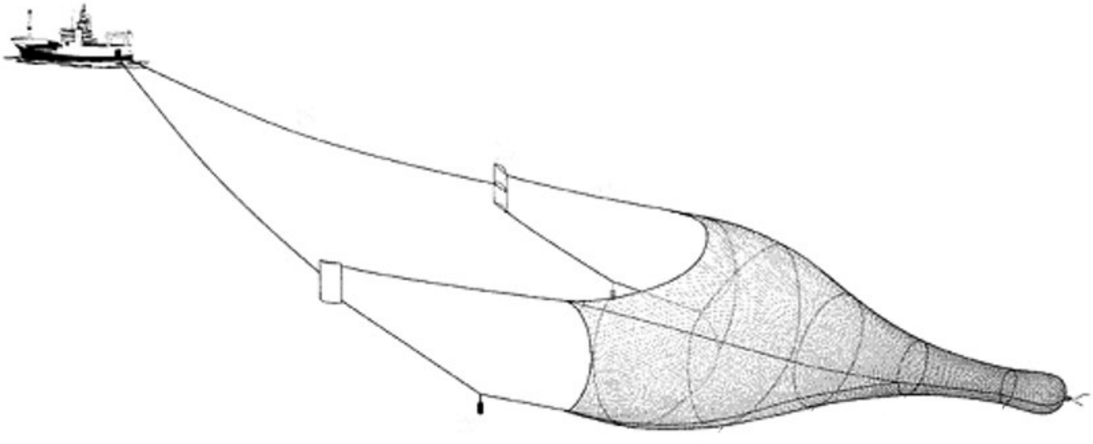

Figure 3.4: Illustration of a pelagic trawling operation (Aubert et al. (2018))

Chapter 4

Alternative Energy Carriers

Traditionally, the marine sector has mainly utilized low-quality fuels from crude oil refining, more commonly known as Heavy Fuel Oil (HFO). This is due to its good storage properties and cheap production method. A drawback is, however, a very poor environmental performance. In recent years there has been a graduate transition to more ships utilizing Marine Diesel Oil (MDO) and Marine Gas Oil (MGO). This is mostly due to their lower sulfur content compared to HFO. The physical properties of both MGO and MDO can be found in Table 4.1. Because existing solutions have been adapted to use these fuels over several decades, it is challenging to find a substitute that performs equally well on an operational basis as for the environmental performance. This chapter presents some of the possible fuels of the future, see Table 4.1 for their physical properties compared to MDO and MGO.

Table 4.1: Physical properties of different energy carriers (de Vries (2019), Gilbert et al. (2018))

Fuel type	**Energy density LHV [MJ/kg]**	**Volumetric energy density [GJ/m3]**	**Storage pressure [bar]**	**Storage temperature [Celsius]**
Marine Gas Oil	42.7	36.6	1	20
Marine Diesel Oil	42.6	38.3	1	20
LNG	50.8	23.4	1	-162
Liquid Hydrogen	120	8.5	1	-253
Compressed Hydrogen	120	7.5	700	20
Liquid Ammonia	18.6	12.7	1 or 10	-34 or 20
Methanol	19.5	15.8	1	20

4.1 Liquefied Natural Gas

Natural gas is a versatile commodity with different possible applications, e.g. around 80% of domestic heat demand in Great Britain was supplied from natural gas in 2018 (Watson et al. (2019)). It is fairly inexpensive to produce and emits significantly fewer emissions and pollutants compared to HFO and MDO. A weakness is a lower energy density and by this a more complex storage system to increase the energy density through liquefaction.

Natural gas varies in composition based on origin and process details. Generally, it consists of methane, ethane, and other light-weight hydrocarbons, but in some cases may also contain carbon dioxide, water vapor, and nitrogen (Ushakov et al. (2019)). Natural gas normally contains 87-96% methane (Demirbas (2010)). With the main component of LNG being methane (CH_4), it is important to avoid methane slip as it is a potent GHG (DNV GL (2019)). Methane is, however, the hydrocarbon containing the smallest amount of carbon which makes LNG favorable compared to diesel. It is important to mention that the storage pressure is the required pressure to keep the LNG in a liquid state at the given storage temperature of -162 Celsius. In reality, boil-off gas would increase the storage pressure in the tank.

Of the alternative fuels presented in this thesis, LNG is the most established with several existing LNG-fuelled vessels. In addition, LNG carriers have been using boil-off gas as fuel from the start in 1964 (Einang and Haavik (2000)). The introduction of natural gas as bunkering fuel was through the use of compressed natural gas (CNG). It was not before 2000 that the first LNG-fuelled ship started operating. The technology has had time to develop over the years, which may be one reason for it being so far ahead compared to other alternative fuels. There are several ways to utilize LNG as a fuel. You have different gas engine concepts, fuel cells, and the method LNG carriers use.

4.1.1 Production

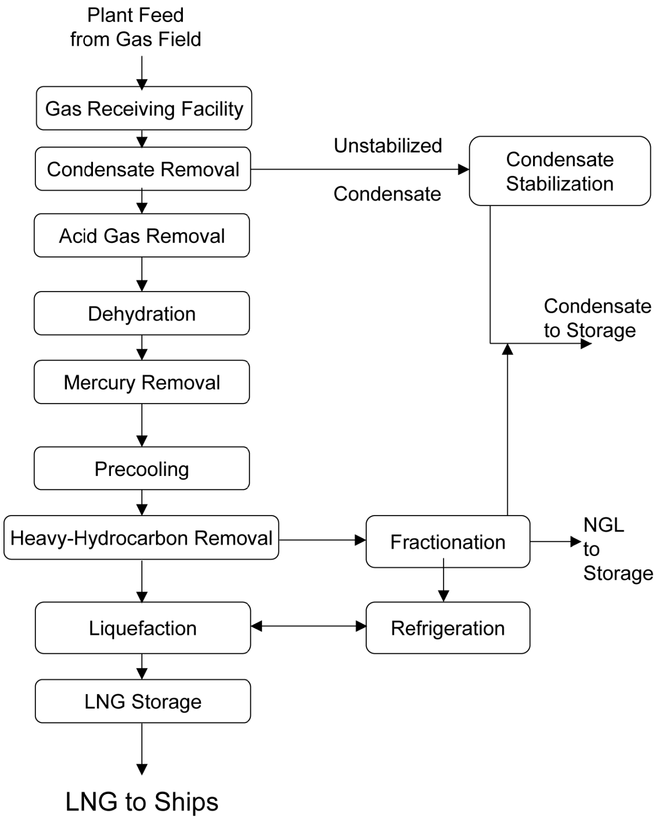

Figure 4.1: Natural gas liquefaction process (PetroWiki (2018))

Natural gas is today mainly fossil-based, but according to van Biert et al. (2016), it can also be produced by biomass or synthesized from CO_2 and renewable hydrogen in the future. The fossil-based natural gas is obtained from different types of reservoirs and processed for impurities. An LNG plant treats natural gas to remove water, corrosive acid gases, dust, helium, and heavy hydrocarbons before reducing the temperature of the feed gas to -162 °C (Demirbas (2010)). Natural gas must be stored below -162 °C at atmospheric pressure to remain liquid (van Biert et al. (2016)). Figure 4.2 illustrates the locations of production facilities in Norway, all varying in size.

Figure 4.2: LNG production facilities in Norway (NHO (2013), MARINTEK (2005))

4.1.2 Storage

A requirement every storage type for LNG must meet is to maintain the cryogenic temperature. The natural gas is kept at a temperature close to the vaporization temperature, and it is impossible to avoid some sort of admission of external heat causing slight evaporation of the cargo. This evaporation is known ass boil-off gas and causes an increase of pressure in the storage tank. Because of these two criteria, there exist three different types of independent tanks for LNG storage. Based on *ADOPTION OF THE INTERNATIONAL CODE OF SAFETY FOR SHIPS USING GASES OR OTHER LOW-FLASHPOINT FUELS (IGF CODE) MSC.391(95)* and Hyuante (2017), an overview of the tank types can be summarized as follows:

- Type A
    - Plane surfaces
    - Complete secondary barrier

  - Design vapor pressure, P_0, shall be less than 0.07 MPa
  - Pros: Space efficient
  - Cons: Boil-off gas handling and more complex fuel system required, leading to high costs

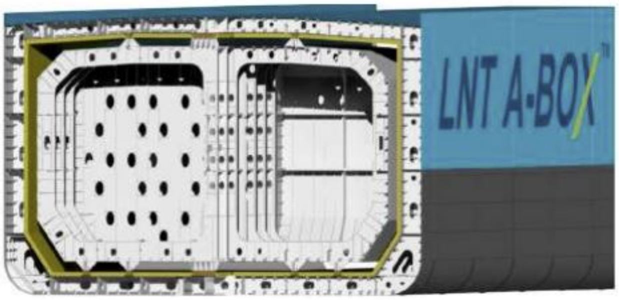

Figure 4.3: Type A tank (Boulougouris and Chrysinas (2015))

- Type B
  - Plane or spherical surfaces
  - Partial secondary barrier
  - Design vapor pressure, P_0, shall be less than 0.07 MPa
  - Pros: Prismatic is space-efficient, spherical is reliable proven in LNG carriers
  - Cons: Boil-off gas handling, complex fuel system, high costs

Figure 4.4: Type B tank (Boulougouris and Chrysinas (2015))

- Type C
  - Based on the pressure-vessel criteria
  - Cylindrical or spherical
  - Design vapor pressure, P_0, shall not be less than 0.2 MPa
  - Pros: Allows pressure increase, simple fuel system, little maintenance, easy installation, lower cost

  - Cons: Onboard space requirements

Figure 4.5: Type C tank (LGM Engineering (N.D.))

For existing ships using LNG as fuel, the type C tank is preferred because it is able to maintain higher pressures while minimizing boil-off.

4.1.3 Infrastructure

According to DNV GL (2019), LNG is in principle available worldwide with several large export and import terminals. Bunkering infrastructure for ships is not available in the same manner, but developing rapidly. Today the refueling of LNG ships is happening through trucks, local deposits, and bunkering vessels. According to KYSTVERKET (2018), there is a lot of small-scale bunkering from trucks in Norway. In 2018 there were 10 established LNG bunkering terminals along the coast of Norway.

4.2 Hydrogen

Hydrogen is the most common element in the world but is seldom found in its pure form, which is gas(van Biert et al. (2016)). Two great sources of hydrogen are water and different hydrocarbons. Some properties of hydrogen at standard temperature and pressure are colorless, odorless, non-toxic, and highly flammable (SHELL (2017)). Pure hydrogen is a potential fuel to secure a sustainable maritime sector in the future because it obtains the possibility of being a zero-emissions fuel if it is produced from renewable sources DNV GL (2019). Some key challenges are a low volumetric energy density and complex storage system, much like LNG, leading to either increased ship length or reduced endurance. It can be utilized in both fuel cells and dual-fuel engines.

4.2.1 Production

Because hydrogen is rare in its pure form, it must be extracted from a compound containing hydrogen. According to Hydrogen Europe (N.D.), these compounds can be converted to hydrogen through either electrolysis, biochemical conversion, or thermochemical conversion. With the many different extraction methods available, hydrogen can be produced using virtually any primary source of energy, both fossil and renewable.

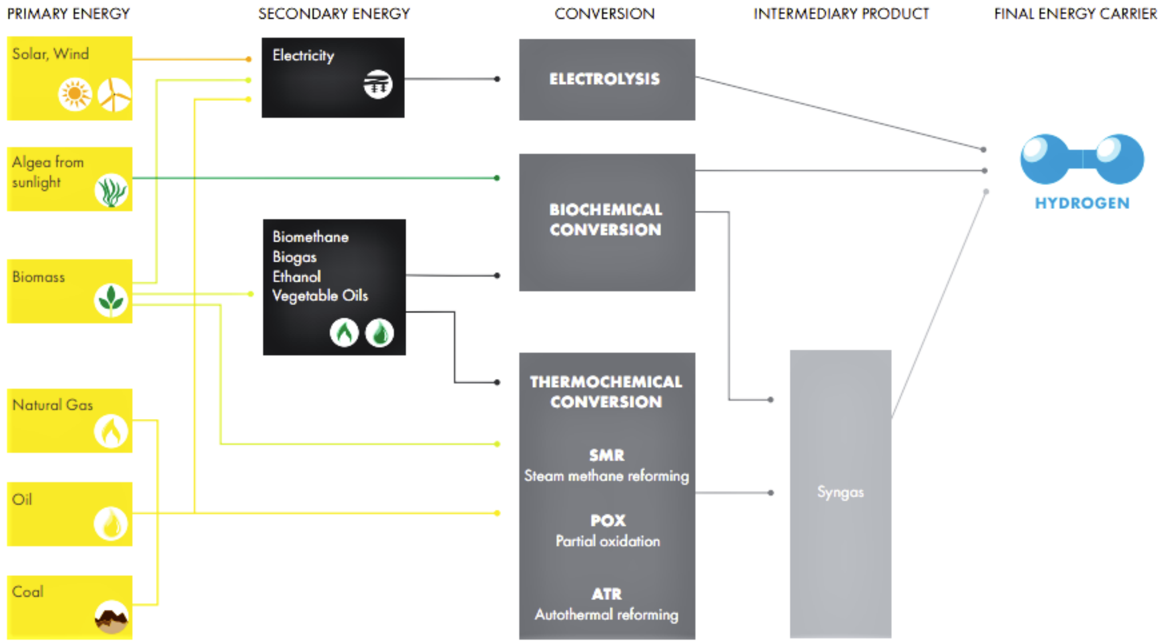

Figure 4.6: Illustration of different production paths for hydrogen (SHELL (2017))

The most common method utilized since the 1960s is Steam Methane Reforming, a thermochemical conversion. This method converts methane, normally natural gas, to hydrogen by the use of high-temperature steam. Some bi-products of this method are carbon monoxide and a small amount of carbon dioxide. The process requires energy to proceed. After the initial conversion, the *water-gas shift reaction*, which is the carbon monoxide and steam reacted by using a catalyst, produces carbon dioxide and more hydrogen. The final step is the *pressure-swing adsorption* where carbon dioxide and other impurities are removed from the gas stream and only clean hydrogen remains (Hydrogen Europe (N.D.)).

Two other thermochemical conversions are partial oxidation and autothermal reforming. Partial oxidation uses oxygen or air instead of water vapor, and the process releases heat. Autothermal reforming is a combination of steam reforming and partial oxidation, making it isothermal (SHELL (2017)).

The most promising production method for hydrogen is through the electrolysis of water because it possesses the potential to produce green hydrogen. Green hydrogen would require the energy in the electrolysis to be from renewable sources like hydro- or wind power. If the hydrogen is used in a fuel cell in addition, it would result in no net emissions (SHELL (2017)). Electrolysis breaks down water to hydrogen and oxygen by the use of electricity.

4.2.2 Storage

Depending on the temperature and pressure, hydrogen can be found in different states. The desired state determines the storage method. For a long time, it was thought to be a permanent gas, impossible to make both liquid and solid. In fact, the boiling point is extremely low at -253 °C (SHELL (2017)). With a very high gravimetric energy density but a low volumetric energy density, the density of hydrogen must be increased drastically before storage.

According to SHELL (2017), there are several different possible ways of storing hydrogen. Some are well-tested and commercial, while others are new and at a testing stage. The most common methods are physical storage based on cooling, compressing, or a combination of both to increase the volumetric energy. The different methods can be summarized as follows (SHELL (2017)):

- High-pressure storage of Compressed Gaseous Hydrogen (CGH_2) is one of these methods. Storage pressures of 350 or 700 bar have become the norm for use in the mobility sector.
- Liquefied Hydrogen (LH_2), storing cryogenic hydrogen in a liquid state, is also a commonly utilized method. This increases the specific energy to 8.5 MJ/l but requires liquefaction at -253 °C, which results in a complex technical plant.
- Cold- and cryo-compressed Hydrogen (CcH_2) is a method combining compression and cooling. The hydrogen is cooled and then compressed. Its advantage is a higher energy density compared to compressed hydrogen.
- Slush Hydrogen (SH_2) is a method of cooling the LH_2 further down to its melting point. The desired state is between solid and liquid, where the hydrogen acts like a gel or slush. This state has a 16% higher energy density than LH_2.

Higher energy density is desired but comes with a higher cost both in energy and design. Currently, it takes 9-12% of the final energy to compress hydrogen from 1 to 350 or 700 bar, while it takes around 30% for liquefaction (SHELL (2017)).

The less commercial materials-based hydrogen storage can be summarized as (SHELL (2017)):

- Hydride storage systems - the hydrogen forms interstitial compounds with metals
- Liquid organic hydrogen carriers - chemical compounds with high hydrogen absorption capacities
- Surface storage systems - hydrogen stored as a sorbate by adsorption on materials with high specific surface areas

Figure 4.7: Illustration of LH_2 storage tank (MAN Energy Solutions (2020))

4.2.3 Infrastructure

According to DNV GL (2019), most hydrogen today is used in the chemicals sector and for ammonia synthesis. The use in shipping is negligible, but with growing interest. There is currently close to no infrastructure for distribution and bunkering developed. Today most hydrogen is transported by trailer and in some specific locations by pipeline. According to SHELL (2017), LH_2 is most suitable for transport over long distances, and small amounts of CGH_2 most suitable for short-distance transportation. When it comes to transporting large volumes, pipelines are favorable. Some future solutions could be local hydrogen production in ports by electrolysis or storage of liquid hydrogen, based on a surplus of renewable energy (DNV GL (2019)). It is worth mentioning that the government in Norway has increased its commitment to hydrogen. This will make it easier for the hydrogen infrastructure to develop in the future.

Figure 4.8 illustrates different planned hydrogen projects along the coast of Norway. The projects cover both mass production and smaller local production. The illustration does not separate the green production from the grey. It is also not realistic to expect all of these projects to be realized, but it does illustrate that a lot of effort and money is being invested in hydrogen. The projects also vary, with some requiring transport before bunkering, and some being local production facilities with short to no transport required before bunkering. By this, the illustration does not necessarily represent specific locations of future bunkering infrastructure, rather possible areas and projects that can drive the infrastructure development forward.

Figure 4.8: Illustration of different hydrogen projects along the Norwegian coast. Adapted from E24 (2021).

4.3 Ammonia

Ammonia (NH_3), also called anhydrous ammonia, is a synthetic product mostly used in the fertilizer industry. Around 80% of the annual production of 180 million tons is used for fertilizers (ALFA LAVAL et al. (2020)). Based on a historical perspective, ammonia has shown potential as a fuel multiple times. In 1822 it was used to fuel a gas locomotive, and in 1943 liquid ammonia was used as fuel for buses in Belgium (MAN Energy Solutions (2019)). There has been an increasing interest in ammonia as an alternative fuel in recent years. Wärtsilä has recently commenced the world's first long term and full-scale testing of ammonia as fuel in a marine four-stroke combustion engine (Wärtsilä (2020)). In addition, MAN Energy Solutions have stated that when the market is ready, they will have the technology for a two-stroke ammonia engine. The technology will be based on Man's electronically controlled engine with liquefied gas injection for propane (ME-LGIP) and their engine with liquid gas injection for methanol (ME-LGIM) (MAN Energy Solutions (2019)).

Because ammonia is free of carbon and sulfur, its GHG emissions during combustion are close to zero. When utilizing it in an Internal Combustion Engine (ICE), an amount of pilot fuel is required to achieve proper combustion (Stenersen, D. (2020)). It is also possible to utilize it in fuel cells, either directly or through cracking to hydrogen depending on the fuel cell type. When produced with renewable energy, it has the potential to be a carbon-free energy carrier with a low carbon footprint both upstream and downstream.

4.3.1 Production

In today's market, no ammonia is produced based on renewable energy sources. The production is solely based on hydrogen from natural gas because this is the most inexpensive method. Until the 1990s, Norsk Hydro utilized alkaline electrolysis and air separation powered by hydropower to produce the hydrogen and nitrogen necessary for the ammonia synthesis through the Haber-Bosch process (ALFA LAVAL et al. (2020)). This could be classified as green ammonia. Yara has recently announced a project planning to produce 500,000 tonnes of green ammonia per year by 2026 dedicated to power emission-free shipping and decarbonized food solutions (Yara (2020)).

The Haber-Bosch process is by far the most used process for industrial ammonia production today. The hydrogen and nitrogen are mixed to form syngas with a ratio of 3:1. This reaction is carried out at 350-550 °C and 100-300 bar over an iron-based catalyst (Tallaksen et al. (2015)).

Another method is electrochemical ammonia production, which is in a study phase with few commercial cases. It produces ammonia by reacting water and nitrogen electrochemically at temperatures below 100 °C and at atmospheric pressure. This method is similar to the electrolysis of hydrogen and makes it possible to produce ammonia directly from a renewable power source (KOREAN REGISTER (2020)).

Figure 4.9 is a flowchart illustration of the the production of green ammonia through the Haber-Bosch process. The required power for the process must be supllied from renewable energy sources if the ammonia is to be classified as green. Possible sources are wind-, hydro-, or solar power, with wind and hydro being the most relevant for production in Norway. For the raw material, both air and water are renewable sources of nitrogen and hydrogen, respectively.

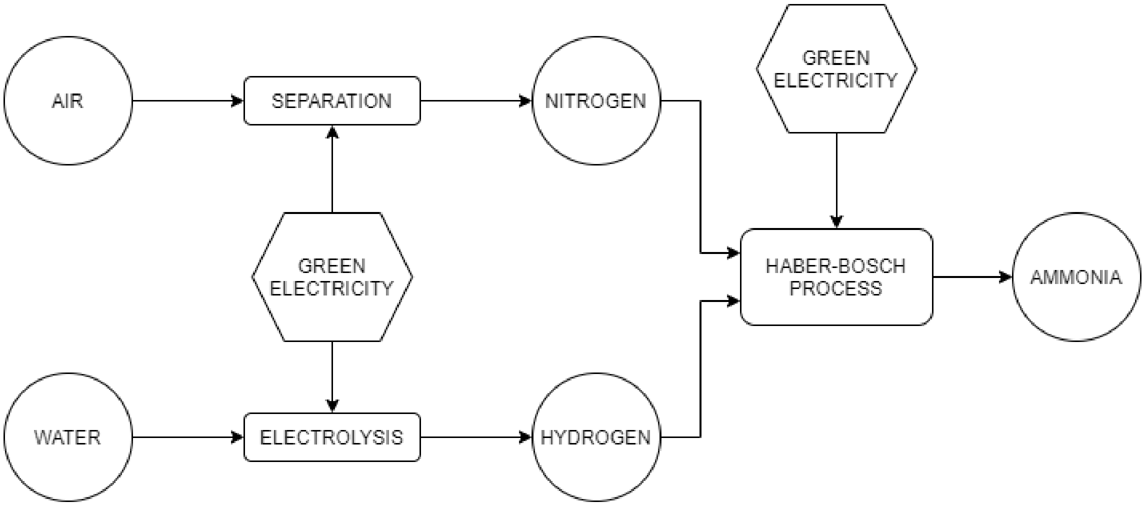

Figure 4.9: Green ammonia production. Adapted from The Royal Society (2020)

4.3.2 Storage

Ammonia is typically stored in pressurized C-type tanks, similar to LNG (DNV GL (2019)), although they can be stored in type A tanks defined in the IGC Code (Green Shipping Programme et al. (2021)). When fully refrigerated, the liquid ammonia has a temperature of -33C° in the tank at atmospheric pressure. This is much higher than LNG and LH_2, meaning future ammonia tanks could be somewhat cheaper than LNG. However, due to the corrosivity of ammonia, the materials used in the tank and associated systems should be assessed thoroughly.

4.3.3 Infrastructure

Currently, there exist no bunkering facilities due to no commercial use in the shipping industry. An advantage for ammonia is the already existing infrastructure used for transportation and handling of ammonia for the fertilizer industry. As for hydrogen, it could be possible in the future for local production of ammonia in ports and storage of liquid ammonia based on a surplus of renewable energy (DNV GL (2019)).

The increase in commitment for hydrogen works somewhat as an advantage for ammonia because the production requires hydrogen. Figure 4.10 illustrates production projects yet to be realized in addition to Yara's existing production facility at Herøya producing grey ammonia. The illustration does not separate grey from green projects. Fewer projects concerning ammonia production have been announced compare to hydrogen. If hydrogen, ammonia, and methanol are to cover some percentage of the future fuel picture each, higher hydrogen production is required as green ammonia and methanol require hydrogen in the production process. The projects drive the development of infrastructure for both bunkering and transportation.

Figure 4.10: Ammonia production projects/existing facilities along the coast of Norway. Adapted from E24 (2021).

4.4 Methanol

Methanol, or MeOH, is the simplest form of alcohol with only one carbon atom per molecule. This makes it the liquid fuel, at atmospheric pressure and temperature, with the lowest carbon to hydrogen ratio (DNV GL (2019)). It is used in various industries, making it one of the top five most widely traded chemicals globally (Verhelst et al. (2019)). An advantageous characteristic for methanol is that much like methane, also consisting of only one carbon atom, it has a very clean burning.

When utilizing methanol as fuel in conventional ship engines, there are only two main options, according to DNV GL (2019). They are a two-stroke diesel-cycle engine or a four-stroke, lean-burn Otto-cycle engine. Only one two-stroke type is commercially available, the MAN liquid gas injection engine (ME-LGI) series. Some methanol tankers use this model. It is also feasible to use fuel cells with methanol.

4.4.1 Production

The total supply of methanol for 2020 per October is 98.9 million metric tonnes, already surpassing last year's supply of 98.2 million metric tons (Methanol Institute (N.D.)). It is possible to produce methanol from fossil and biomass feedstock and also as a green fuel. As is the case for many alternative fuels, the cheapest and least environmentally friendly is the most commonly used, i.e. from fossil feedstock. The methods used are then a combination of steam reforming and partial oxidation of natural gas and gasification of coal (DNV GL (2019)). Production from biomass also uses gasification. The mentioned methods are the first of three basic steps which today's production comprises of, according to Verhelst et al. (2019). The first step is to produce synthesis gas, a gas consisting of CO, H_2, and CO_2. The two next steps are the conversion of the synthesis gas to methanol and the distillation.

A way to produce methanol in a renewable way is by taking hydrogen synthesized from electrolysis by using renewable power and captured CO_2 to produce the synthetic gas. The synthetic gas then goes through the reactor and distillation process to produce green methanol, see Figure 4.11. This can be defined as an e-fuel or E-MeOH. This method of capturing CO_2 from the atmosphere is not a fully mature technology today. A more temporary near-future solution to provide CO_2 to this process is using captured flue gas from industrial processes where the CO_2 is defined as bio-carbon. It is, however, a discussion of how renewable this method can be defined.

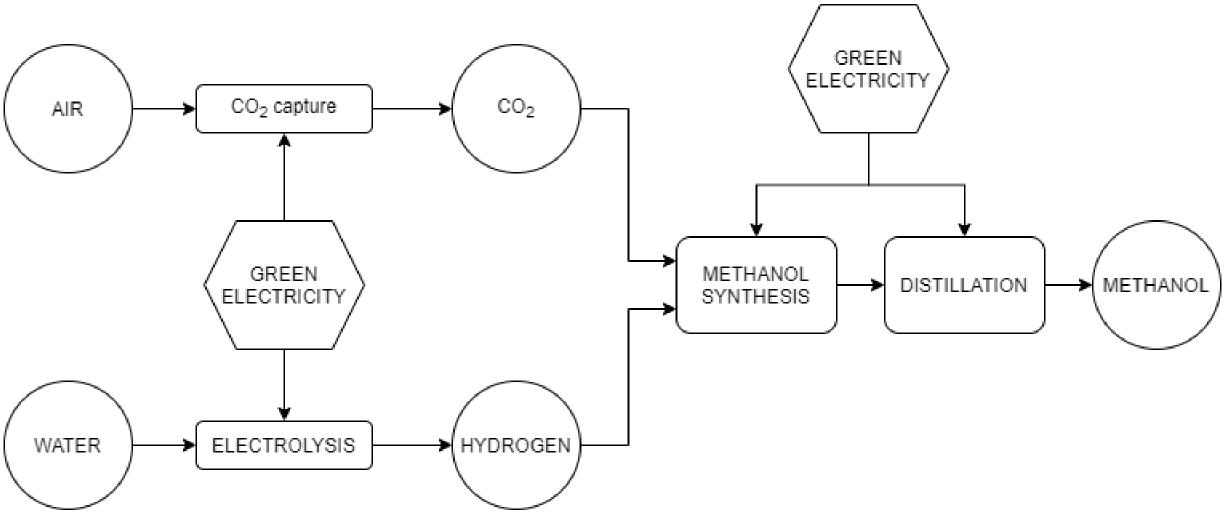

Figure 4.11: Green methanol production

4.4.2 Storage

An advantage of methanol is that it remains liquid in a wide range of temperatures, from -93°C to 65°C at atmospheric pressure (DNV GL (2019)). This makes it possible to store methanol in conventional double bottom tanks, provided they are adapted using a methanol-compatible coating.

4.4.3 Infrastructure

With methanol being a highly traded chemical, a global distribution infrastructure exists. According to DNV GL (2019), it is well-positioned to supply the marine industry. Infrastructure dedicated to the bunkering of ships is still limited. It is, however, possible to use trucks or bunkering vessels to accomplish distribution to ships in the early stage of the segment. A slight advantage is that is it easier to adapt existing bunkering infrastructure to use methanol than compared to hydrogen and ammonia.

Figure 4.12 illustrates production projects yet to be realized in addition to Equinor's existing production facility at Tjeldbergodden, producing grey methanol. The illustration does separate green and grey production.

Similar to hydrogen and ammonia, local production facilities are initially planned for green methanol. The daily production amount impacts if it is profitable to transport the methanol to more central distribution hubs or if it is to be used locally. If the transport is done by traditional ships, it will worsen the environmental performance.

Figure 4.12: Methanol production projects/existing facilities along the coast of Norway. Adapted from E24 (2021).

Chapter 5

Energy Converters for Alternative Energy Carriers

5.1 Internal Combustion Engines

Internal combustion engines are a well-proven technology utilized in many different segments. For marine use, they are often divided into slow-, medium- and high-speed engines which again can be divided into 2-stroke and 4-stroke engines. The most suitable engine varies from ship to ship based on the operational requirements.

A way to combat the lack of bunkering options for alternative fuels along the coast of Norway is to utilize dual-fuel engines. This makes the operation more versatile and less dependent on bunkering infrastructure. Fishing vessels like purse seines/pelagic trawlers have large operational areas, while bunkering and distribution infrastructure for alternative fuels is underdeveloped to cover this need in general. This makes the dual-fuel engine a viable option for the transition to alternative fuels. The vessel then has the flexibility to utilize alternative low emission fuels or standard fuels like MDO, MGO, and HFO without interrupting the fishing voyages. MAN Energy Solutions claim to produce dual-fuel engines that can switch easily between fuels without impacting performance. The four different dual-fuel engine concepts can be summarized as follows (Ushakov et al. (2019)):

- Low-Pressure Dual-Fuel (LPDF) engines:
  - Medium speed, 4-stroke cycle (LPDF): 1-18 MW
  - Low speed, 2-stroke cycle (LPLSDF): 5-63 MW
- High-Pressure Dual-Fuel (HPDF) engines:
  - Medium speed, 4-stroke cycle (HPMSDF): 2-18 MW
  - Low speed, 2-stroke cycle (HPLSDF): $>$ 2.5 MW

Based on a conversation with SINTEF, the big 2-stroke engines are not applicable for fishing vessels. A 4-stroke LPDF engine would fit the operational requirements of a fishing vessel best (Stenersen, D. (2020)). As a reference, Salt Ship Design has designed the first battery and LNG-fueled fishing vessel Libas. The vessel is installed with the MAN 6L51/60 DF engine.

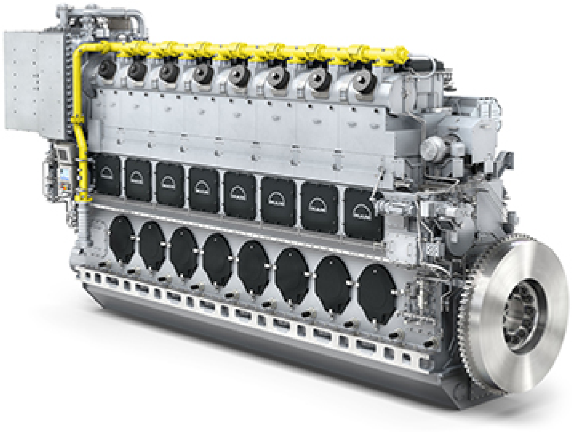

Figure 5.1: MAN 51/60 DF Engine (Linquip (N.D.))

It is a low-pressure dual-fuel engine and serves as a good reference. From its project guide (MAN Energy Solutions (2018)), the Specific Fuel Consumption (SFC) at 85% of Maximum Continuous Rating (MCR) can be defined as 7090 kJ/kWh or approximately 139.6 g/kWh when burning LNG. By using Equation 5.1 it is possible to calculate the efficiency of the engine. The resulting efficiency is then 50.8%. In addition, a small amount of pilot fuel is required when combusting LNG in an LPDF. From the same project guide, the amount can be found to be 100 kJ/kWh (MAN Energy Solutions (2018)). The amount of pilot fuel can then be calculated to 1.4%. The pilot fuel is assumed to be MDO in this thesis.

$$\eta = \frac{1}{sfc \cdot Q_{HV}} \tag{5.1}$$

Recently a company named Anglo Belgian Corporation released a dual fuel engine able to run on hydrogen (Anglo Belgian Corporation (2020)).

Figure 5.2: BEHYDRO (Anglo Belgian Corporation (2020))

According to them, it has a substitution rate up of to 85% hydrogen and 15% diesel. A general substitution rate of 80% hydrogen and 20% diesel can be assumed for the thesis (Steinshamn, T. S. (2021)). It is also able to run 100% on diesel if necessary. This makes it a very flexible solution. Based on the number of cylinders, it has a power range from 1000 kW to 2660 kW. The efficiency can be assumed to 42% (Steinshamn, T. S. (2021)).

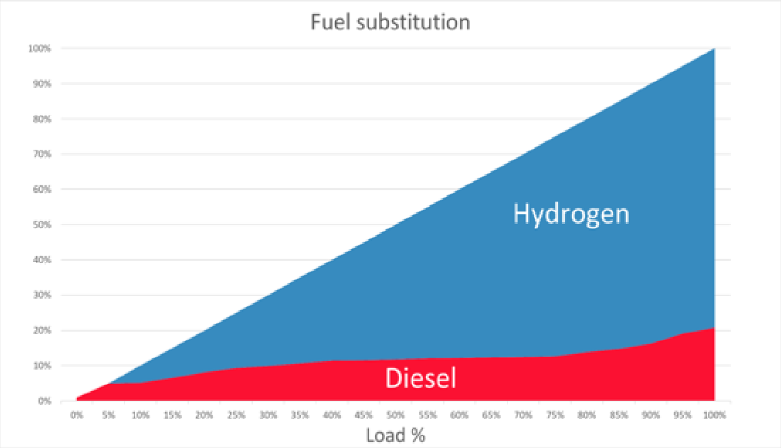

Figure 5.3: ABC BEHYDRO: Fuel mix for different loads (Anglo Belgian Corporation (2020))

Low-pressure dual-fuel engines for methanol and ammonia are less commercial. No LPDF engines for methanol are found during the literature search. As previously stated, the testing of dual-fuel engines utilizing ammonia has commenced with long endurance testing planned to start from June this year. Wärtsila is budgeting for an efficiency of 44% for this ammonia dual-fuel engine. The same efficiency is assumed for methanol. A pilot fuel injection is also needed for methanol and ammonia when utilizing an LPDF engine. For methanol, a general amount is found to be 8% through conversations with DNV. With the development and testing of ammonia LPDF engines in the early stages, a precise fuel mix is hard to define. However, based on conversations with SALT some engine manufactures think they will be able to commercialize dual-fuel engines utilizing a 70/30 mix of ammonia and pilot fuel respectively (Steinshamn, T. S. (2021)). They are also looking into the possibilities of utilizing a mix consisting of 95% ammonia. For this thesis, an amount of 30% pilot fuel is assumed for ammonia. According to Brohi (2014) it is possible to use hydrogen as a combustion promoter with ammonia as fuel when utilizing a Dual-Fuel Spark Ignition engine. The hydrogen amount is then a minimum of 3-5% of the weight basis.

One challenge with dual-fuel engines is the slow response time (Steinshamn, T. S. (2021), Nor-Fishing (2018)). To improve the response time a battery pack is required to peak shave short load variations. A good response time is important for the operation of a fishing vessel, especially during maneuvering and fishing. The size of the battery pack for Libas is 500 kWh (Nor-Fishing (2018)).

5.2 Fuel Cells

A fuel cell consists of three main components; a fuel electrode(anode), an oxidant electrode(cathode), and an electrolyte placed between them. By combining the fuel with an oxidant electrochemically, the fuel cell produces electrical work. The most common fuel utilized in fuel cells is hydrogen.

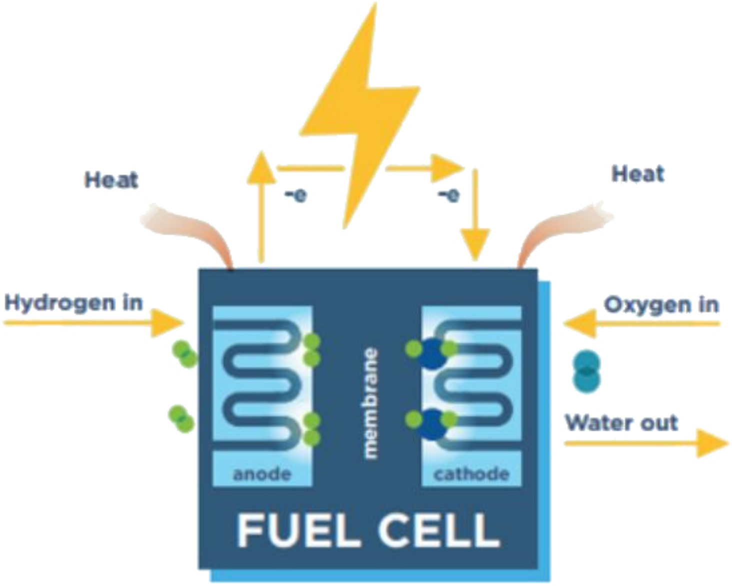

Figure 5.4: Working principle of a Fuel Cell (FCHEA (N.D.))

There are many different types of fuel cells. According to EMSA (2017), the three most promising fuel cell technologies for shipping are the Proton Exchange Membrane Fuel Cell (PEMFC), the High Temperature PEMFC (HT-PEMFC), and the Solide Oxide Fuel Cell (SOFC). The PEMFC and HT-PEMFC were the two technologies receiving the highest score in this study. According to Sharaf and Orhan (2014), PEMFCs are extremely flexible and the most promising candidates for transport applications. This is due to its high power density, fast start-up time, high efficiency, low operating temperatures, in addition to easy and safe handling. Based on this, the PEMFC is defined as the most relevant fuel cell for this project. One drawback with PEMFCs is that they are sensitive to impurities in the hydrogen.

According to ABB and Ballard (2020), the PEMFC has a higher efficiency than an ICE. This is given that it works in the favorable load range which is 30-80%. To ensure a favorable load range, batteries are needed to take the peak and transient loads, in addition to supporting starting and stopping. An efficiency of 60% can be expected at lower loads, while maximum loads could result in 50% efficiency. Generally, an efficiency of 55% is assumed.

The use of fuel cells in shipping is limited. According to EMSA (2017), 23 different fuel cell projects can be identified in the maritime sector. These projects are more of the study and testing nature and not of the commercial type. None of these projects cover fishing vessels.

5.3 Batteries

Batteries alone are not deemed as a viable option for ship propulsion in this thesis. This is due to a very low gravimetric and volumetric density. This results in large and heavy battery packs. In this thesis, battery packs will serve as a way of improving the power management onboard. Based on the loading condition and power requirement of the vessel the batteries are either charged or discharged, e.g. through peak shaving. A sudden increase in the loading condition would result in a discharge and a sudden decrease would result in charging. Another way of utilizing batteries onboard fishing vessels is through electrical winches. The shooting of the trawl or seine would then charge the batteries and the retrieval would use electricity from the batteries.

5.4 Technological Maturity

Based on the chosen energy converter for the different fuels, a technical maturity level can be assigned to the given converter, including all necessary components. The definitions of the technical maturity levels are adapted from DNV GL (2019). The levels go from 1-4, and are defined as follows:

1. Measures that have not been tested in full scale and no piloting or full-scale testing underway
2. Measures that are under piloting, and/or with only a few commercial applications
3. Measures that are commercially available, but not fully mature
4. Measures that are off the shelf and commonly used on new ships

Based on the maturity levels, each fuel with the specified energy converter and components can be assigned a value, see Table 5.1. LNG is commonly used as a fuel, and low-pressure dual-fuel engines are commercially available. This provides LNG with high a technical maturity. For the three other fuel solutions, the technical maturity is much lower. Mainly because low-pressure dual-fuel engines are less available for these fuels. The ICE from ABC using hydrogen is relatively new, with few reference cases to provide experience on the operation. For ammonia, Wärstila has started an R&D project concerning ammonia dual-fuel engines, with full-scale testing commencing about to start. Lastly, dual-fuel engines capable of operating on methanol already exist, but not in the sense of the low-pressure type relevant for fishing vessels. The existing types are much bigger and often two-stroke engines.

Table 5.1: Technical maturity levels for the different fuels

Fuel	Converter	Components	Maturity
LNG	ICE Low-Pressure Dual-Fuel	Engine Storage tank Process system Batteries	4
Hydrogen	ICE Low-Pressure Dual-Fuel	Engine Storage tank Process system Batteries	1-2
Ammonia	ICE Low-Pressure Dual-Fuel	Engine Storage tank Process system NO_x reduction system Batteries	1-2
Methanol	ICE Low-Pressure Dual-Fuel	Engine Process system NO_x reduction system Batteries	1-2

Chapter 6

Rules and Regulations

IMO is responsible for regulating all use of fuels through the International Convention for the Safety of Life at Sea (SOLAS). This convention covers conventional fuels in a good manner based on decades of experience. Alternative fuels often have a lower flashpoint compared to conventional fuels and to better cover them in SOLAS, the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code) was implemented in 2015. With Classification Societies being more independent compared to IMO, they have a tendency of having a faster development of new rules (Green Shipping Programme et al. (2021)). If these developed rules are specific design requirements and not covered by the IGF Code, a Flag Administration may accept the new rules making the alternative design process less complicated. The new rules developed by the Class Societies may also serve as a basis when IMO is to develop international regulations.

6.1 The IGF Code

The IGF Code was implemented to provide an international standard for ships, other than gas carriers, operating with gas or low-flashpoint liquid as fuel (IMO (2015)). This standard requires that the level of safety, reliability, and dependability achieved by new systems, main and auxiliary machinery should be equal to or better than the level achieved by conventional fuelled systems, main and auxiliary machinery (Green Shipping Programme et al. (2021)).

The functional requirements are more general and applicable for all fuel types covered by the Code. LNG is the only fuel covered by specific design requirements. The design for other low-flashpoint fuels must follow the alternative design approach, also known as the risk-based approval process, to demonstrate that it complies with the general functional requirements in the IGF Code. The team conducting the risk assessment should include subject matter experts and a facilitator with no vested interest in the fuel system (IACS (2016b)). The process will often include a workshop and the writing of a report. This means it can be a time-consuming process with a high degree of uncertainty, making it a barrier against the expansion of alternative fuels.

Chapter 7

Safety

Most chemicals come with a potentially negative effect on both the environment and human health. With the use of chemicals being spread around the world, it is important to have some sort of regulation and safety framework. Alternative fuels often have a different safety picture compared to more traditional marine fuels. This makes the implementation more challenging and is one of the bigger barriers to overcome in the transition to alternative fuels.

To better understand the risks related to the different fuels, Safety Data Sheets (SDS) are used. All SDSs follow the safety standard Globally Harmonized System of Classification and Labelling of Chemicals (GHS). GHS has been developed over a decade with different countries, organizations, and stakeholders involved in the process. The GHS includes criteria for classifying chemicals according to hazard statements. The part of the SDS that covers hazards and precautionary statements is most interesting for this thesis, see Table 7.1 for the hazard statements for the assessed fuels. In the statement code, the letter H stands for hazard statement. The first number is designated to the type of hazard statement. 2 is for physical hazards, 3 for health hazards, and 4 for environmental hazards.

These hazards impose safety requirements and the bowtie diagram in Figure 7.1 illustrates that the fulfillment of one single safety requirement could prevent an accident on several levels (Jafarzadeh et al. (2017)). The safety requirements could prevent accidents that are not sequential and with different causes. An example of a critical event could be leakage and the consequences of this could be fire or explosion.

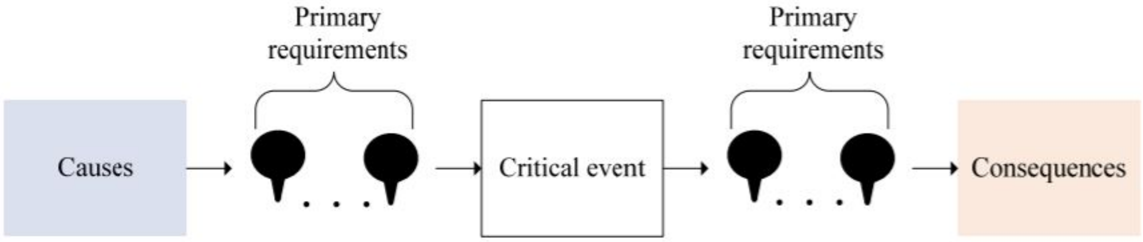

Figure 7.1: Bowtie diagram (Jafarzadeh et al. (2017))

Table 7.1: Safety Data Sheets; Hazards Identification

Code	Physical Hazard Statement	MDO Merck (2020b)	LNG PGW (2015)	Hydrogen Linde (2020)	Ammonia Merck (2020a)	Methanol Merck (2020c)
H220	Extremely flammable gas		X	X		
H221	Flammable gas				X	
H225	Highly flammable liquid and vapor					X
H226	Flammable liquid and vapor	X				
H280	Contains gas under pressure; may explode if heated			X*	X**	
H281	Contains refrigerated gas; may cause cryogenic burns or injury		X	X**		
H301	Toxic if swallowed					X
H304	May be fatal if swallowed and enters airways	X				
H311	Toxic in contact with skin					X
H314	Causes severe skin burns and eye damage				X	
H315	Causes skin irritation	X				
H331	Toxic if inhaled				X	X
H332	Harmful if inhaled	X				
H351	Suspected of causing cancer	X				
H370	Causes damage to organs					X
H373	May cause damage to the organs through prolonged or repeated exposure	X				
H410	Very toxic to aquatic life with long lasting effects				X	
H411	Toxic to aquatic life with long lasting effects	X				

*compressed gas, **liquefied gas

7.1 LNG

The LNG industry, including LNG carriers, has an excellent safety record (Mokhatab et al. (2014)), however fishing vessels and fishermen have no experience with handling LNG (Jafarzadeh et al. (2017)). Being a fisherman is classified as Norway's most dangerous occupation with a very high fatality rate compared to the offshore industry (Lindøe (2007)). According to McGuinness et al. (2013), the main contributors to this high fatality rate are vessel accidents and man overboard. It is important that switching to LNG does not increase an already high fatality rate. To prevent this, safety must be built into both the design and the operational control.

From Table 7.1 it can be seen that LNG is extremely flammable and can therefore be ignited by almost anything causing heat, sparks, flames, or static electricity. The vapor is capable of traveling great distances to a source of ignition where it can either ignite, flash back, or explode (PGW (2015)). This makes avoiding leaks extremely important, but also detection and isolation should a leak occur. It can also be seen that LNG can cause cryogenic burns which is another reason to avoid leakage. The cryogenic state of the LNG may also cause metals and other materials subject to embrittlement and fracture (Mokhatab et al. (2014)). Some supplementary hazard information not covered by the general hazard statements in Table 7.1 (PGW (2015)); high concentrations of LNG vapors may displace oxygen, LNG vapor does not possess the characteristic smell of natural gas and pressurized LNG containers may explode if heated.

Based on the IGF Code and DNV GL rules, the specific design requirements focus mainly on managing different leakage scenarios. Green Shipping Programme et al. (2021) summarizes the safety barriers as follows:

- Segregation: Protect fuel installation from external events like collisions or groundings, external fires, cargo handling, or other ship operations.
- Double barriers: Protect ship against leakages. In practice, this could be specially designed spaces like the tank connection space or the fuel preparation room and double piping arrangement.
- Leakage detection: Give warning and enable automatic safety actions when a leakage is detected. The detection method often includes gas detection, low temperature measurement, and changes in pressure and temperature.
- Automatic isolation of leakages: Reduce the consequence of a leakage. This requires several isolation devices in the system.

7.2 Hydrogen

Hydrogen possesses some of the same characteristics as LNG when liquefied. Based on Table 7.1, it is an extremely flammable gas that may explode if heated and in compressed form and may cause cryogenic burns, embrittlement, and fractures when in liquid form. Some supplementary hazard information about liquid hydrogen (Linde (2020)); may displace oxygen and cause rapid suffocation, burns with an invisible flame, and may form explosive mixtures with air. Being stored much colder in liquid form compared to the temperature of LNG, it may be even more important to avoid leakage of liquid hydrogen.

Vogler and Würsig (2009) mention the single failure criterion as the main criterion applied in general when assessing safety. The single failure criterion is defined as one single failure should not lead to a dangerous situation alone. This principle is implemented in the specific design requirements for LNG previously presented. Based on Vogler and Würsig (2009) some safety barriers that must be met can be summarized as follows:

- Double barriers: Contain a possible leak. Important for gas supply lines and other sources of fuels.
- Separation of systems: Safe areas should be gas-tight and separated from possible hazardous areas in general. For gas systems the separation could be double-block-bleed valve configuration, fire insulation could secure separation of rooms from fire loads, and separate independent ventilation systems for the ventilation airflow. Separation of systems also means separating the fuel system to different rooms like e.g. the tank room and machinery room.
- Safe venting: Any leakages should be vented out of the ship to prevent dangerous situations. The arrangement of such venting is important to achieve a sufficient safety distance from operations on deck.
- Explosion protection: All areas where flammable gasses can occur must meet necessary explosion protection measures; prevention of explosive atmosphere, prevention of ignition sources, and reduction of explosive effects.
- Protection of high-pressure storage vessel: Avoid rupture of the pressure vessel through active systems like combined fire detection and extinguishing system and passive systems like safety valves.
- Protection from external influences: The fuel system should be protected against damages from collisions, groundings, mechanical damage, and fires.

7.3 Ammonia

Ammonia differs some from LNG and hydrogen when it comes to the related hazards. In Table 7.1 it can be seen that ammonia is a flammable gas, but the main hazard is toxicity. The explosion hazard is lower than for LNG and hydrogen, but should not be ignored. Ammonia can, however, be lethal in much smaller concentrations than the flammability range of where ammonia vapors become flammable (Green Shipping Programme et al. (2021)). The exposure limit for humans is a function of both concentrations and exposure time, see Table 7.2.

Table 7.2: Acute Exposure Guideline Levels (ppm) for Ammonia (EPA (2016))

	10 min	30 min	60 min	4 h	8 h
AEGL 1	30	30	30	30	30
AEGL 2	220	220	160	110	110
AEGL 3	2700	1600	1100	550	390
AEGL 1 - Notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure. *AEGL 2 - Irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.* *AEGL 3 - Life-threatening health effects or death*					

Ammonia or anhydrous ammonia as it is called in its pure form is hygroscopic. This means that it attracts water from the surroundings when released. This puts our eyes, skin, and lungs at high risk because of high moisture content. Because of the low boiling point, it freezes on skin contact at room temperature causing chemical burns (Green Shipping Programme et al. (2021)).

The safety principles described for LNG are suitable guidance for developing safety requirements for ammonia (Green Shipping Programme et al. (2021));

- Segregation: Protect fuel installation from external events like collisions or groundings, external fires, cargo handling, or other ship operations.
- Double barriers: Protect against leakages due to toxicity and explosion risk. Important with an arrangement that makes it possible to handle possible leakages safely.
- Leakage detection: Very important to detect both gas and liquid leaks from the fuel system even at low concentrations because ammonia is a lethal toxin.
- Automatic isolation of leakages: Limit the consequences of a possible leak. This could be through venting and gas-tight rooms.

7.4 Methanol

Similar to the other fuels assessed in this thesis, methanol is a low flashpoint fuel and is a highly flammable liquid and vapor (Merck (2020c)). It also has a quite wide explosion range from 6.7% to 35% proportion of air to methanol (Andersson and Salazar (2015)). This means it can vaporize and form highly flammable vapor clouds at relatively low temperatures. With a boiling point of 65 °C, it is important to avoid such high temperatures in the storage holds to limit evaporation and thus limiting unnecessary operational discharges. According to IACS (2016a), machinery and electrical installations should be designed to operate at ambient temperatures ranging from 0 to 45 °, meaning vaporization should not be a major problem in the machinery room.

According to Merck (2020c), it is also toxic to both swallow and inhale. This and the explosion risk makes the prevention of leaks important to address in the safety assessment. Apart from the low flashpoint, it is however very similar to MDO; it is liquid at ambient temperature and pressure, meaning it can be stored in standard storage tanks with a few modifications. Thus much of the best practice related to the use of MDO could be used for methanol (Andersson and Salazar (2015)). Similar to ammonia, the vapors are very toxic and the venting arrangement should be carefully assessed to ensure safe operations for personnel on deck.

Chapter 8

Impact on Ship Design

Before assessing the impact the different fuel solutions will have on the design, the fuel system configurations must be defined. Fuel cells are deemed not viable for fishing vessels because of the wide operational area and somewhat unpredictable operational pattern. The dual-fuel engine provides flexibility which is crucial while the infrastructure for bunkering is underdeveloped.

Table 8.1: Selected fuel technology configurations

Fuel	Fuel System Components
LNG	Low-Pressure Dual-Fuel Engine Cryogenic Storage Tank Fuel Processing System NO_x Reduction System Battery Pack
Hydrogen	Low-Pressure Dual-Fuel Engine Cryogenic Storage Tank Fuel Processing System NO_x Reduction System Battery Pack
Ammonia	Low-Pressure Dual-Fuel Engine Cryogenic Storage Tank Fuel Processing System NO_x Reduction System Battery Pack
Methanol	Low-Pressure Dual-Fuel Engine Fuel Processing System NO_x Reduction System Battery Pack

8.1 Length Extension

Fishing vessels are in general very compact designed with a lot of equipment. Thus the implementation of a cryogenic storage tank would require a length extension if the same RSW capacity is to be kept. For a given amount of energy capacity in the tank, the extension will be different for the fuels because of the difference in energy density. Due to a lower storage temperature for liquid hydrogen, the storage tank may require heavier insulation compared to the LNG tank and therefore take up more space. Figure 12.7 illustrates how the placement of the tank is intended between the RSW holds.

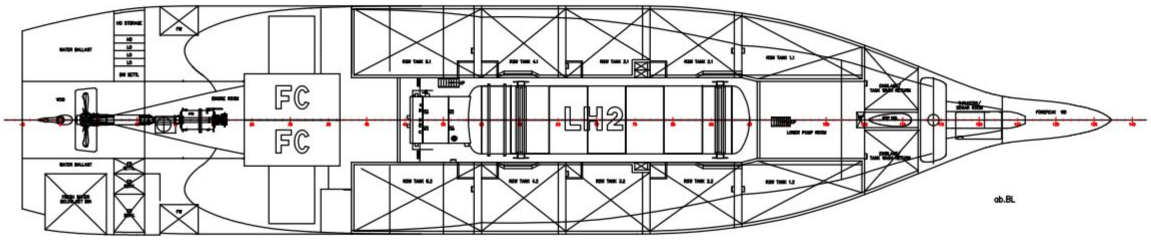

Figure 8.1: Illustration of the tank placement. Retrieved from Thorkildsen (2019)

8.2 Separation of Systems

It is required to separate the fuel storage room from the engine room (Vogler and Würsig (2009)). In addition to these rooms, there should be arranged a tank connection space (TCS) and a fuel preparation room (FPR), where double-walled piping is not practical. These spaces must be gas-tight to prevent possible leaks to reach other areas in the ship. The IGF Code specifies that the access point to the TCS should be through a bolted hatch for LNG.

8.3 Fuel Storage

Segregation is important to protect the fuel installation from external events. Following, the placement of the tank should be carefully assessed. The specific design requirements for LNG in the IGF Code specifies that the tank should be placed at a minimum distance of B/5 or 11.5 meters from the ship side and a minimum of B/15 or 2 meters over the bottom shell plating (IMO (2015)). These requirements are considered a relevant reference for both ammonia (Green Shipping Programme et al. (2021)) and hydrogen (Steinshamn (2019)). Methanol can be stored in conventional tanks with some minor tweaks, making standard rules for MDO a good reference.

8.4 Fuel Supply

All four fuels assessed are low-flashpoint fuels, and some toxic, which makes it important to avoid leaks. Therefore all primary fuel piping should fulfill the double barrier principle. This could be through double-walled piping, a gas pipe within a ventilation duct or a location in a tank connection space or a fuel preparation room (Vogler and Würsig (2009), Green Shipping Programme et al. (2021)).

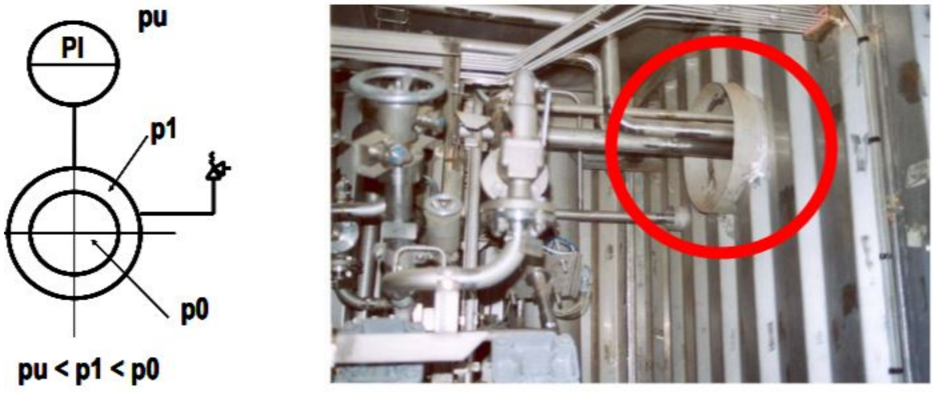

Figure 8.2: Examples of double barriers (Vogler and Würsig (2009))

This is required for methane pipes in the IGF Code and is considered relevant for the three other fuels in this thesis. This applies to the engine room as well where double-walled piping would be most relevant.

8.5 Ventilation

It is crucial with a good ventilation arrangement for potential leakage points, e.g. the TCS and FPR, to remove potential leaks and create an under-pressure in the spaces. Assessing the ventilation outlet placement is important to lower the risk of personnel exposure and the spreading of the discharged vapors to other ship spaces. All four fuels pose an explosion risk to some degree, but ammonia and methanol are classified as toxic to inhale making it even more important for them. The ventilation fans have to run constantly if the ventilation system is to work as a safety barrier. This establishes another criterion for the inlets and outlets to be placed at a height where the Load Line Convention does not require watertight devices (Green Shipping Programme et al. (2021)). It is also important with dedicated ventilation ducts for the ventilation of fuel leakages to prevent spreading to other spaces in the ship.

The IGF Code requires mechanically venting of the secondary enclosure in the double-walled piping for methane pipes. Thus every segregated methane pipe segment must have a dedicated ventilation inlet and outlet ducts and a fan.

Chapter 9

Emissions

The emissions assessed in this project can be divided into two groups, Greenhouse gases and Local pollutants based on the environmental effect they possess. Based on the emissions of GHGs, the fuels can be divided into color-codes based on their environmental performance. Grey fuels are fossil-based fuels. Blue fuels are often fossil-based fuels with emission reduction measure applied, e.g. Carbon Capture and Storage (CCS). Green fuels, or e-fuels, are fuels produced with renewable sources and energy.

9.1 Greenhouse Gases

As previously stated, the emission of greenhouse gases is important to reduce to tackle global warming. This is because they absorb energy and limits the amount of energy escaping from the atmosphere to space, making the atmosphere warmer. The three most common GHGs are CO_2, CH_4 and N_2O. A viable future fuel must be able to reduce these emissions both upstream and downstream in its life-cycle. The emission of these GHGs will have a different impact on the environment based on two factors according to the United States Environmental Protection Agency (EPA (N.D.)): how much energy the gas is able to absorb and how long it stays in the atmosphere.

9.2 Local Pollutants

The local pollutants do not contribute to global warming in the same manner as the greenhouse gases but are still harmful to the environment. In addition, they can be harmful to human health. The most common local pollutants are SO_x, NO_x, and PM. Both SO_x and NO_x can lead to acid rain, while NO_x also can lead to the formation of smog and tropospheric ozone (Ushakov and Li (2017)). PM affects the climate but also affects human health in the form of cardiovascular and pulmonary systems (Ushakov and Li (2017)). These emissions are regulated by IMO through the International Convention for the Prevention of Pollution from Ships (MARPOL).

The emission of NO_x is regulated based on emission value limits, g NO_x/kWh, which varies for different engine speeds. The maximum emission values are in addition divided into different Tiers dependent on construction date and operation area, see Table 9.1 where n denotes engine speed. For this thesis, engines with a speed range of around 750-1000 rpm are most relevant. The resulting Tier II and Tier III emission limits for an engine speed of 1000 rpm are then respectively 8.99 g/kWh and 1.84 g/kWh.

Table 9.1: NO_x emission limits, g/kWh (Trozzi and Lauretius (2020))

Tier	Ship Construction Date	$n < 130$	$130 \leq n < 2000$	$n \geq 2000$
I	1 January 2000	17.0	$45 \cdot n^{-0.2}$	9.8
II	1 January 2011	14.4	$44 \cdot n^{-0.23}$	7.7
III	1 January 2016*	3.4	$9 \cdot n^{-0.2}$	1.96

* in NO_x ECA. Tier II standards apply in open water outside ECA.

9.3 Life Cycle Inventory

In order to calculate the emissions both upstream and downstream for a given fishery, a Life Cycle Inventory (LCI) must be established for the different fuels. It is common to define an LCI while performing a Life Cycle Analysis (LCA) of e.g. different fuels. The scope of this thesis does not cover performing an LCA and therefore existing LCAs will be used when establishing the LCI. Defining the LCI based on different LCAs is a sub-optimal solution, but ammonia and methanol produced in a renewable way is poorly covered when it comes to LCAs. The LCI is to cover the emission of CH_4, N_2O, SO_x, NO_x, PM, and CO_2. The fuel emission factors are defined as g/kWh, seeTable 9.2.

Table 9.2: LCI: emission values defined as g/kWh (Gilbert et al. (2018), Al-Breiki and Bicer (2021), Singh et al. (2018))

	CH_4		**N_2O**		**CO_2**		**SO_x**		**NO_x**		**PM**	
	Oper.	Prod.	Oper.	Prod.	Oper.	Prod.	Oper.	Prod.	Oper.	Prod.	Oper.	Prod.
MDO	0.01	0.64	0.03	0.00	524	56	0.32	0.35	14.8	0.2	0.16	0.02
MDO w/SCR	0.01	0.64	0.03	0.00	524	56	0.32	0.35	2.22*	0.2	0.16	0.02
LNG	3.00	0.35	0.02	0.02	412	46	0.00	0.16	1.19	0.11	0.03	0.00
NG-LH_2	0.00	1.76	0.00	0.04	0.00	926	0.00	0.87	0.00	0.96	0.00	0.14
E-LH_2	0.00	0.41	0.00	0.01	0.00	98	0.00	1.15	0.00	0.98	0.00	0.06
NG-NH_3	0.0008	1.76	0.007	0.0037	0.00	587	0.00	0.35	0.12	0.32	0.001	0.05
E-NH_3	0.0008	0.41	0.007	0.01	0.00	96	0.00	0.43	0.12	0.32	0.001	0.06
NG-MeOH	0.00	0.53	0.00	0.02	522	358	0.00	0.00	0.46*	0.39	0.00	0.00
E-MeOH	0.00	0.41	0.00	0.01	0.00	100	0.00	0.43	0.46*	0.32	0.00	0.06

**Assumed SCR-efficiency of 85%*

9.3.1 MDO

The emission values for MDO are based on the LCA study Gilbert et al. (2018) and serves as a reference. The system in the LCA is defined to cover the production steps of crude oil, pre-treatment, refining, and hydrocracking. It is then transported on tankers to central hubs. In the LCA, it is assumed combusted in a slow-speed diesel engine. No difference is considered between a slow-speed diesel engine and a medium-speed diesel engine in this thesis. For the MDO with SCR technology, the efficiency is assumed to be 85%. This does not bring the NO_x emission value below the Tier III limit calculated for the type of engines used for this thesis. The assumed SCR-efficiency of 85% is, however, kept as a conservative assumption.

9.3.2 LNG

Emission values for LNG are based on the LCA study Gilbert et al. (2018). The system is defined to include natural gas drilling and extraction, both offshore and onshore in Europe. The data covers desulphurization and water removal, dedicated processing, and separation. It also includes liquefaction and cryogenic transport of 460 km. During ship operations, the LNG is combusted in a spark-ignition gas engine. For the LCI, it is assumed no difference between the combustion of LNG in a spark-ignition gas engine and a low-pressure dual-fuel engine.

9.3.3 Liquid Hydrogen

Emission values for liquid hydrogen are based on the LCA study Gilbert et al. (2018). All the steps including liquefaction defined for LNG are the same for Hydrogen. In addition, data for steam reforming of the natural gas, purification, carbon capture and storage (CCS), and transportation in a cryogenic truck for 50 km are included. It is utilized in a fuel cell in the LCA. It is assumed that the emissions for hydrogen are the same when utilized in a dual fuel ICE and that the pilot fuel (MDO) is responsible for the emissions. It is unclear from the LCA if this can be classified as blue hydrogen based on the CCS, or if it is somewhere inbetween grey and blue.

9.3.4 Green Liquid Hydrogen

Emission values for renewable liquid hydrogen are based on the LCA study Gilbert et al. (2018). It covers production by mean wind-powered electrolysis. Data for the embodied emissions of the electricity generation from wind and standard storage requirements for conventional H_2 production is included. It is utilized in a fuel cell in the LCA. It is assumed that the emissions for hydrogen is the same per kWh when utilized in a dual-fuel ICE, and that the pilot fuel (MDO) is responsible for the emissions.

9.3.5 Ammonia

The emission values for ammonia are based on two different LCAs and some assumptions. This is because none of the LCAs covers all six emissions to be assessed. All emissions during operation and emissions of N_2O, SO_x, NO_x, and PM during production are based on the LCA Al-Breiki and Bicer (2021). Here natural gas is used as the primary feedstock. Emissions from recovering, processing, and transportation in a pipeline of natural gas are accounted for. The defined production pathway for this study is by reforming natural gas through the Haber-Bosch process. The study also covers transportation of the produced fuels for 5000 nautical miles, but these emissions are subtracted for this project. The CO_2 emissions during production are based on Singh et al. (2018). Lastly, the CH_4 emissions during production are assumed to be equal to the production of LH_2 from natural gas.

9.3.6 Green Ammonia

The emissions during operation are assumed to be equal to those defined for ammonia by Al-Breiki and Bicer (2021). Emissions of CO_2 and SO_x during production are retrieved from Singh et al. (2018). The value is calculated for ammonia production from wind-based electrolysis of water and cryogenic air separation. The rest of the values are assumed to be equal to renewable LH_2, as no source is found for these values.

9.3.7 Methanol

Emission values for methanol are based on the LCA study Gilbert et al. (2018). The main processes included are equal to the process steps for LNG up until liquefaction. The other main processing steps covered by the LCA are steam reforming, methanol synthesis, and purification/distillation. Storage is assumed to be equal to refined petroleum, with no long-distance transportation considered. The methanol is combusted in a medium-to-fast speed diesel engine converted to a dual fuel engine in the LCA. Initially, the emissions of NO_x during operation were 3.05 g/kWh. This is higher than Tier III limits, so NO_x-reduction measures are assumed applied with an efficiency of 85%.

9.3.8 Green Methanol

The emission values for renewable methanol are solely based on assumptions as no proper LCA has been found. The emission values during operation are assumed equal to those defined for natural gas based methanol, except the CO_2 emissions which is particularly hard to define. There are different schools of thought regarding net emissions. If the CO_2 provided to the syngas process is captured emissions from other industries, you are better off reusing these emissions one time producing methanol, before finally releasing it through the combustion of the methanol compared to just releasing it from the industry. If the CO_2, however, could be captured and stored through CCS, it would be better from an environmental perspective. The business aspect of it also gives industries an incentive to keep on producing CO_2 to sell for E-MeOH production instead of reducing their own emissions. It is therefore assumed that E-MeOH production utilizes CO_2-capture from the atmosphere in this thesis. This makes the emissions of CO_2 during operation zero. The method of capturing CO_2 from the atmosphere is not fully matured and commercialized yet but assumed applied for this thesis based on the challenging process of defining net emissions from Carbon Capture and Utilization (CCU). For the production emissions, it is assumed that the emissions, other than CO_2, are equal to those during the production of renewable ammonia. Renewable ammonia has a similar process to methanol, where hydrogen must be produced through electrolysis from water and mixed with a gas captured from the atmosphere. The emissions of CO_2 during production is estimated in Appendix A.

Chapter 10

Case Study

The case study shall cover how the implementation of alternative fuels affects different parameters of the fishing vessel and how this ultimately influences both the environmental and economical performance. To perform some of the analyses in the case study, a general operation pattern over the course of a year will be defined. It is assumed that this operation pattern will be equal every year. The environmental performance is assessed for this general year, while the economy aspects over the anticipated lifetime of the vessel before selling it. The case study will be a single instrumental case study, but the outcome of the case study can be applied to similar fishing vessels in general.

The following case study is based on Harvest, designed by Wärtsila and owned by Hardhaus AS. It is a purse seiner/pelagic trawler participating in many relevant fisheries. The system boundaries for the case study are as follows; technical, environmental, and economic aspects of the alternative marine fuels compared to that of a conventional fishing vessel. The technical is to cover the major and relevant components and resulting design consideration for the ship length. The environmental performance covers the total life cycle of the fuel from extraction to combustion, i.e. both upstream and downstream. For the economic aspect, it is to address the extra capital costs, operational costs, and voyage-related costs based on a general year of operation. Based on this the Life Cycle Cost of the vessel can be estimated. Additionally, the fuel price necessary to break even after 10 years is to be assessed for the different fuel solutions.

10.1 Vessel Characteristics

The characteristics of *Harvest* can be found in Table 10.1. The vessel was delivered in 2014 with a main engine from Wärtsila and two auxiliary engines from Caterpillar.

Table 10.1: Vessel Characteristics

Characteristics	**Value**	**Unit**
Length over all	67.00	m
Breadth moulded	14.80	m
Depth	9.00	m
Main engine	4000	kW
Aux. engine	2x683	kW
RSW capacity	1830	m3
MDO tank capacity	460	m3

Through communication with the owner of Harvest, some additional information about the vessel was retrieved. LNG was investigated as a solution when designing the vessel but was deemed not profitable. In regards to bunkering intervals, the vessel always refuels after fishing for Blue Whiting. This is the most demanding fishery with a duration of up to 14 days. The fishery takes place west of Ireland around February/March. It is not unusual to wait several days on the weather during this fishery. Because of this, it is often set as required duration capacity when designing a fishing vessel. When fishing in the North Sea they can go several trips without refueling diesel.

The different species-specific fisheries with the respective quotas accounted for in this thesis can be found in Table 10.2.

Table 10.2: Harvest's quotas in tonnes

Species	Quota	Unit
Blue Whiting	2700	tonne
Mackerel	962	tonne
NSS Herring	3816	tonne
North Sea Herring	1287	tonne
Sandeel	13000	tonne

10.2 Operational Profile

During the design of a vessel, an operational profile is often developed to map the required power for both propulsion and equipment, and the time spent in the different modes. The operational profile in Table 10.3 was developed in the design process of the vessel but should be somewhat correct compared to the operation today, with some variation due to quota variations and weather.

Table 10.3: Operational Profile

Mode	**Percentage**	**Days**	**Propulsion Load [kW]**	**Equipment Load [kW]**
Searching	12%	30	1000	500
Steaming	51%	130	1700	400
Trawling Norway Pout	9%	20	1500	600
Trawling Blue Whiting	9%	20	2600	900
Trawling Sandeel	5%	15	2000	500
Purse Seining	5%	15	1700	1000
Unloading	4%	10		500
Harbour	5%	15		300

From Table 10.3, it can be seen that the trawling operation for blue whiting is the most power demanding, but steaming at around 14 knots is the most time-consuming mode. Figure 10.1 illustrates the operation profile graphical.

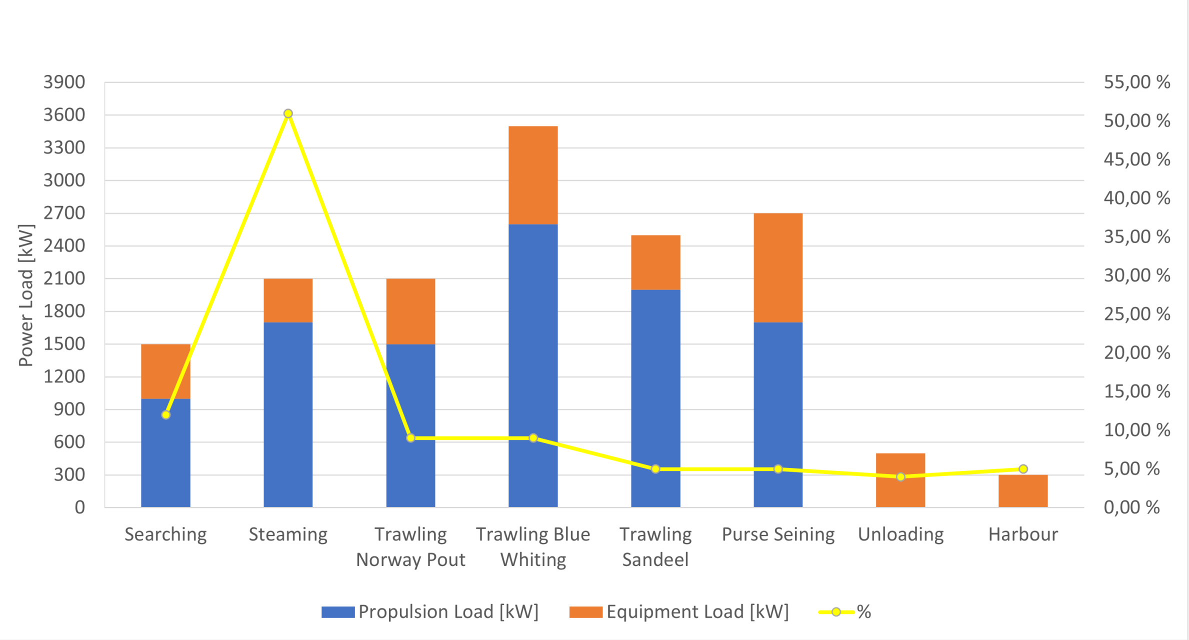

Figure 10.1: Graphic representation of the operational profile

It is possible to estimate the power consumption and thus the estimated fuel consumption for any given duration of the operation, based on the operational profile. By multiplying the power consumption with the time percentage for every mode and summarizing them, you get an average power consumption per hour. To get the power consumption per day, you multiply it by 24 hours, see Table 10.4.

Table 10.4: Estimated power demand

Mode	Propulsion Load [kW]	Equipment Load [kW]	Total Average [kW]	Total per Day [kWh/day]
Searching	120	60	2050	49200
Steaming	867	204		
Trawling Norway Pout	135	54		
Trawling Blue Whiting	234	81		
Trawling Sandeel	100	25		
Purse Seining	85	50		
Unloading		20		
Harbour		15		

After defining the average daily power demand, a general number of different trips during a normal year must be defined. The voyage statistics for Harvest during 2018 and 2019 can be found in Appendix B. Based on this, the number of fishing trips for the different species and distribution of economic zones can be defined, see Table 10.5. The economic zones are interesting because fishing vessels are only obligated to pay taxes on emissions when located in close waters, defined as 250 nautical miles from the coast (Skatteetaten (2020)). The areas defined as close waters are closely related to the Norwegian exclusive economic zones illustrated in Figure 10.2.

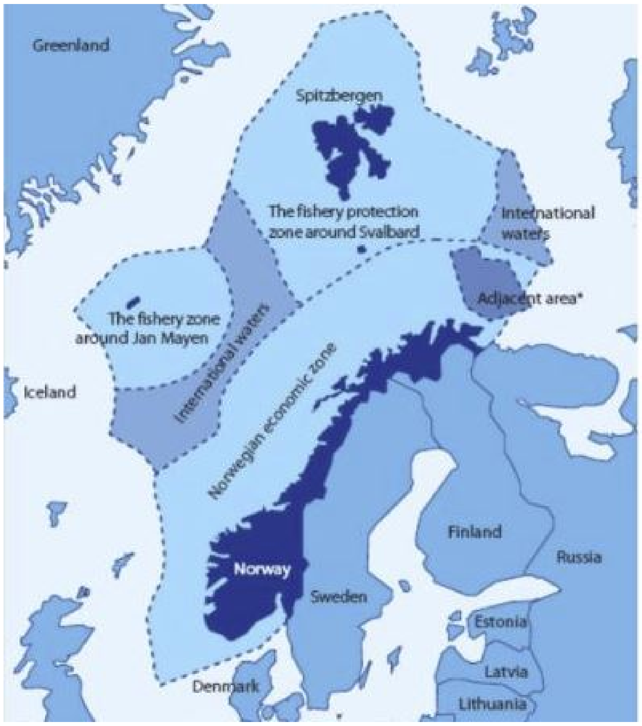

Figure 10.2: Overview of Norwegian waters (Source: http://www.fao.org/fishery/facp/nor/en)

The required duration for the closer fisheries are set to 7 days, while the duration for Blue Whiting is set to 14 days.

Table 10.5: General annual operation: Distribution of fishing trips

	Trips	**Duration [days]**	**Total Duration [days]**	**Norwegian Economical Zone**	**EU Zone**
Blue Whiting	4	14	48	0	4
Trawl	10	7	70	7	3
Purse Seine	14	7	98	8	6
Total	**28**		**224**	**15**	**13**

For the trips where the fish is landed in the EU-zone, the vessel will sail through close water both when leaving and returning. This is defined as the time it takes to sail 250 nautical miles at 14 knots. Based on this the total distribution of economical zones can be defined, see Table 10.6.

Table 10.6: Economical zone distribution based on the defined operation

Norwegian Economical Zone	EU Zone	Unit
124.3	99.7	Days
55.5	44.5	%

10.3 Extension

Based on the previously estimated daily power demand, the power demand for the different trips can be defined. For the vessel using hydrogen, it is not deemed viable to run in hydrogen mode for the entirety of the Blue Whiting trip. The ABC dual-fuel engine for hydrogen can run 100% on diesel if required, the vessel is therefore set to use hydrogen when subject to taxation in close waters and diesel when in remote waters for the Blue Whiting fishery. This is due to the required tank volume and thus large extension required for 14 days of hydrogen operation. The daily power demand for hydrogen will then be somewhat lower because the Blue Whiting trawling mode is removed from the operation profile.

Table 10.7: Power demand for the estimation of the tank size

	Hydrogen	Other	Unit
Daily power demand	45.7	49.2	MWh/day
7 days power demand	319.9	344.4	MWh
14 days power demand	-	688.8	MWh

Based on the energy amount it is possible to calculate the required tank size and by this the resulting extensions of the reference vessel. *Libas* designed by SALT, became approximately 10 meters longer by implementing the LNG tank and systems (Steinshamn, T. S. (2021)). This tank has a capacity of 350 m^3 and is 21.5 meters long. In addition to the tank, a Tank Connection Space (TCS) is required. For Libas, the TCS is 5.5 meters long and the length of the TCS is assumed to be equal for all different tank lengths, i.e. independent from tank size.

The required tank sizes can be calculated based on the required available energy and the density of the different fuels. The calculation procedure can be found in Appendix C.2.

Table 10.8: Estimated tank sizes required for the fuels when implemented in the reference vessel

	LNG	LH_2	NH_3	MeOH	MDO	Unit
Power demand	688.8	319.9	688.8	688.8	688.8	MWh
Tank Size	241	272	331	335	144	m3

Harvest has a fuel capacity of 460 m^3. Based on this, it is not needed to extend the vessel utilizing methanol, provided the tanks are fitted with a methanol-compatible coating. For the three other fuels, it is possible to estimate the length extension that follows the tank volume based on a few assumptions. By assuming the tank is equally as wide as the reference tank in Libas, it is possible to define an areal per meter of the tank in the length direction. The reference tank can then be scaled in the length direction to fit the required tank volumes.

$$\text{Areal per meter} = \frac{350m^3}{21.5m} = 16.3m^2 \tag{10.1}$$

It is then possible to derive the tank length for the different fuels by dividing the derived volume by areal per meter. E.g. for Libas, it would be performed as follows:

$$\text{Tank length} = \frac{350m^3}{16.3m^2} = 21.5m \tag{10.2}$$

Table 10.9: Resulting tank lengths

Fuel Type	LNG	LH_2	NH_3	Unit
Tank length	14.8	16.7	20.3	m
Tank+TCS	20.3	22.2	25.8	m

The length extension of the vessel based on tank length is calculated based on available volume under deck. A tank room volume of 6 meters times 6 meters times the length of tank + TCS with an additional meter is defined as the required space under deck. The idea is then that the available area from the tank top to the A-deck at midship is extruded in the length direction to fit this tank-room volume. The ship is extruded at midship, where the hull is assumed the fullest. By measuring in the General Arrangement of the reference vessel, the height is set to 7.7 meters and the breadth to 14.4 meters.

$$\Delta L = \frac{6 \cdot 6 \cdot (\text{Tank} + \text{TCS} + 1)}{7.7 \cdot 14.4} \quad [m] \tag{10.3}$$

The resulting length extensions are then:

Table 10.10: Resulting length extensions

Fuel Type	LNG	LH_2	NH_3	Unit
Length extension	6.9	7.5	8.7	m
LOA	73.9	74.5	75.7	m

10.4 Power and Fuel Consumption

By extending the reference vessel, the resistance will change in the different modes. The change is, however, challenging to define without performing a more extensive hydrodynamic analysis. When designing *Libas*, SALT investigated how an extension of the ship would affect the resistance. For the alternative that was extended 10 meters to fit the LNG system, the resistance actually decreased at higher speed and increased a bit at lower speed.

Table 10.11: Estimates of how a hull extension of 10 meter affects the resistance for different operation modes (Steinshamn, T. S. (2021))

	Difference (10 meter)
Steaming (14 kn)	-9%
Trawling	5%
Searching (9-10 kn)	0%
Purse net shooting	2%

To interpreter these results, it is crucial to know the approach and assumptions used. The estimates are based on deadweight. An extension of the hull will lead to an increase in both volume and weight. By this, the resistance can't be calculated at the same depth, but at a depth resulting in equal deadweight. A depth of 6.5 m is used for the base case and 6.2 m for the extended hull in said estimates. This results in a Block coefficient reduction of 0.014 for the extended hull, i.e. a "slimmer" hull. A more slim hull will result in lower wave resistance at higher speeds. Frictional resistance is more dominating at lower speeds but increases slowly with increasing speed. This could be the explanation for the differences in resistance.

For ammonia, the length extension is closer to 8 meters than 10, making the found differences non-applicable when defining the power consumption. It is, however, hard to assess how they can be related to vessels with shorter extensions. A simplified and conservative assumption is made for the relevant length extensions, see Table 10.12.

Table 10.12: Estimated difference in resistance due to length extensions

Extension	6 meters	8 meters
Steaming (14 kn)	-3%	-5%
Trawling	1%	3%
Searching (9-10 kn)	0%	0%
Purse net shooting	0%	1%

Based on the defined differences in resistance, the new power demands are defined in Table 10.13. The calculation can be found in Appendix D.1.

Table 10.13: New average power demands for the reference vessel implemented with the alternative fuels

Fuel Type	LNG	LH_2	NH_3	Unit
Length extension	6.9	7.5	8.7	m
Daily power demand	48 688	48 518	48 518	kW/day

With the new daily power demand defined for the extended vessels, the annual power and fuel consumption can be defined. As previously mentioned, the vessel using hydrogen will use 100% diesel when operating in remote waters during the Blue Whiting fishery and run normally on a hydrogen-diesel mix when in close waters. The Blue Whiting fishery consists of 56 days per year, where 6 of these are defined as close waters. The derivation of this number can be found in Appendix D.2. When operating in 100% diesel mode, the

SFC for MDO is used. This results in a somewhat higher pilot fuel consumption for hydrogen, which can be found in Table 10.14.

Table 10.14: Annual power and fuel consumption for the reference vessel implemented with the alternative fuels

	LNG	LH_2	NH_3	MeOH	MDO
Main fuel, SFC [kg/kWh]	0.140	0.057	0.308	0.386	0.188
Pilot fuel, SFC [kg/kWh]	0.002	0.040	0.058	0.015	-
Annual power consumption [MWh]	10,906.2	10,868.0	10,868.0	11,020.8	11,020.8
Annual main fuel consumption [tonnes]	1,530.3	482.3	3,346.4	4,254.2	2,069.6
Annual pilot fuel consumption [tonnes]	18.4	795.6	626.2	169.3	-

The SFCs are calculated based on the efficiency and distribution mix of main- and pilot fuel. The calculation can be found in Appendix C.1. Given the approach of comparing the resistance based on the same deadweight, the three extended vessels have a lower yearly power consumption compared to the reference vessel. Ammonia and liquid hydrogen have the lowest annual power consumption. The decrease is a result of the transit mode being responsible for 51% of the operation in the operational profile. During transit the vessel is defined to have a speed of 14 knots, where the wave resistance is dominating.

10.5 Life Cycle Impact Assessment

Based on the annual fuel consumption and the already defined Life Cycle Inventory (LCI) and Life Cycle Impact Method (LCIA) ReCiPe2016, the environmental performance of the different fuels can be assessed. First, the annual release of the different emissions is defined by using the annual power consumption and the LCI. It is assumed that the emissions follow the same ratio of main fuel and pilot fuel in the fuel mix. This means that the pilot fuel is included in the LCIA. Next, the modeling results must be translated to Midpoint. The characterization factors used at Midpoint for the different impact categories can be found in Table 10.15. The values are retrieved from Huijbregts et al. (2016) and are region-specific to Norway with a Hierarchist value choice when applicable.

Table 10.15: Midpoint characterization factors (Huijbregts et al. (2016))

Emission to	Substance	Impact category	Factor	Characterization factor unit
Air	CO_2	Climate change	1	kg CO_2-eq./ kg CO_2
Air	CH_4	Climate change	34	kg CO_2-eq./ kg CH_4
Air	N_2O	Climate change	298	kg CO_2-eq./ kg N_2O
Air	$PM_{2.5}$	PFMP	0.34	kg $PM_{2.5}$-eq./ kg $PM_{2.5}$
Air	NO_x	PFMP	0.06	kg $PM_{2.5}$-eq./ kg NO_x
Air	SO_x	PFMP	0.05	kg $PM_{2.5}$-eq./ kg SO_x
Air	NO_x	HOFP	1.03	kg NO_x-eq./ kg NO_x
Air	NO_x	EOFP	3.24	kg NO_x-eq./ kg NO_x
Air	NO_x	TA	0.73	kg SO_x-eq./ kg NO_x
Air	SO_x	TA	2.28	kg SO_x-eq./ kg SO_x

Starting with the impact category of Climate Change, or Global Warming Potential (GWP), the results can be found in Figure 10.3. NG-MeOH exhibits the highest GWP. NG-LH_2 has a higher GWP per kWh, but the MDO brings the GWP for LH_2 below NG-MeOH. All three e-fuels perform well with a low GWP during production. They are defined to have zero emissions of GHGs during operation, which can make the resulting GWP during operation seem a bit high. The explanation for this is the fact that all three burns diesel as a pilot fuel to some extent causing the footprint. For the production, the emissions are quite similar for the three, thus the amount of pilot fuel burned is the parameter causing different performances. E-MeOH scores better than E-NH_3 and E-LH_2 in that order.

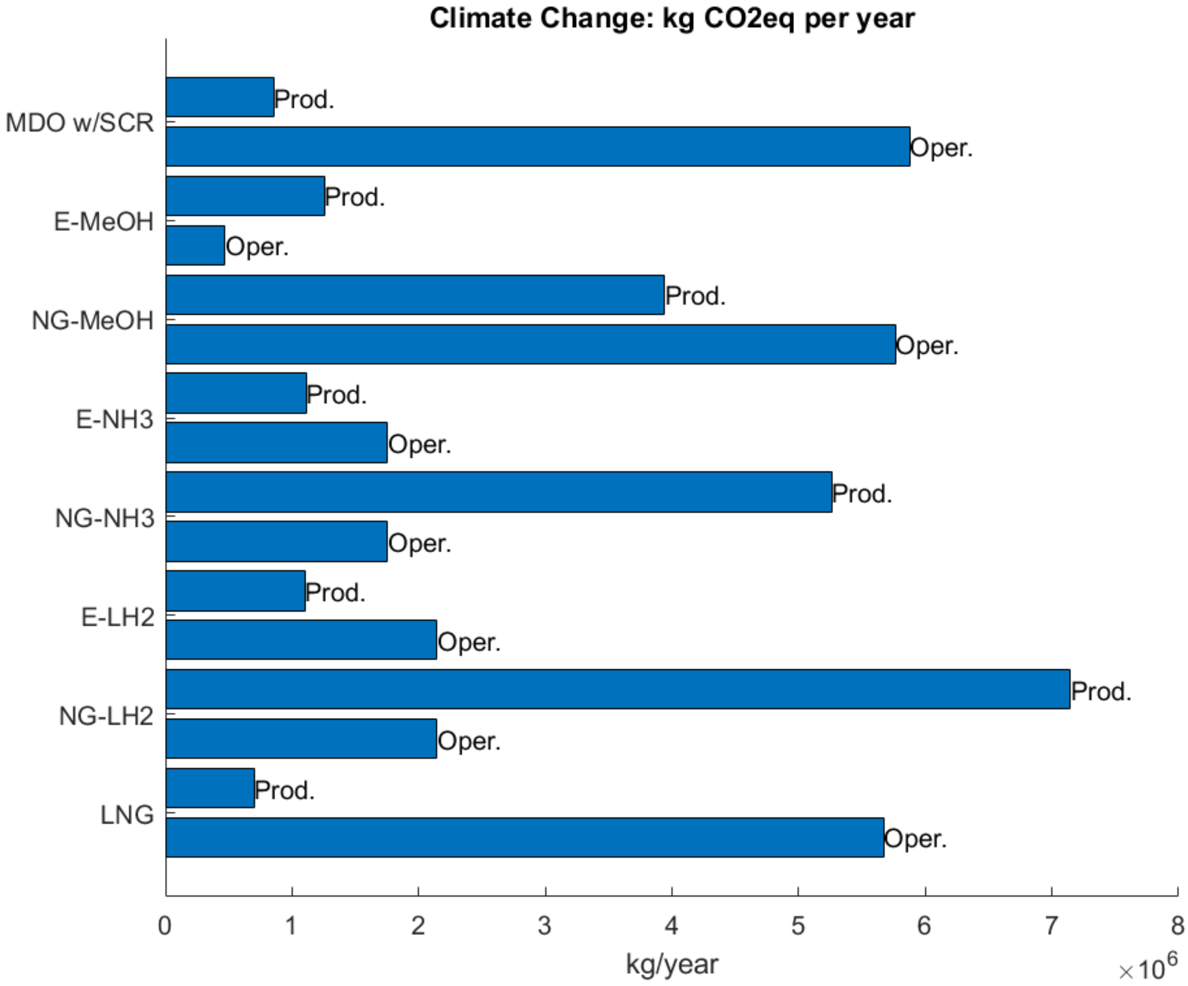

Figure 10.3: ReCiPe2016H Midpoint: Climate Change

If we are to focus purely on emissions during operation the ranking changes somewhat in the bottom. It would then be no difference between natural gas-based and green for liquid hydrogen and ammonia, while E-MeOH would still perform the best. It is important to assess the total emissions of both production and operation to find the alternatives with the best environmental performance. Focusing only on the operation part would lead to the cheapest alternative, which is the natural gas-based alternatives in most cases, to be the chosen fuel. This would only move the emissions upstream and make no impact in the big picture.

Next, the results at Midpoint for the impact category Particulate Matter Formation Potential can be found in Figure 10.4. There are no distinct patterns regarding natural gas-based and e-fuels, meaning that e-fuels do not necessarily perform better than natural gas-based for this impact category. MDO w/SCR performs the worst and NG-MeOH the best. Again, the pilot fuel worsens the performance of the e-fuel. Based on the LCI, E-NH_3 has a lower particle matter formation potential compared to LNG, but due to a high potential for MDO during operation it makes E-NH_3 perform worse than LNG.

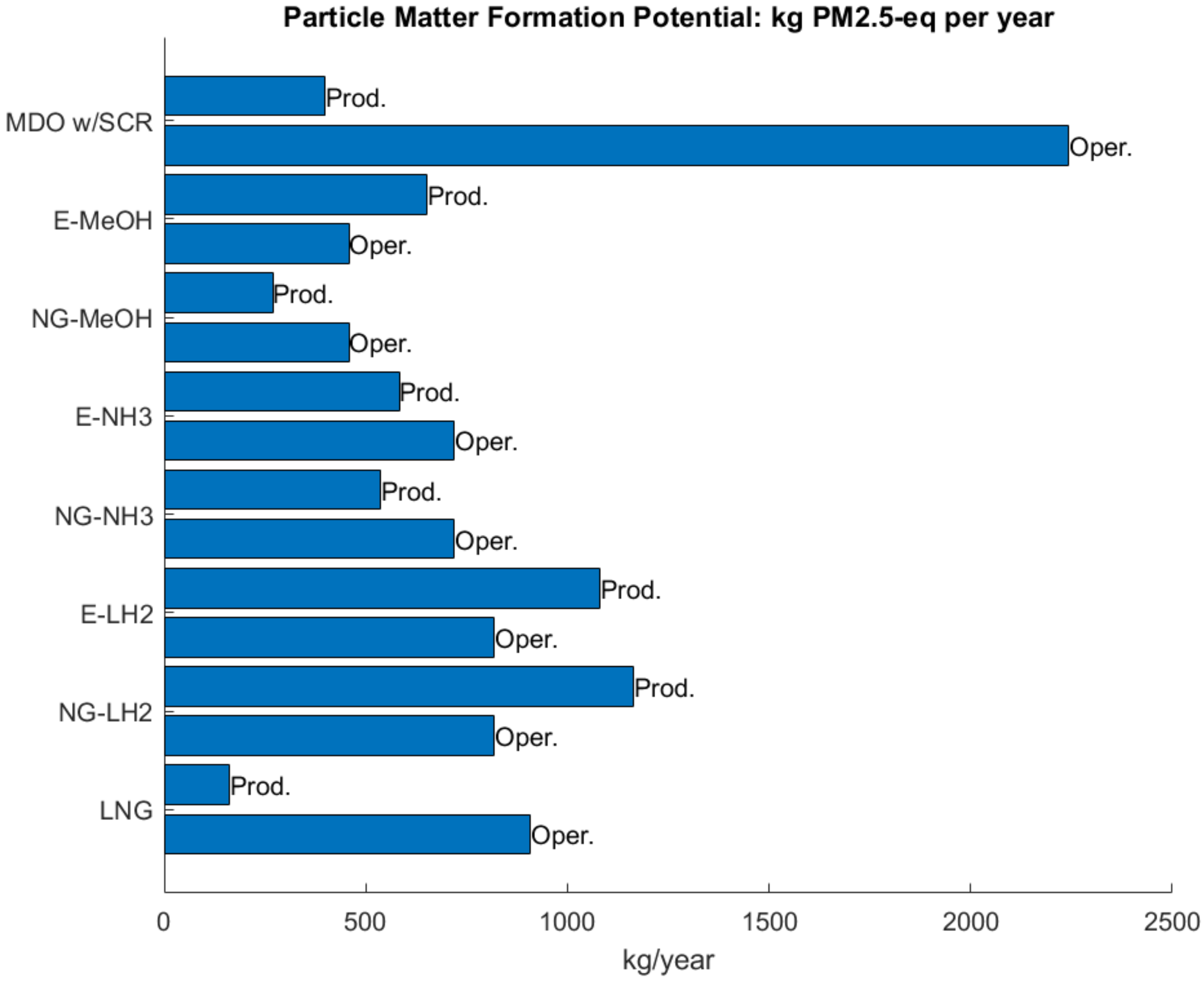

Figure 10.4: ReCiPe2016H Midpoint: Fine Particulate Matter Formation

From Figure 10.5, it can be seen that the Photochemical Ozone Formation is highest for MDO even with SCR technology applied. The biggest part of the ozone-forming emissions affects the terrestrial ecosystem, indicated by the red bars. E-MeOH and NG-MeOH perform the best. It is worth mentioning that methanol's fuel emission factor for for NO_x during operation defined in the LCI, is with SCR because the original values did not comply with Tier III standards. If the SCR was removed for methanol, both NG-MeOH and E-MeOH would perform the worst for this impact category.

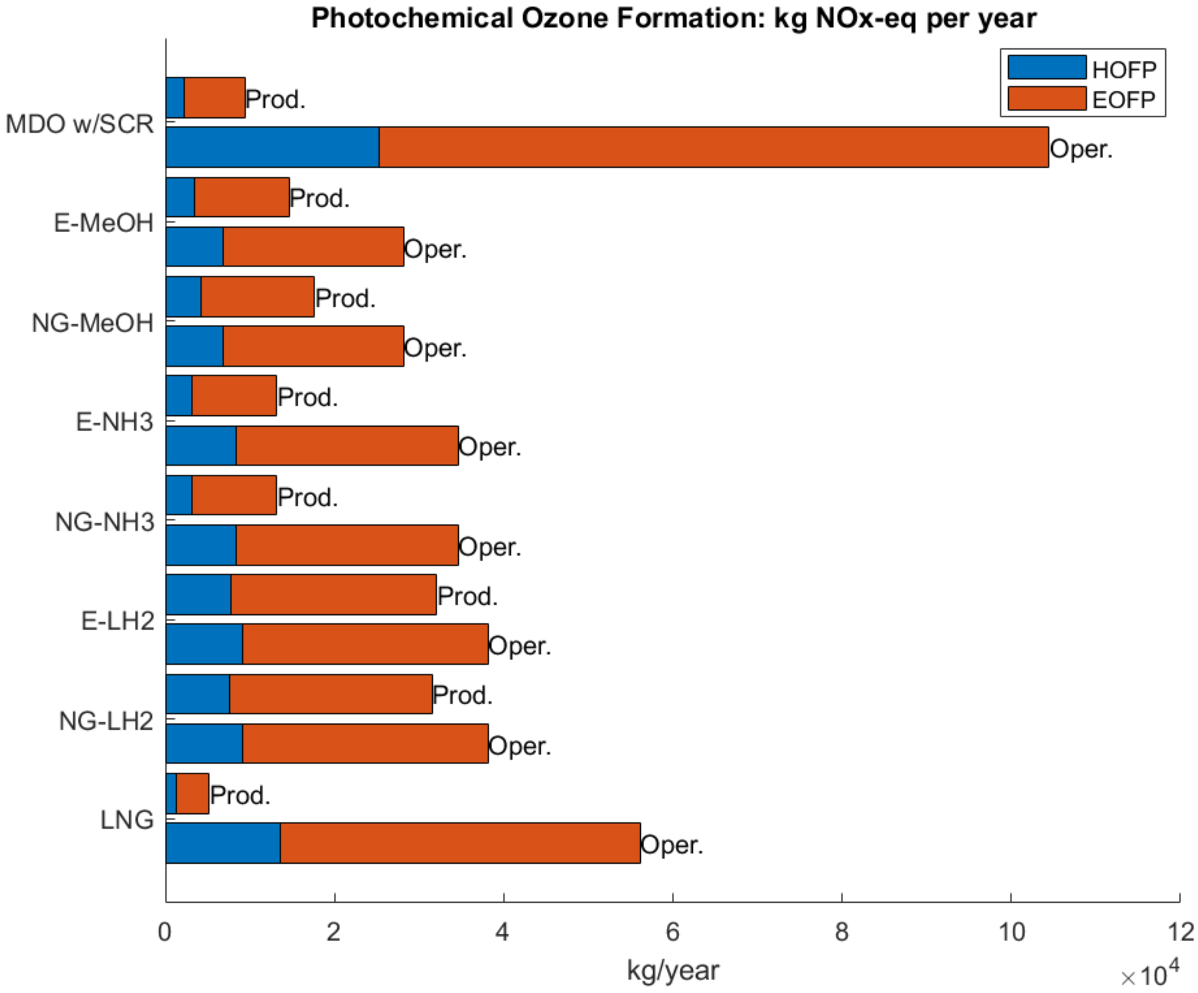

Figure 10.5: ReCiPe2016H Midpoint: Photochemical Ozone Formation

The final impact category assessed at Midpoint is Terrestrial Acidification, see Figure 10.6. For this category, emissions of SO_x highly impacts the result while NO_x impacts it to a certain extent. None of the alternative fuels have emissions of SO_x during operation. LH_2 is the only fuel not having emissions of NO_x during operation. MDO w/SCR performs the worst again, followed by NG-LH_2. Ammonia, both natural gas-based and green, has a lower TA potential than LNG solely based on the LCI. However, as has been the case for several of the impact categories, the implementation of pilot fuel in the LCIA makes LNG perform better than both NG-NH_3 and E-NH_3. NG-MeOH has the lowest total TA potential.

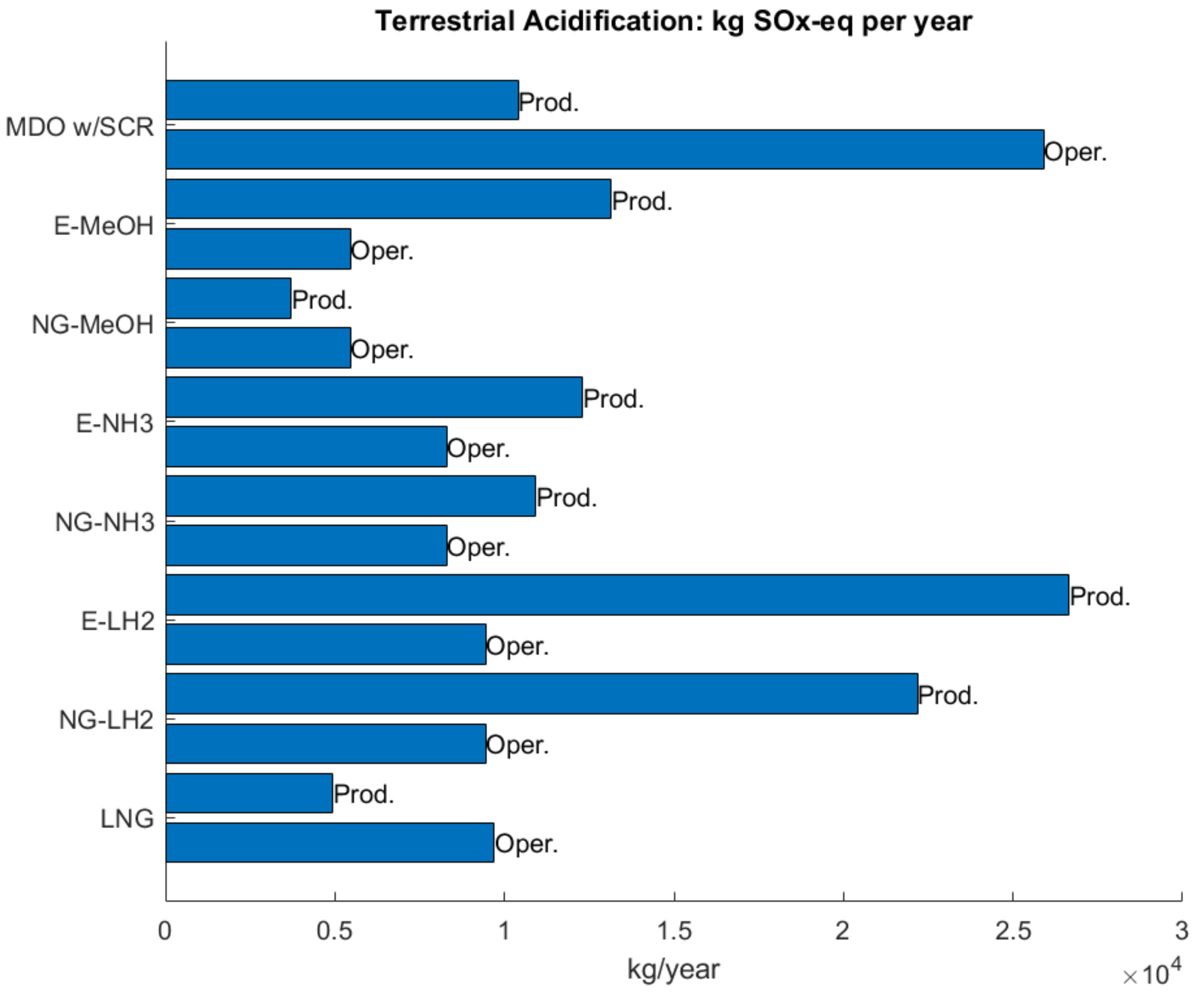

Figure 10.6: ReCiPe2016H Midpoint: Terrestrial Acidification

The annual values for the different impact categories are summarized in Table 10.16. The values are production and operation summarized, and represent the reference vessel implemented with the fuels. The effect of the pilot fuel is included.

Table 10.16: ReCiPe2016H: Annual impact category values at Midpoint for Well-to-Propeller

Fuel	GWP [kg CO_2-eqv]	PFMP [kg $PM_{2.5}$-eqv]	POF[kg NO_x-eqv]	TA [kg SO_x-eqv]
LNG	6,371,405	1,071	61,270	14,309
NG-LH_2	9,288,559	1,982	69,619	31,626
E-LH_2	3,243,917	1,901	70,203	36,097
NG-NH_3	7,013,067	1,256	47,822	19,227
E-NH_3	2,867,351	1,302	47,822	20,615
NG-MeOH	9,704,431	727	45,802	9,177
E-MeOH	1,724,200	1,109	42,772	18,600
MDO w/SCR	6,734,150	2,644	113,882	36,047

The next step is to translate the environmental mechanisms at Midpoint to the Endpoint damage categories and weigh them accordingly. As previously mentioned, this makes it easier to understand the total environmental performance based on the importance of the different environmental mechanisms relevant to each other. The Mid- to Endpoint characterization factors applied in this thesis can be found in Table 10.17. The values are retrieved from Huijbregts et al. (2016) and region-specific to Norway with a Hierarchist value choice when applicable.

Table 10.17: Mid- to endpoint characterization factors (Huijbregts et al. (2016))

Emission to	Impact category	Damage category	Factor	Characterization factor unit
Air	Climate change	Human health	9.28E-07	DALY/kg CO_2-eq.
Air	PFMP	Human health	6.29E-04	DALY/kg $PM_{2.5}$-eq.
Air	HOFP	Human health	9.10E-07	DALY/kg NO_x-eq.
Air	Climate change	Terrestrial ecosystem	2.80E-09	Species.year/kg CO_2-eq.
Air	EOFP	Terrestrial ecosystem	1.29E-07	Species.year/kg NO_x-eq.
Air	TA	Terrestrial ecosystem	2.12E-07	Species.year/kg SO_2-eq.

After translating the results at Midpoint to Endpoint, the last step is to weigh and normalize the Endpoint categories Human health and Terrestrial ecosystem. The weights are defined as Pt/DALY or Pt/Species.year, where Pt stands for Potential environmental impact. The values, including weights and normalizing, used in this thesis are defined in Table 10.18 and retrieved from Aanondsen (2021).

Table 10.18: Weighting and normalization of Endpoint

Emission to	Impact category	Damage category	Weights	Weighting factor unit
Air	Climate change	Human health	16840	Pt/DALY
Air	PFMP	Human health	16840	Pt/DALY
Air	HOFP	Human health	16840	Pt/DALY
Air	Climate change	Terrestrial ecosystem	558400	Pt/Species.year
Air	EOFP	Terrestrial ecosystem	558400	Pt/Species.year
Air	TA	Terrestrial ecosystem	558400	Pt/Species.year

The final annual potential environmental impact can be found in Figure 10.7. At first glance, it can be noticed that the impact on human health caused by climate change is the greatest contributor of the different impact categories. Although the damage category Terrestrial ecosystem is weighted 30 times higher than Human health. One reason could be that the results of the impact category climate change at Midpoint is of a greater magnitude compared to the others. Next, the particle matter formation potential affecting human health is a noticeable contributor. For the total environmental performance, there is a distinct difference between natural gas-based fuels and e-fuels. Based on the total life cycle of the fuel, both NG-MeOH and NG-LH_2 perform worse than MDO with SCR, with NG-MeOH performing the worst. By using MDO with SCR technology as a benchmark, there is no point in implementing LH_2 or MeOH from an environmental perspective if it is to be produced from natural gas.

All three e-fuels perform rather similarly. They have a slightly higher impact from operation compared to production and have a Pt/year within a short interval. E-MeOH performs the best of all the fuels assessed, followed closely by E-NH_3 and E-LH_2 in that order. E-LH_2 could possibly be closer to E-NH_3 and E-MeOH if it did not operate purely on diesel during the fishing trips west of Ireland.

LNG performs better than all other natural gas-based fuels. This seems reasonable given that NG-MeOH, NG-LH_2, and NG-NH_3 would require processing in addition to many of the production steps already performed for LNG, increasing the emissions. By using LNG as a benchmark instead of MDO, there would be nothing to gain environmentally from implementing any natural gas-based fuels. Given that LNG is the most established of the alternative fuels assessed it is fitting to use to benchmark future green fuels. By LNG's environmental standards, it is only reasonable to implement e-fuels in the reference vessel with E-MeOH as the best choice.

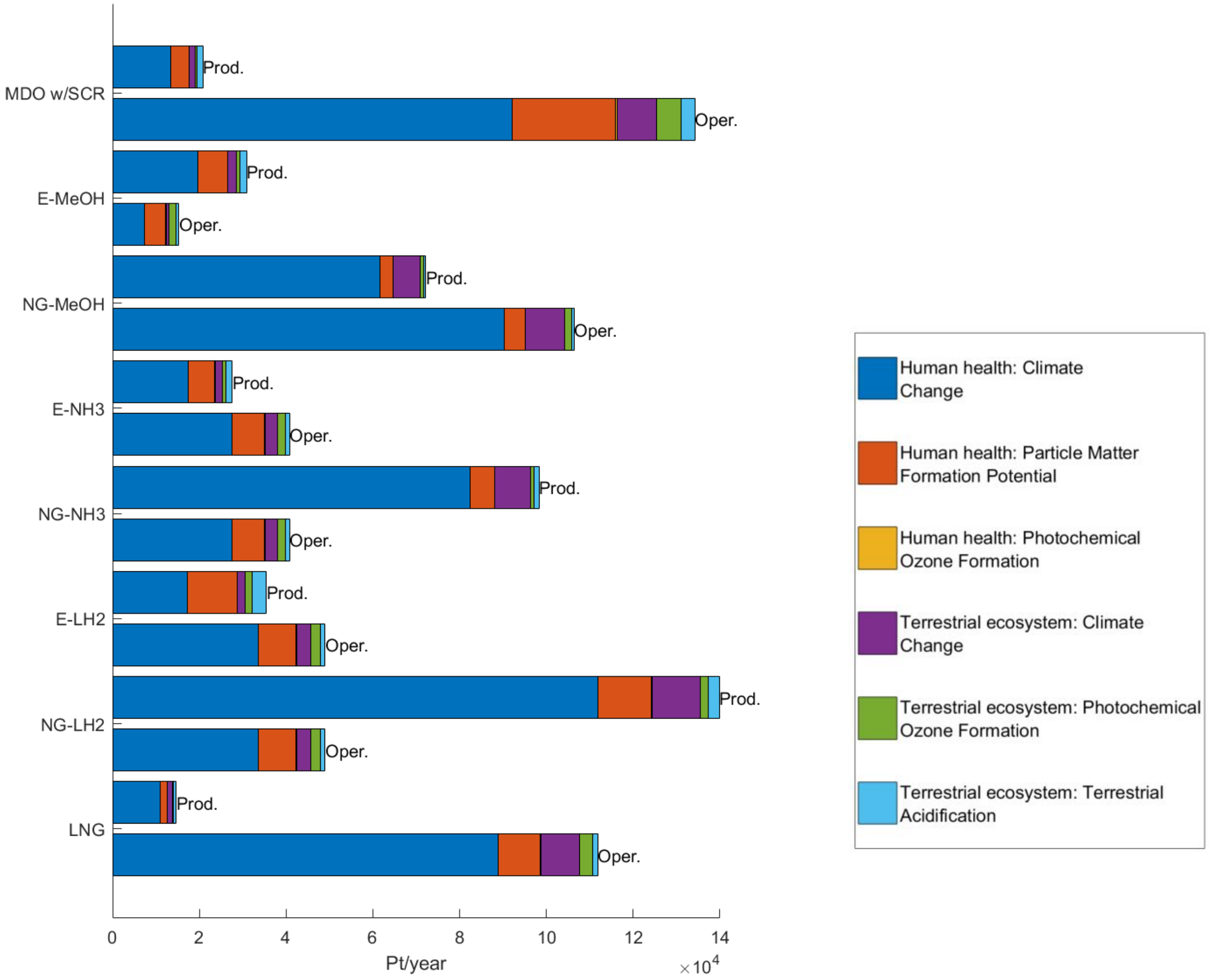

Figure 10.7: ReCiPe2016H: Yearly potential environmental impact (Pt/year)

Table 10.19: The performance of the fuels implemented in the reference vessel ranked based on the yearly potential environmental impact

Rank	Fuel	Pt/year
1	E-MeOH	46147
2	E-NH_3	68412
3	E-LH_2	84378
4	LNG	126399
5	NG-NH_3	139170
6	MDO w/SCR	154942
7	NG-LH_2	188801
8	NG-MeOH	204142

It is important to emphasize is that the defined Life Cycle Inventory is based on different LCAs, making it difficult to control that the different values are based on the same input and assumptions. Some values are also based on qualitative assumptions. This makes it important to be somewhat critical of the results and to use them more as a pointer rather than hard facts. The results are not deemed as useless because they do reflect reality to a certain extent.

10.6 Capital Expenditures (CAPEX)

The CAPEX covers the ship acquisition cost which covers steel and equipment costs including labor at the yard, in addition to administration costs, design costs, yard costs, and financing. The reference vessel was valued at 205 million NOK in 2014. Because fishing vessels are poorly covered in regards to empirical ship acquisition cost formulas, this value will be treated as the CAPEX for the ship when using MDO as fuel. All extra costs related to alternative fuels will be added to this initial value.

The length extension required to fit the tank when using LNG, LH_2, and NH_3 as fuel, comes with an extra cost. For this thesis, the cost of this extension is simplified to the cost of the material and labor costs based on the extra hull weight this extension will provide. From Ventura (2011), an empirical formula for the estimation of hull weight is retrieved. The formula is based on a statistical analysis regression performed by *d'Almeida* in 2009.

$$\mathrm{W}_H = k1 \cdot \mathrm{L}_S^{k2} \cdot \mathrm{B}^{k3} \cdot \mathrm{D}^{k4} \tag{10.4}$$

Fishing vessels are not covered by this formula, so the values for a general cargo ship will be used, k1=0.0313, k2=1.675, k3=0.85, and k4=0.28. With the weight estimated, the extra hull cost can be estimated. The material cost is:

$$\mathrm{CA}_H = \mathrm{W}_H \cdot \mathrm{m}_H \tag{10.5}$$

where W_H is the hull weight in tonnes and m_H represents the unit cost of structural steel set to 546 EURO/-tonne in this thesis (Santos (N.D.)). The labor cost of the hull is defined as:

$$\mathrm{CF}_H = \mathrm{Hh}_H \cdot \mathrm{m}_{HhH} \tag{10.6}$$

where Hh_H represents the number of man-hours necessary to construct the hull and m_{HhH} the unit cost of one man-hour set to 19.4 EURO/hour (Santos (N.D.)). The required number of man-hours can be defined by the following formula (Santos (N.D.)):

$$\mathrm{Hh}_H = \mathrm{y} \cdot \mathrm{W}_H^x \cdot \mathrm{P}_r \tag{10.7}$$

where W_H represents the hull weight in tonnes, x and y factors for ship type and size, and P_r the productivity factor dependent on yard location. Again a general cargo type is chosen for the ship type, thus the size factors are x=0.7 and y=1250. For the productivity factor, the yard is defined as located in western Europe, resulting in P_r=1. It is then possible to estimate the cost of extension.

Table 10.20: Estimated cost of extension

	LNG	LH_2	NH_3	Unit
Extension	6.9	7.5	8.7	m
Hull weight	13.64	15.74	20.07	tonne
Material cost	7,445	8,596	10,961	EUR
Labour cost	151.0	167.0	198.0	kEUR
Extension cost	**158.4**	**175.6**	**208.9**	**kEUR**

The reference vessel is equipped with a main engine of 4000 kW and two auxiliary engines of 680 kW each. The highest increase in power consumption during the most power-demanding operation is 130 kW. Based on this, the engine sizes of the reference vessel are deemed fitting for the vessels using alternative fuels as well. Through conversations with Steinshamn, T. S. (2021), general rule of thumb estimates used for engine costs is 300 EURO per kW for standard ICE and 400 EURO per kW for dual-fuel engines using LNG. This number is not necessarily applicable for all sizes of engines, but for the intended low-pressure dual-fuel engines in this thesis, it is deemed fitting. Because some dual-fuel engines using methanol exist, the same cost is assumed for low-pressure dual-fuel engines using methanol. Dual-fuel engines using ammonia and hydrogen will require a different injection system and R&D before entering the market, so it can be expected that some of this cost will be included in the engine price resulting in a higher cost per kW. From Hansson et al. (2020), an estimated ICE cost per kW for ammonia in 2050 is found to be approximately 500 EURO per kW. They also assume that the cost is equal for hydrogen. This value is for Deep Sea Shipping.

Table 10.21: Additional cost for dual-fuel engines

	LNG	LH_2	NH_3	MeOH	Unit
Engine type	DF	DF	DF	DF	-
Unit cost	400	500	500	400	EUR/kW
Total installed power	5360	5360	5360	5360	kW
Baseline ICE cost	1,608.0				kEUR
Extra engine cost	**536.0**	**1,072.0**	**1,072.0**	**536.0**	**kEUR**

As previously mentioned, dual-fuel engines require batteries to compensate for a slow response time through peak shaving. This makes it somewhat tricky to define the required power for the battery pack. Libas is installed with a 500 kWh battery pack which is seen as sufficient for peak shaving. Hardhaus, also designed by Salt, is equipped with a 1000 kWh battery pack to use in the harbor in addition to peak shaving. This is mostly to avoid noise and pollution in the harbor. For this thesis, a battery pack size of 1000 kWh is chosen. In DNV (2019), they have tried to predict the system cost of marinized batteries from 2016 to 2030. Based on the more conservative prediction, the unit system cost for 2021 is approximately 800 EURO/kW. This results in an extra battery cost of 800,000 EURO for all four alternative fuels.

One of the main cost drivers for alternative fuels is often associated with the cost of the storage tank for fuels that require C-type tanks to remain liquid. These tanks must be made from materials suitable for cryogenic temperatures and require insulation, in addition to being complex systems. A tank unit cost of 10,000 EURO/m3 is set for LNG (Steinshamn, T. S. (2021)). It has proven challenging to retrieve any unit costs for hydrogen. The tank unit cost for liquid hydrogen is assumed to be 12,000 EURO/m3 because it requires a much lower temperature than LNG. Hansson et al. (2020) has assessed the potential of ammonia as a marine fuel and assumed the storage unit cost to be half the cost for LNG. Based on this, the storage unit cost for ammonia is set to 5000 EURO/m3. This is not necessarily accurate, but it can be assumed that ammonia tanks will be cheaper than LNG tanks (Steinshamn, T. S. (2021)).

Table 10.22: Tank costs

	LNG	LH_2	NH_3	Unit
Tank volume	241	272	331	m3
Unit cost	10,000	12,000	5,000	EUR/m3
Tank cost	**2,407.4**	**3,261.5**	**1,653.8**	**kEUR**

Some additional equipment necessary for the fuel supply of LNG, LH_2, and NH_3 is a gas control system, increased ventilation and purging of fuel pipelines compared to diesel, and insulation of gas pipelines due to low temperatures. The cost of a gas control system for LNG is somewhere around 300,000 EURO (Steinshamn, T. S. (2021)). The cost for LH_2 and NH_3 is assumed to be equal to LNG. The cost of ventilation and purging of diesel pipelines is around 200,000-300,000 EURO, and the cost increase for LNG is 10-15% (Steinshamn, T. S. (2021)). The cost increase is set to 15% for LNG and LH_2 and 10% for NH_3. The reason for a lower increase for NH_3 is Green Shipping Programme et al. (2021) stating ammonia ventilation from double walled piping is less complex compared to the required ventilation of LNG. Lastly, the cost of insulating gas pipelines for LNG is roughly 100,000 EURO (Steinshamn, T. S. (2021)). Because LH_2 is stored at a lower temperature, it requires more insulation resulting in a cost of 130,000 EURO. By this, the insulation cost of NH_3 is 50,000 EURO due to a lower storage temperature.

Lastly, the cost of NO_x reduction measures must be defined. Based on the calculated Tier III emission limit for ship engines, 1.84 g/kWh, all of the assessed fuels require some sort of NO_x reduction measures. Some of the alternative fuels meet the Tier III requirement, but because the reasoning behind the choice of dual-fuel engines is that they should be able to run purely on diesel if required, all of the assessed alternative fuels require NO_x reduction measures. The chosen NO_x reducing technology is Selective Catalytic Reduction (SCR) which is capable of reducing the NO_x emissions by 85-95% (Trozzi and Lauretius (2020)). It is assumed that this is not implemented in the initial cost of the reference vessel. The cost of SCR is approximately 85.4 EURO/kW (DNV (2018)). The resulting cost for the SCR technology is then 457,744 EURO for each fuel.

Table 10.23: The additional costs related to the implementation of the fuels summarized

Additional costs	LNG	LH_2	NH_3	MeOH	Unit
Extension	158.5	175.6	228.0	-	kEUR
DF engine	536.0	1,702.0	1,702.0	536.0	kEUR
Batteries	800.0	800.0	800.0	800.0	kEUR
Tank cost	2,407.4	3,261.5	1,653.8	-	kEUR
Gas control system	300.0	300.0	300.0	-	kEUR
Ventilation and purging	37.5	37.5	25.0	-	kEUR
Insulating	100.0	130.0	50.0	-	kEUR
SCR	457.8	457.8	457.8	457.8	kEUR
Total	**4,797.1**	**6,234.4**	**4,567.4**	**1,793.8**	**kEUR**

The costs of administration, design, finance, and yard must be added to the additional cost as well. These costs are defined as a percentage of the total cost of the ship. For this thesis, administration is set to 10%, design to 8%, finance to 5%, and yard to 5%.

Table 10.24: Final CAPEX

	LNG	LH_2	NH_3	MeOH	MDO w/SCR	Unit
Initial cost	20,065.0	20,065.0	20,065.0	20,065.0	20,065.0	kEUR
Additional cost	6,140.2	7,978.0	5,846.3	2,296.0	585.9	kEUR
CAPEX	**26,205.2**	**28,045.0**	**25,911.3**	**22,361.0**	**20,650.9**	**kEUR**

From this, it can be seen that methanol has the lowest extra costs concerning the CAPEX. This is mainly due to it not requiring an extension or an expensive pressurized tank. Implementing liquid hydrogen is the most costly alternative. Much because of a lower tank cost, ammonia has a lower CAPEX compared to LNG.

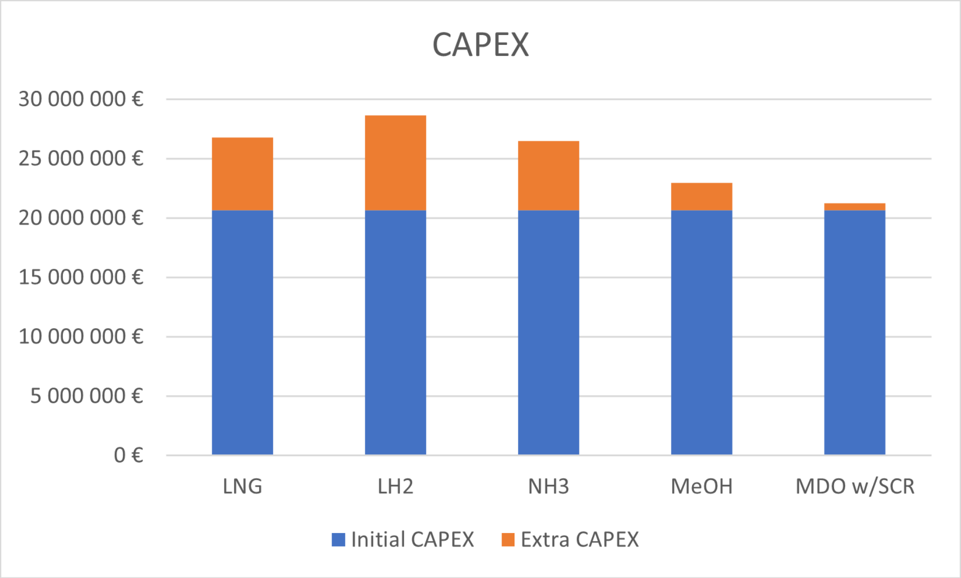

Figure 10.8: CAPEX for the different fuel alternatives implemented in the reference vessel

10.7 Operational Expenditures (OPEX)

The OPEX covers expenses related to the operation of the vessel. It is defined to include costs of maintenance and repairs, and insurance for this thesis. As a reference value, the OPEX for MDO is set to be 5% of the total CAPEX for both maintenance and insurance (Steinshamn (2019)).

$$\text{OPEX}_{\text{MDO}} = 20,650,912 \cdot (0.05 + 0.05) = 2,065,091 \quad [\text{EURO}] \tag{10.8}$$

For the alternative fuels, the OPEX is assumed to increase by 10%. According to Horvath et al. (2018), this is a fitting number for LNG. For the three others, the same value is assumed based on the less proven technology.

Table 10.25: OPEX

	LNG	LH_2	NH_3	Methanol	MDO	Unit
Initital OPEX	2,065.1	2,065.1	2,065.1	2,065.1	2,065,091	kEUR
Increase	10	10	10	10	-	%
OPEX	**2,271.6**	**2,271.6**	**2,271.6**	**2,271.6**	**2,271.6**	**kEUR**

10.8 Voyage Related Expenditures (VOYEX)

Generally, the VOYEX includes expenses like fuel costs, UREA costs, and taxation of emissions, i.e. all expenses dependent on the voyage duration. Fuel costs are a tricky subject, especially considering many of the alternative fuels assessed are little to not in use today. This makes it hard to predict any prices. Table 10.26 shows some different price estimations and predictions for different fuels carried out by NCE Maritime CleanTech and Lloyd's Register in co-operation with UMAS.

Table 10.26: Different fuel cost estimations and predictions. All values in EUR/tonne

	CleanTech (2019)	LR and UMAS (2020) 2020	LR and UMAS (2020) 2030	Steinshamn (2019)
MDO/MGO	6100	-	-	504
LNG	760	-	-	378
E-LNG	-	2944	2560	-
NG-LH_2	5400-15400	2520	2318	-
E-LH_2	-	5242	4435	-
NG-NH_3	250-300	438	406	-
E-NH_3	5100	859	794	-
NG-MeOH	-	-	-	-
E-MeOH	8000	1376	1196	-

It can be seen that there is a huge variation in estimations, which can come from a variety of reasons. Both the production and production technology comes with a cost. The producer must be able to pay down the expenses related to the facility, in addition to making a profit. The electricity price has a sufficient impact on production costs. If the fuel requires transportation and storage, this would also impact the fuel price. Another could be the bunkering fees demanded by the supplier during sales. Different assumptions of these costs could be the reason behind the difference in fuel cost estimations. The technology related to producing alternative fuels will likely have a rapid development shortly, lowering production costs. One example of a technology expected to be improved is electrolysis, required during the production of renewable hydrogen, ammonia, and methanol. All of these variables are hard to predict when estimating future fuel prices.

For the taxation of emissions, the fees related to the emission of CO_2 and NO_x are included. Based on Skatteetaten (2020) and Lovdata (2019), it is understood that fishing vessels are exempted from these taxes when fishing in remote waters, i.e. more than 250 nautical miles of the coast. For the NO_x-tax, they are however mandated to pay taxes for the emissions during transit in close waters. It is unclear if this is the case for CO_2, but it is assumed that it is. There is also a basic fee for purchasing mineral oil, but fishing vessels are exempted from this fee through a refunding system.

Table 10.27: Taxation of emissions. Values in EURO/tonne

	CO_2 (Regjeringen (2021))	NO_x (Skatteetaten (2021), Fiskebaat (2019))
2021	58	2305
2025	-	2750
2030	196	-

Based on the values found, the parameters for calculating the VOYEX can be found in Table 10.28. For the fuel costs, the values from LR and UMAS (2020) are chosen. These values are based on a lower bound scenario where the electricity cost decreases until 2050. The values are defined as $/GJ in LR and UMAS (2020). Two different scenarios are defined for the LCCA:

- Scenario 1 (S1): A more present scenario with today's taxation and 2020 fuel costs
- Scenario 2 (S2): A future scenario with 2030 taxation and fuel costs

Over the years, the fuel prices for traditional fuels like MDO and LNG are predicted to increase because of the taxation fees. The alternative fuels are, however, predicted to become somewhat cheaper. Meaning in future scenarios, the alternative fuels are supposed to become more competitive compared to traditional fuels. The taxable emissions represent 55% of the yearly emissions based on the defined annual operation.

Table 10.28: Parameters for calculating the VOYEX. Two different cost scenarios, S1 and S2, for fuel price and taxation.

	MDO w/SCR	LNG	E-LH_2	E-NH_3	E-MeOH	Unit
Main fuel consumed	2,069.6	1,530.3	482.3	3,346.4	4,254.2	tonne
Pilot fuel consumed	-	18.4	795.6	626.2	169.3	tonne
Taxable CO_2	3,206	2504	632	948	256	tonne
Taxable NO_x	14	7	3	5	4	tonne
UREA	103.5	0.9	39.8	31.3	221.2	tonne
Fuel price (S1/S2)	504	378	5,242/4,435	859/734	1,376/1,196	EUR/t
Pilot fuel price	-	504	504	504	504	EUR/t
CO_2 tax (S1/S2)	58/196	58/196	58/196	58/196	58/196	EUR/t
NO_x tax (S1/S2)	2,305/2,750	2,305/2,750	2,305/2,750	2,305/2,750	2,305/2,750	EUR/t
UREA cost	291	291	291	291	291	EUR/t

Table 10.29: VOYEX - Scenario 1

	MDO w/SCR	LNG	E-LH_2	E-NH_3	E-MeOH	Unit
Main fuel cost	1,043.1	578.6	2,527.9	2,875.6	5,853.4	kEUR
Pilot fuel cost	-	9,290.0	401.0	315.6	85.3	kEUR
CO_2 cost	185.9	145.2	36.7	55.0	14.9	kEUR
NO_x cost	31.3	16.9	6.2	10.4	8.4	kEUR
UREA cost	30.1	0.3	11.6	9.1	64.4	kEUR
VOYEX	**1,290.5**	**750.0**	**2,983.3**	**3,265.8**	**6,026.4**	**kEUR**

Table 10.30: VOYEX - Scenario 2

	MDO w/SCR	LNG	E-LH_2	E-NH_3	E-MeOH	Unit
Main fuel cost	1,043.1	578.5	2,139.0	2,457.4	5,086.9	kEUR
Pilot fuel cost	-	9,290.0	401.0	315.6	85.3	kEUR
CO_2 cost	628.3	490.7	123.9	185.9	50.3	kEUR
NO_x cost	37.5	20.1	7.4	12.4	10.1	kEUR
UREA cost	30.1	0.3	11.6	9.9	64.4	kEUR
VOYEX	**1,738.9**	**1,098.8**	**2,682.8**	**2,980.4**	**5,297.0**	**kEUR**

For both scenarios, it can be seen that methanol has a very high VOYEX compared to the other fuels. This is mainly due to its high annual fuel consumption. The two other green fuels do also have a relatively high VOYEX compared to MDO and LNG. Figure 10.9 illustrates the two scenarios for the different fuels. Only the green alternatives of hydrogen, ammonia and methanol are included in the VOYEX based on the results in the environmental assessment.

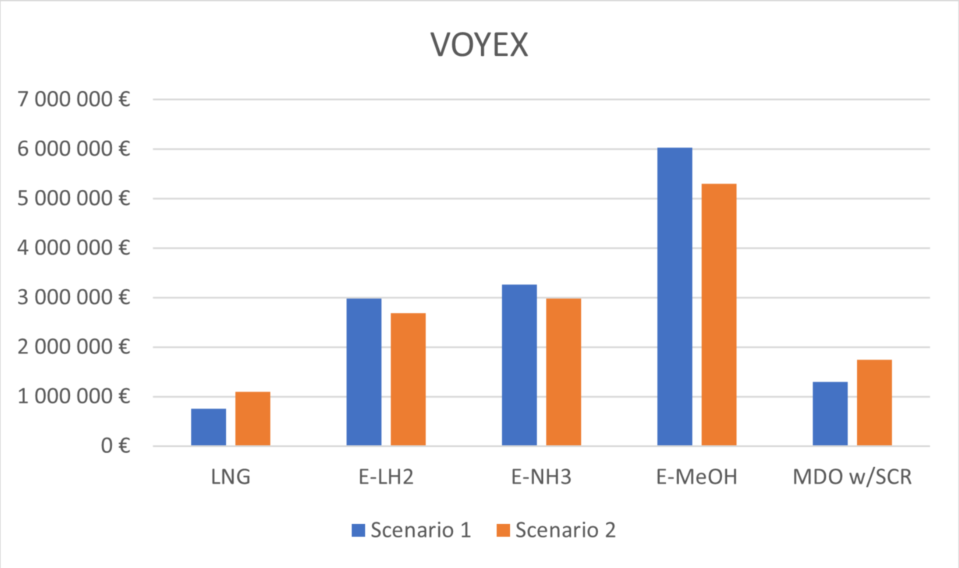

Figure 10.9: Graphical representation of the VOYEX for the two different scenarios

10.9 Financial Analysis

Enova's NO$_x$-fund is an arrangement where it is possible to retrieve subsidiary funding for the extra costs of implementing NO$_x$-reducing measures. This can be batteries, SCR technology, and implementation of fuels emitting less NO$_x$ compared to traditional fuels. Before the North Sea became a NO$_x$-ECA zone, meaning the NO$_x$ emissions are regulated by Tier III demands, it was possible to cover up to 80% of the extra costs related to implementing a NO$_x$-reducing alternative fuel. Vessels supported by this fund would be exempted from the NO$_x$-taxation but would pay 1 NOK/kg emitted back to the NO$_x$-fund. However, due to the subtle difference possible to achieve by alternative fuels compared to Tier III demands, the NO$_x$-fund now makes little to no impact on the profitability for the vessels using alternative fuels. According to DNV (2018), one can assume that newbuilds keel laid from 2021 and on will not receive funding from the NO$_x$-fund from emission-reducing measures in the North Sea.

Another existing funding arrangement is Pilot-E, established by The Research Council of Norway, Enova, and Innovation Norway. The goal of this arrangement is more rapid development and implementation of more environmentally friendly energy technology. One of the demands for a project to receive funding is that it covers a process all the way from research to full-scale demonstrations of new concepts. It is unclear how much funding is possible to achieve through this arrangement and if it supports the implementation of low emission technology on fishing vessels, although some existing projects have received funding from 11-46 million NOK.

Enova (2017) states the criteria for participation in their funding program for energy- and climate change measures in ships. Most of the formal criteria seem to be in order. The applicant is a fishing vessel owner looking to improve the environmental performance of its fishing fleet, and the extra investment cost is based on physical measures and equipment mostly related to the vessel's conversion of energy. One specific criterion for climate change measures is that it must reduce emissions greenhouse gases by a minimum of 26 tonne CO$_2$-equivalents per year compared to a traditional solution. Based on the taxable CO$_2$ emissions in Table 10.28, every alternative fuel fulfills this criterion. 26 tonnes is a small amount over a year. The funding rates are different based on the size of the businesses. A medium-sized business is assumed resulting in a funding rate of 40% of the extra costs related to the requiring of a ship with measures that improve the environmental performance compared to EU-standards.

Table 10.31: Assumed funding based on Enova (2017)

	LNG	E-LH$_2$	E-NH$_3$	E-MeOH	Unit
Extra CAPEX	6,140.2	7,978.0	7,963.1	2,296.0	kEUR
Funding rate	40	40	40	40	%
Funding	2,456.1	3,192.0	2,338.5	918.4	kEUR
Resulting extra CAPEX	**3,684.1**	**4,788.0**	**3,507.8**	**1,377.6**	**kEUR**

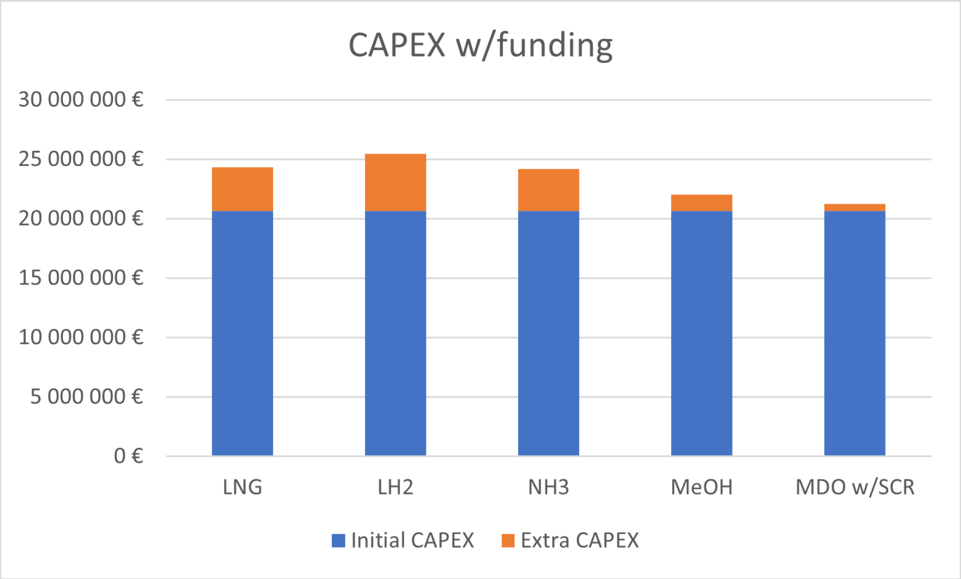

Figure 10.10: CAPEX with funding for the different fuel alternatives implemented in the reference vessel

With the CAPEX, OPEX, and VOYEX defined, it is possible to calculate the Life Cycle Cost of the vessels. How the investment is funded, e.g. loan type and the amount of loan, is not assessed in this thesis. Implementing the loan would increase the CAPEX somewhat if the annual installments are included as a capital expenditure.

First, the real interest rate must be calculated. With a nominal interest rate of 8% and an inflation rate of 2.20% the real interest rate is calculated as follows.

$$p' = \frac{1+0.08}{1+0.022} - 1 = 5.68\% \tag{10.9}$$

For an investment duration of 15 years, the discount factor is equal to 9.92. The residual value of the ship after 15 years is qualitatively assumed to be 10% of the CAPEX without funding.

Table 10.32: LCC results for the different fuels implemented in the reference vessel. Both scenarios included.

	MDO w/SCR	LNG	E-LH$_2$	E-NH$_3$	E-MeOH	Unit
CAPEX w/funding	20,650.9	23,749.1	24,853.0	23,572.8	21,442.6	kEUR
- Residual value	2,065.1	2,620.5	2,804.5	2,591.1	2,236.1	kEUR
LCC CAPEX	18,585.8	21,128.6	22,048.5	20,981.6	19,206.5	kEUR
LCC OPEX	20,482.8	22,531.1	22,531.1	22,531.1	22,531.1	kEUR
LCC VOYEX S1	12,799.4	7,439.4	29,590.1	32,391.8	59,773.7	kEUR
LCC VOYEX S2	17,247.2	10,898.6	26,609.9	29,561.0	52,538.1	kEUR
LCC S1	**51,868.0**	**51,009.0**	**74,169.6**	**75,904.5**	**101,511.3**	**kEUR**
LCC S2	**56,374.4**	**54,558.3**	**71,189.5**	**73,073.7**	**94,275.7**	**kEUR**

E-MeOH performs by far the worst. It has a higher volumetric energy density than ammonia, but because it barely uses any pilot fuel, the annual fuel consumption is extremely high compared to that of ammonia which is defined to use 30% pilot fuel. The annual fuel consumption combined with a relatively high fuel price gives E-MeOH a high VOYEX, driving the LCC up. One solution to lower this expenditure could be a dual-fuel engine similar to that of ammonia and hydrogen, with a higher pilot amount. This would, however, worsen the environmental performance, but it could be a solution in a short-term perspective while the production technology matures and lowers the cost. Because of the higher consumption of diesel, E-LH$_2$ performs better than E-NH$_3$. The hydrogen vessel is defined to have a maximum of 7 days capacity when utilizing hydrogen, requiring a smaller tank and length extension. Higher consumption of MDO yearly helps to lower the VOYEX.

Based on the results from these two scenarios, illustrated in Figure 10.11 and Figure 10.12, it is evident that the planned increase in taxation combined with the small projected drop in green fuel prices is far from sufficient to make liquid hydrogen, ammonia, or methanol competitive with LNG and MDO. One could argue that the predicted fuel prices from LR and UMAS (2020) are higher than expected from production in Norway. This is, however, speculations due to the lack of an existing market. An increase in the funding of the additional costs related to the implementation of the alternative fuels would help to even the difference, but without a substantial drop in alternative fuel prices, the VOYEX will make the alternative fuels not competitive for a fishing vessel with the defined operation. Another solution could be that companies looking to buy fish from the vessel would be willing to pay a higher price for 'green' fish. This would increase the income and give the vessel owner a bigger margin for the VOYEX.

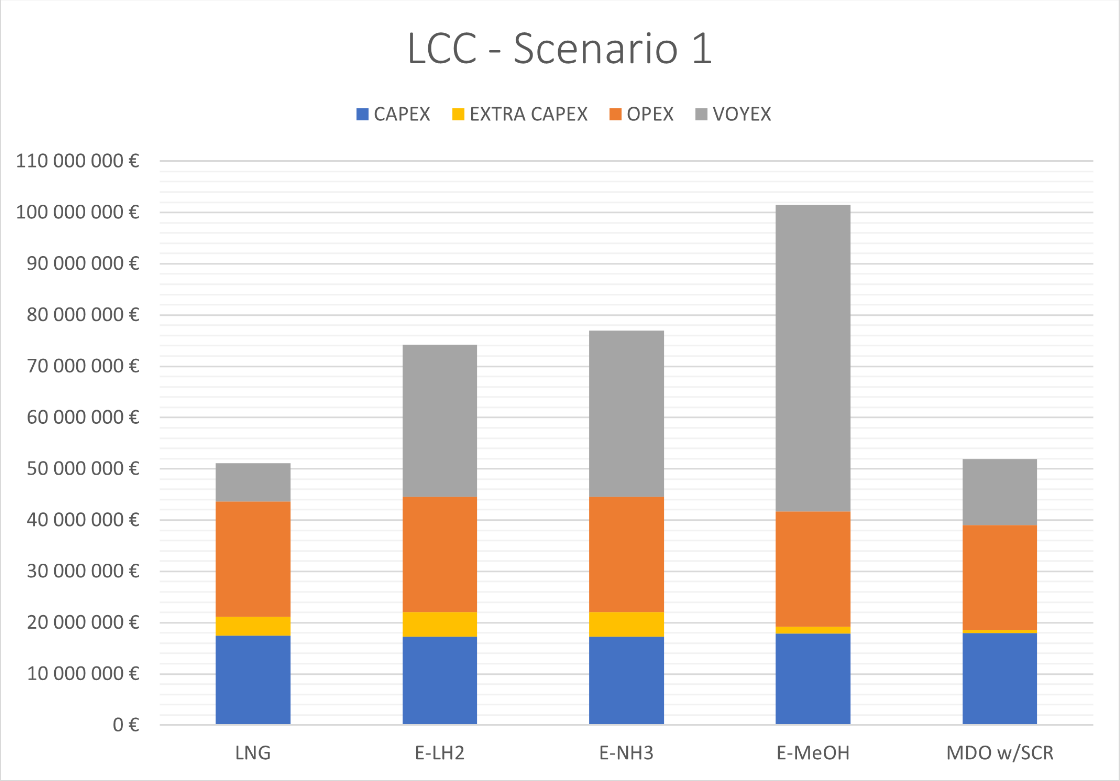

Figure 10.11: Scenario 1: Graphical representation of the LCC for the fuels implemented in the reference vessel.

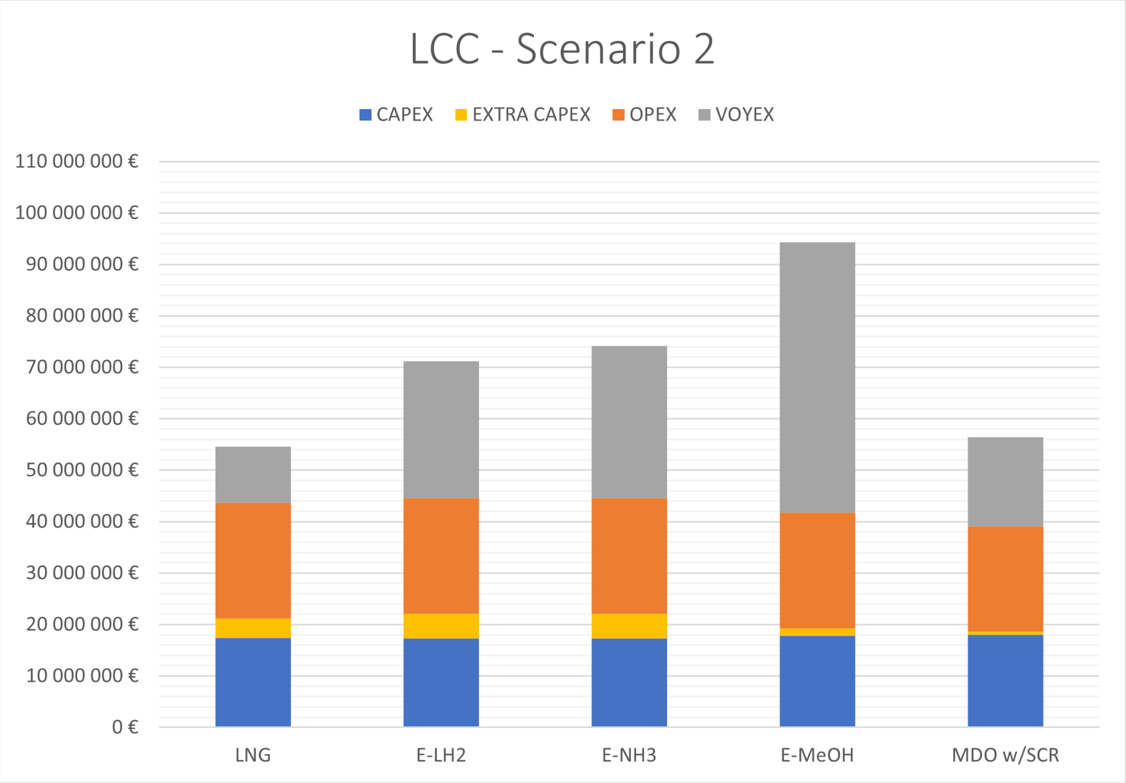

Figure 10.12: Scenario 2: Graphical representation of the LCC for the fuels implemented in the reference vessel.

Because the fuel price has such a considerable impact on the financial viability of alternative fuels, it is interesting to investigate what the average fuel price has to be over 10 years for the investment to be break-even. The previously defined generalized annual operation will be the basis of this analysis. Additionally, a generalized annual income must be defined. Based on Fiskeridirektoratet (N.D.), the fish price Harvest has received at every delivery can be retrieved. By taking the annual average for each species and then averaging them over a certain period, an estimated unit price is defined for each species. Compared to the average species-specific fish prices per year for the entire Norwegian fishing fleet retrieved from SSB, the values seem reasonable. Both the annual averages for Harvest and from SSB can be found in Appendix F.

Table 10.33: Generalized annual income for the reference vessel

	Quota [tonne]	Unit price [EUR/tonne]	Income [kEUR]
Blue Whiting	2700	198.1	534.9
Mackerel	962	1335.1	1,284.4
NVG-herring	3816	436.0	1,663.8
North Sea Herring	1287	475.9	612.5
Sandeel	13000	224.6	2,919.8
Total			**7,015.3**

Based on the averages, the vessel has an annual income of around 7 million Euros. The same real interest rate is used to discount future expenses to today's value. 10 years is defined as the break-even point for the analysis. This results in a discount factor (DF) of 7.47. The values used in the calculation can be found in Table 10.34.

Table 10.34: Required fuel prices for the reference vessel, with the different fuels implemented, to break even after 10 years

	MDO w/SCR	LNG	E-LH_2	E-NH_3	E-MeOH	Unit
CAPEX w/funding	20,650.9	23,749.1	24,853.0	23,572.8	21,442.6	kEUR
Residual value (10% CAPEX)	2,065.1	2,650.5	2,804.5	2,591.1	2,236.1	kEUR
OPEX	15,435.9	16,979.5	16,979.5	16,979.5	16,979.5	kEUR
VOYEX (excluded main fuel costs)	4,975.7	3,887.5	3,978.7	3,841.0	1,088.9	kEUR
Income	52,437.2	52,437.2	52,437.2	52,437.2	52,437.2	kEUR
Fuel cost to break even	13,439.8	10,441.6	9,430.6	10,635.0	14,243.9	kEUR
Fuel consumption	20,696.3	15,303.0	4,822.7	33,464.4	42,541.8	tonne
Break even fuel price	**649.4**	**682.3**	**1,955.4**	**317.8**	**334.8**	**EUR/tonne**

LNG and MDO have a higher fuel price to break even after 10 years compared to the fuel prices used in the LCCA, making them preferable on a financial basis. LH_2 seems to have a high margin but based on its relatively low fuel consumption in tonnes based on the low density of liquid hydrogen it is quite low. The three e-fuels have a low fuel price margin to break even due to a higher CAPEX and lower energy density. It is interesting to benchmark the fuel prices derived from the break-even analysis with the predicted/estimated fuel prices from LR and UMAS (2020) in the LCCA. This would clarify the effort required to make alternative green fuels for the future competitive. From Figure 10.13, it can be seen that the gap is big for E-LH_2, E-NH_3, and E-MeOH. E-LH_2 has the biggest price difference of around 2500 EUR/tonne. Because the fuel prices in the LCCA are predictions/estimations, it is hard to assess what this gap will be in reality in the future.It is, however, unrealistic to expect such a big drop in fuel prices in reality. Some sort of funding favoring greener fuels is most likely necessary to ensure the implementation of greener fuels in the future. One solution could be a system that refunds some of the extra fuel costs. How this could work in practice is hard to say, and developing such a funding system will be very challenging.

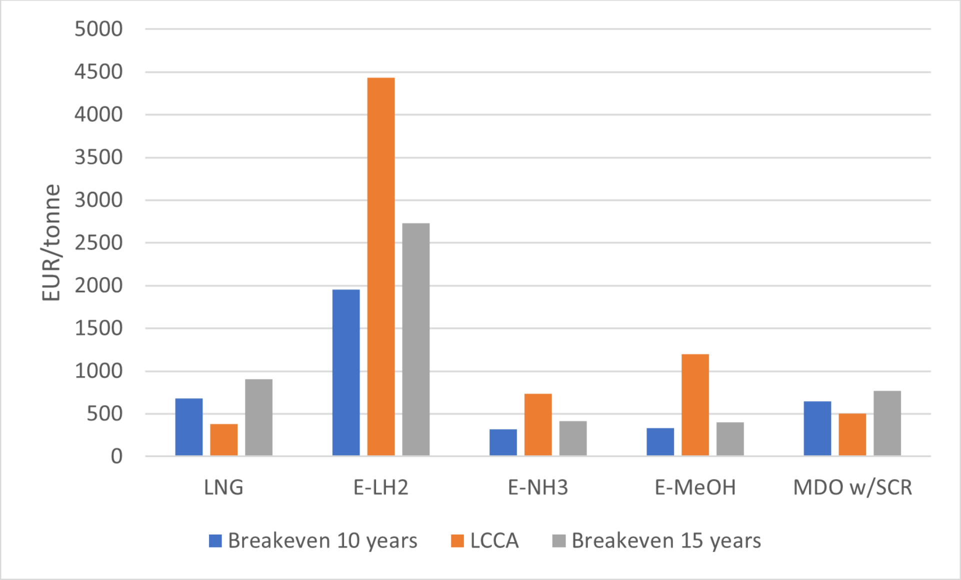

Figure 10.13: Comparison of the fuel prices used in the LCCA and the calculated fuel prices required to break even

Chapter 11

Multi-Criteria Decision Analysis

To compare the performance of the alternative fuels, both quantitative and qualitative information must be translated to fit the same quantitative parameter scale. For the more qualitative sub-criteria, the performances can be quantified by a four-level scale from 1 to 4, see Table 11.1. The more quantitative criteria represented by numbers in the Case Study are also translated to fit this scale but in a slightly different manner. By assuming that 1 represents the lowest-performing value in that criteria and 4 the fuel with best performing value, the fuels in between this range get a number calculated relative to the max and minimum allowing decimals. This method of rating the performance of the different fuel solutions is adopted from Hansson et al. (2019).

Table 11.1: Rating scale of criteria

Performance	Value
Poor	1
Moderate	2
Fairly good	3
Good	4

The goal of this multi-criteria decision analysis (MCDA) is to assess how the different fuels perform based on a set of criteria. It is important to remember that it is the reference vessel with the defined general annual operation and implemented with the alternative fuel being assessed, and not the alternative fuel alone. There are different underlying assumptions for the assessed fuels presented throughout the Case Study, and being aware of this is crucial when assessing the results of this decision analysis.

The most relevant criteria are assumed to be; VOYEX, Extra CAPEX, Environmental performance, Reliable supply of fuel, Infrastructure, and Safety. Including these six criteria covers the main focus areas in a sustainability definition; economic, technical, environmental, and social. When defining the pairwise comparison matrix for the AHP, the input can vary based on which stakeholder the decision analysis is carried out. Each stakeholder would rank these criteria differently, e.g. a shipowner will define economical aspects as more important than environmental performance while the governmental authority might define them opposite. Other stakeholders could be engine manufactures, fuel producers, researchers, and businesses looking to ship their products. For a ship design office, it is most natural to rank the criteria as a shipowner would. The shipowner will not go through with a project if it does not perform well in their eyes, leaving the ship design office with no work. By this, the decision analysis will be conducted focusing on fulfilling the interests of a shipowner.

A shipowner will always value economic aspects the highest. The two economical aspects assessed are VOYEX and Extra CAPEX. Because it is possible to retrieve some funding for the additional investment costs and because the VOYEX had the most significant impact on the life cycle cost in the Case Study, VOYEX is defined as somewhat more important than Extra CAPEX. The next criteria are more tricky to rank and could vary some from owner to owner. Environmental performance is important to meet regulations, avoid taxes, and sometimes front a green image, but it is not necessary the greenest fuel that performs the best economically. Safety is always an important concern, especially for the assessed alternative fuels, even though it can be expected that the classification societies and the Norwegian Maritime Directorate will ensure a safe regulation in the future. Next, a reliable supply of fuel is important because there is no point in investing 100 MNOK extra if you only run on diesel anyway. These three criteria are all defined to have equal importance. Lastly, the infrastructure is ranked the lowest based on the fact that tanking by trucks does occur for LNG and because it is hard to develop infrastructure for alternative fuels if no vessels use them and vice versa. Through the AHP-method, the resulting weighting of the criteria can be found in Table 11.2, see Appendix G for the derivation.

Table 11.2: Resulting criteria weights based on the AHP-method

Criteria	Weights
VOYEX	0.356
Extra CAPEX	0.221
Environmental performance	0.124
Reliable supply of fuel	0.124
Infrastructure	0.050
Safety	0.124

11.1 VOYEX

The VOYEX from scenario 2 is used for the decision analysis. This scenario uses fuel price predictions for 2030 as well as future emission taxes. The VOYEX is a more fitting criterion than just the fuel price because it includes the main fuel cost, pilot fuel cost, UREA cost, and taxation for the different defined vessels. Based on the results from the Case Study, it is E-MeOH that performs the worst, scoring a value of 1, and LNG that performs the best, obtaining a value of 4.

Table 11.3: Rating of the criteria *VOYEX* for the fuels implemented in the reference vessel

	MDO w/SCR	LNG	E-LH$_2$	E-NH$_3$	E-MeOH
VOYEX	**3.5**	**4**	**2.8**	**2.7**	**1**

11.2 Extra CAPEX

The extra investment costs defined in the Case Study are used for the rating of this criteria. Because funding is possible to retrieve and improves the performance for this criterion, the extra investment cost with funding is used. Because it is more to gain from 40% funding for higher costs it makes the differences between the fuels somewhat smaller, but it paints a more realistic picture. It does not change the ranking order however due to all four alternative fuels being eligible for funding. Both E-LH_2 and E-NH_3 has the highest extra investment costs and scores the worst. As expected, MDO w/SCR scores the best.

Table 11.4: Rating of the criteria *Extra CAPEX* for the fuels implemented in the reference vessel

	MDO w/SCR	LNG	E-LH_2	E-NH_3	E-MeOH
Extra CAPEX	**4**	**1.8**	**1**	**1.9**	**3.4**

11.3 Environmental performance

This criterion covers emissions of GHGs and local pollutants both upstream and downstream combined to a single score of potential environmental impact. Based on the results in section 10.5, the different fuels can be distributed on the scale of 1-Poor to 4-Good. This results in all three e-fuels scoring high and the oil and natural gas-based poor.

Table 11.5: Rating of the criteria *Environmental performance for the fuels implemented in the reference vessel*

	MDO w/SCR	LNG	E-LH_2	E-NH_3	E-MeOH
Environmental performance	**1**	**1.8**	**2.9**	**3.4**	**4**

11.4 Reliable supply of fuel

The criteria reliable supply of fuel is made up of a set of sub-criteria. This assessment follows a more qualitative approach. The first sub-criteria is *raw material availability*, representing the abundance of raw material required to produce the different fuels. MDO and LNG require oil and natural gas, which are constrained by reserves and production. For the e-fuels, the electrolysis uses water to produce hydrogen. Further, both nitrogen and CO_2 are assumed captured from the atmosphere. The sub-criteria *current fuel production* and *current use in the maritime sector* are highly connected. Both the production capacity and current use are high for MDO and LNG. Some projects on the production of e-fuels in Norway exist, e.g. Finnfjord and Herøya, but there is no current production capacity in Norway and thus close to no use. The rating of the criteria *reliable supply of fuel* is an average of the sub-criteria.

Table 11.6: Evaluation of the criteria *Reliable supply of fuel* for the fuels

	MDO w/SCR	LNG	E-LH_2	E-NH_3	E-MeOH
Raw material availability	3*	3*	4*	4	4
Current fuel production	4*	4*	1*	1	1
Current use in maritime sector	4*	3*	1*	1	1
Reliable supply of fuel	**3.7**	**3.3**	**2**	**2**	**2**

*Hansson et al. (2019)

11.5 Infrastructure

The criterion *Infrastructure* is divided into different sub-criteria. *Compatibility of the alternative marine fuel to existing infrastructure* covers to what degree it is possible to utilize existing infrastructure for the fuels. Methanol is the closest to MDO based on its properties. *Adaptability to existing ships* refers to the work required to adapt current ships to use the alternative fuel. Again methanol scores closest to MDO because of its properties. The complicated storage solutions required for LNG, LH_2, and NH_3 makes it hard for current ships, especially fishing vessels, to implement them. Next, the *Engine technology maturity* is assigned values based on section 5.4. One could argue that technological maturity has a low impact on the decision analysis in this thesis, given that none of the e-fuels have highly available commercial dual-fuel engines. The reasoning behind this low weighting is that most engine manufacturers express that they are working on this, thus it can be assumed that it will be available in the future. Wärstila is working specifically on this with both an ammonia dual-fuel engine and a concept they call a multi-fuel solution that is more focused on a versatile nozzle before the engine. Lastly, the *Current amount of storage and bunkering capability* is high for the more established solutions and low for the more alternative. Again the total score for *Available infrastructure* is defined as an average of the sub-criteria.

Table 11.7: Evaluation of the criteria *Available infrastructure* for the fuels

	MDO w/SCR	LNG	E-LH_2	E-NH_3	E-MeOH
Compatibility of the alternative marine fuel to existing infrastructure	4*	1.4*	1*	1	2.4*
Adaptability to existing ships	4*	2*	1*	1	2.75*
Engine technology maturity	4*	3	2	2	2
Current amount of storage and bunkering capability	4*	3*	1*	1	1
Available infrastructure	**4**	**2.4**	**1.3**	**1.3**	**2**

*Hansson et al. (2019)

11.6 Safety

The criterion *Safety* is divided into the sub-criteria *Risk of explosion or fire*, *Toxicity*, *Health hazards*, and *Cryogenic liquid*. These are the main safety issues related to the alternative fuels assessed. Based on the literature presented in chapter 7, the fuels can be rated. The total rating of *Safety* is an average of the sub-criteria.

Table 11.8: Evaluation of the criteria *Safety* for the fuels

	MDO w/SCR	LNG	E-LH_2	E-NH_3	E-MeOH
Risk of explosion or fire	3	1	1	3	2
Toxicity	2	4	4	1	1
Health hazards	2	4	4	1	1
Cryogenic liquid	4	1	1	4	4
Safety	**2.8**	**2.5**	**2.5**	**2.3**	**2**

11.7 Results

Figure 11.1 illustrates the relative weighted performances of the included criteria for the assessed alternative marine fuel solutions. Each column represent each fuel's estimated performance for the different criteria. A higher value will represent a more preferable performance, with the columns denoted by *Optimal Performance* representing the maximum weighted value possible to achieve for each criterion. LNG has the lowest VOYEX and thus the most favorable performance for this criterion. MDO with SCR has the best performance in terms of extra investment cost, reliable supply of fuel, available infrastructure, and safety. E-MeOH has the lowest potential environmental impact.

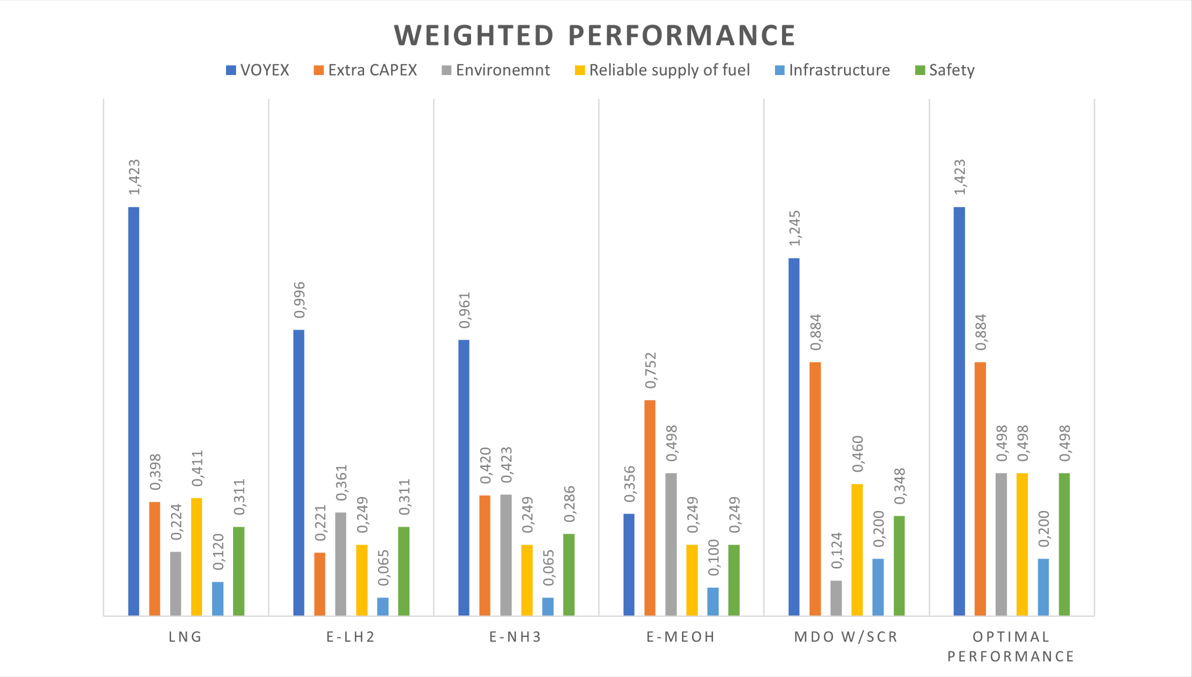

Figure 11.1: The weighted criteria performance of the alternative fuels assessed, implemented in the reference vessel

Figure 11.2 illustrates the total weighted performance of the different alternative marine fuel solutions assessed in this thesis. By gathering all the weighted performances for the criteria to a single performance value, it is possible to rank the different solutions. Again, a higher value represents a more preferable performance. For the weighted case based on a shipowner as the stakeholder, MDO with SCR ranks the highest, followed by LNG, then E-NH_3 barely outperforms E-LH_2, and last comes E-MeOH. This is not all that surprising considering the economy of the different solutions is defined as most important. MDO with SCR is not defined as an alternative fuel, but it is included as a benchmark with LNG. None of the alternative marine fuel solutions assessed outperforms more standard and conservative solutions, providing shipowners of fishing vessels, similar to the reference vessel in the Case Study, no reason to implement alternative marine fuels in future new ships. This conclusion is based on the choices and assumptions made throughout the Case Study and weighted based on a shipowner's perspective. If we only focus on the green solutions, it is a close race, but E-NH_3 performs the best. To understand how different parameters affect this conclusion, a sensitivity analysis must be performed. This will make the results more transparent and easier to assess.

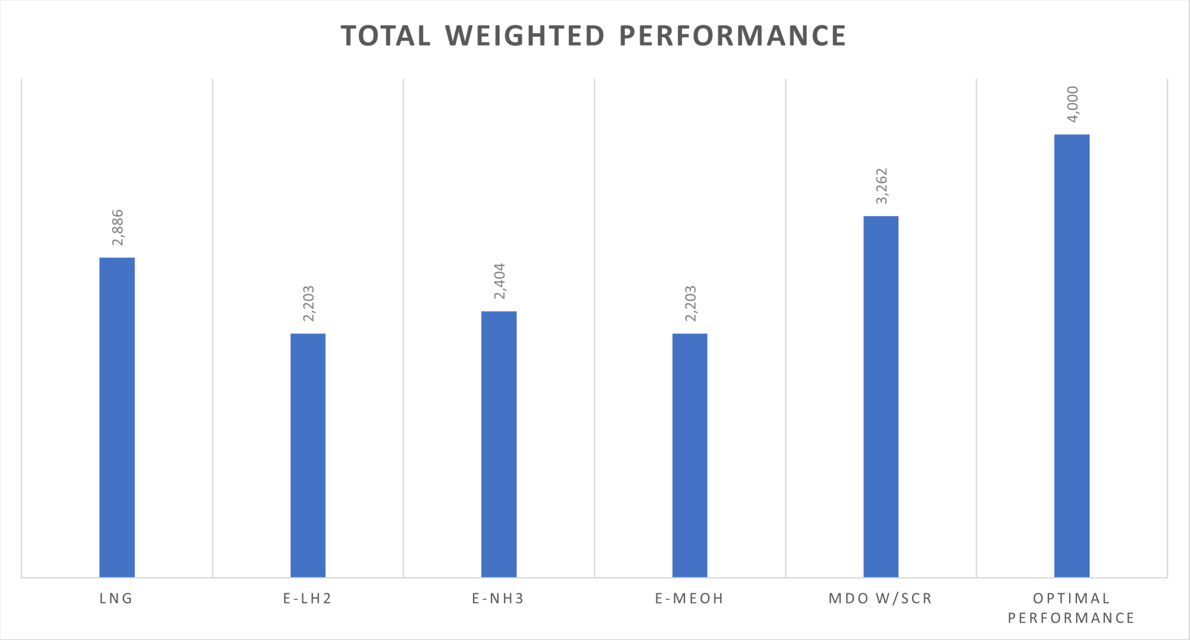

Figure 11.2: The total weighted performance of the alternative fuels implemented in the reference vessel, on the scale: Poor 1, Moderate 2, Fairly good 3, Good 4

11.8 Sensitivity Analysis

11.8.1 Case 1: Reduction in green fuel prices

One very uncertain parameter is the future fuel prices. In particular, those who are not available and produced today. As previously mentioned, the prices predicted by LR and UMAS (2020) may be somewhat conservative given the natural possibilities Norway possesses. Based on the high weighting of the criterion VOYEX, it could be an interesting test to lower the fuel price of the e-fuels and see how this affects the result. Some fuel prices future Norwegian facilities can be able to deliver is qualitatively assumed , see Table 11.9. The reduction is defined to be different for the three fuels because the fuels have different initial prices. The fuel price for ammonia is the lowest of the three, and thus a smaller reduction potential is achievable. Liquid hydrogen has by far the highest initial fuel price, having a higher reduction potential. Methanol shares a somewhat similar production process to ammonia, consequently the methanol fuel price is set just higher than the initial ammonia fuel price. It can be speculated in possibly lower prices than this further into the future when the electrolysis technology, and additional production technology, matures and becomes cheaper.

Table 11.9: Case 1: Fuel price

Fuel	Fuel price [EUR/tonne]	Reduction
E-LH$_2$	3500	21%
E-NH$_3$	630	14%
E-MeOH	800	33%

Implementing these fuel prices in the Case Study changes the outcome of the decision analysis. E-MeOH performs better than both E-LH_2 and E-NH_3, see Figure 11.3.

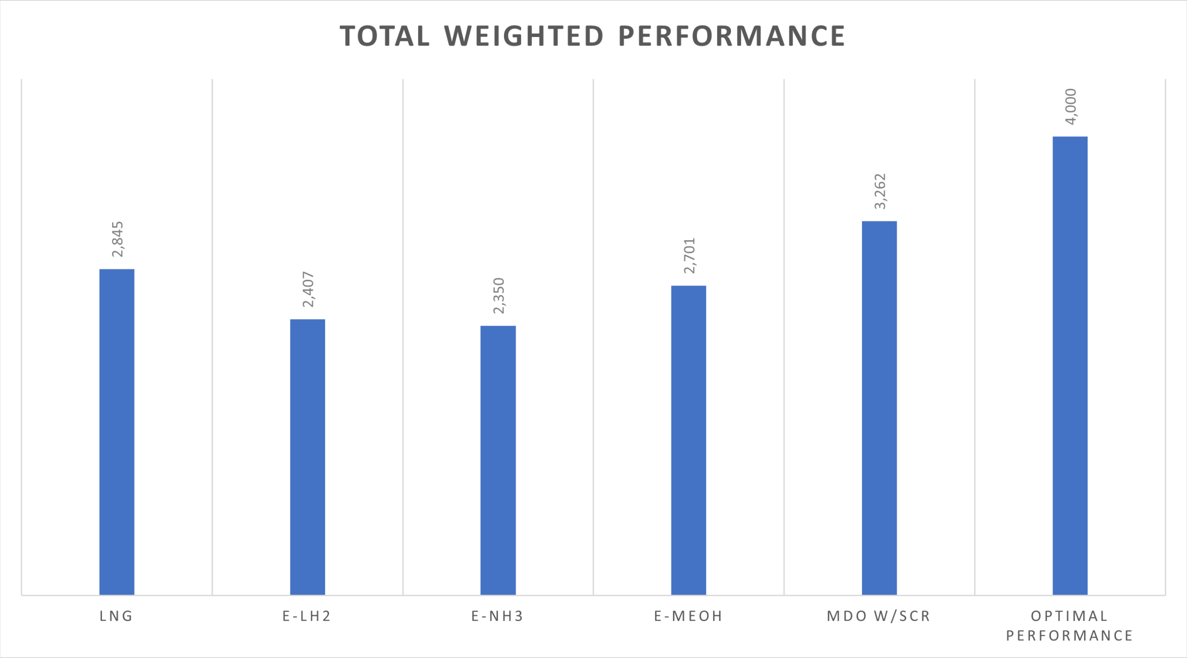

Figure 11.3: Case 1: Total weighted performance of the alternative fuels implemented in the reference vessel

11.8.2 Case 2: Weighting based on different stakeholders

The weighting in the decision analysis is based on securing a shipowner's interests, heavily impacting the results. Hansson et al. (2019) have through interviews derived how different Swedish stakeholders would prioritize different criteria in a multi-criteria decision analysis, see Figure 11.4. The economic criterion represents the VOYEX and extra CAPEX, technical covers infrastructure and reliable supply of fuel, while social focuses on safety.

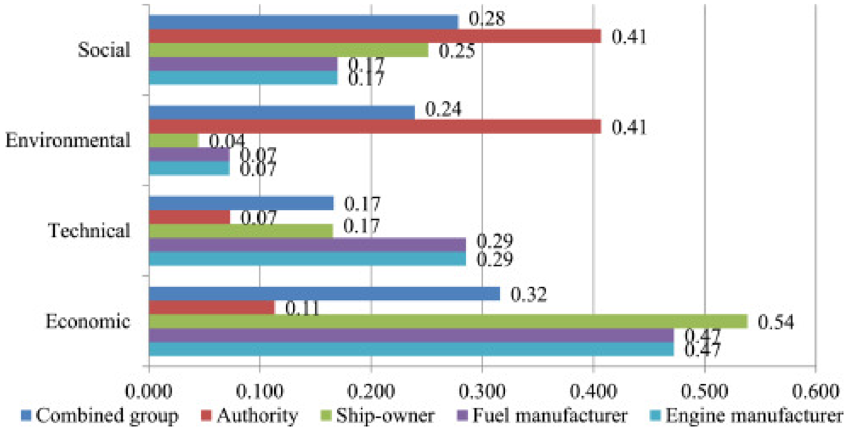

Figure 11.4: Relative importance of the main criteria for the different stakeholders from Hansson et al. (2019)

With this as a reference, the weights for an Authority, meaning the Norwegian Government, and for a Fuel/Engine Manufacturer is derived through the AHP-method. The weights are then implemented in the multi-criteria decision analysis, see Table 11.10 for the respective weights.

Table 11.10: Case 2: Weights for different stakeholders

	Authority	Fuel/Engine Manufacturer
VOYEX	0.074	0.279
Extra CAPEX	0.074	0.209
Environmental performance	0.382	0.067
Reliable supply of fuel	0.045	0.193
Infrastructure	0.045	0.153
Safety	0.382	0.100

Implementing the weights based on the preference of the stakeholder group Authority heavily influences the ranking of the options. Because the environmental performance is heavily weighted, both LNG and MDO with SCR technology rank lower than all three e-fuels. This seems reasonable because the Norwegian government is determined to reduce GHG emissions from the maritime sector by 50% by 2030. E-MeOH ranks the highest, followed by E-NH_3 and then E-LH_2. See Figure 11.5 for the total weighted performance.

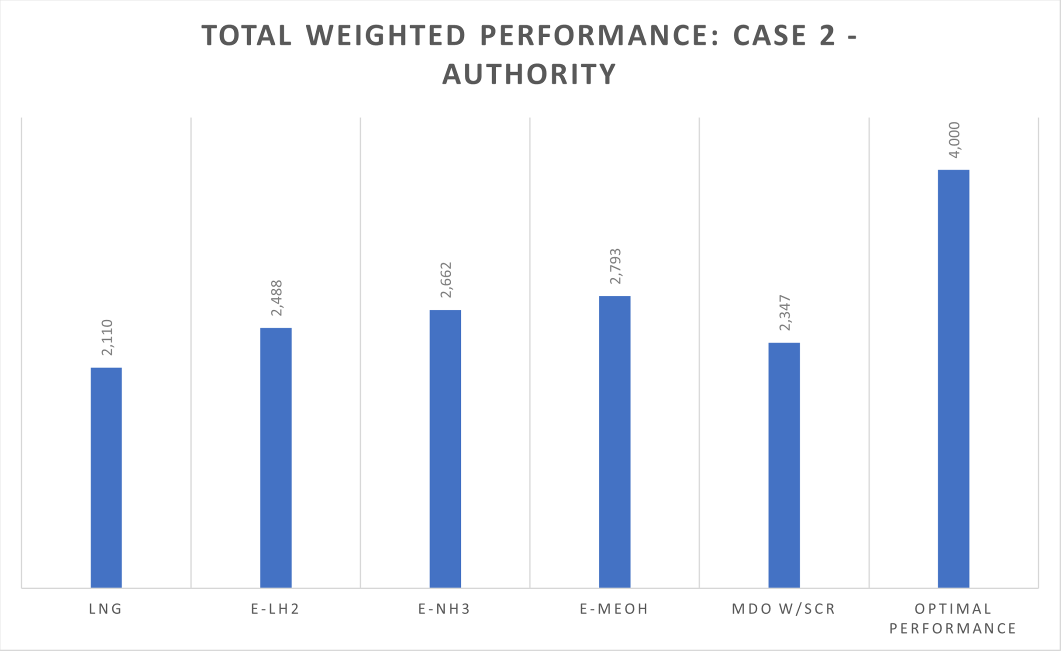

Figure 11.5: Case 2 - Authority: Total weighted performance of the alternative fuels implemented in the reference vessel

For the case of the Fuel/Engine Manufacturer as the stakeholder, the weights are somewhat similar to the shipowner's weights. The difference is the heavier weighting of the technical criteria, available infrastructure, and reliable supply of fuel, for fuel and engine manufacturers. In addition, the environmental performance is weighted less compared to a shipowner. Based on this, the green solutions perform worse compared to the initial results. There is no difference in ranking.

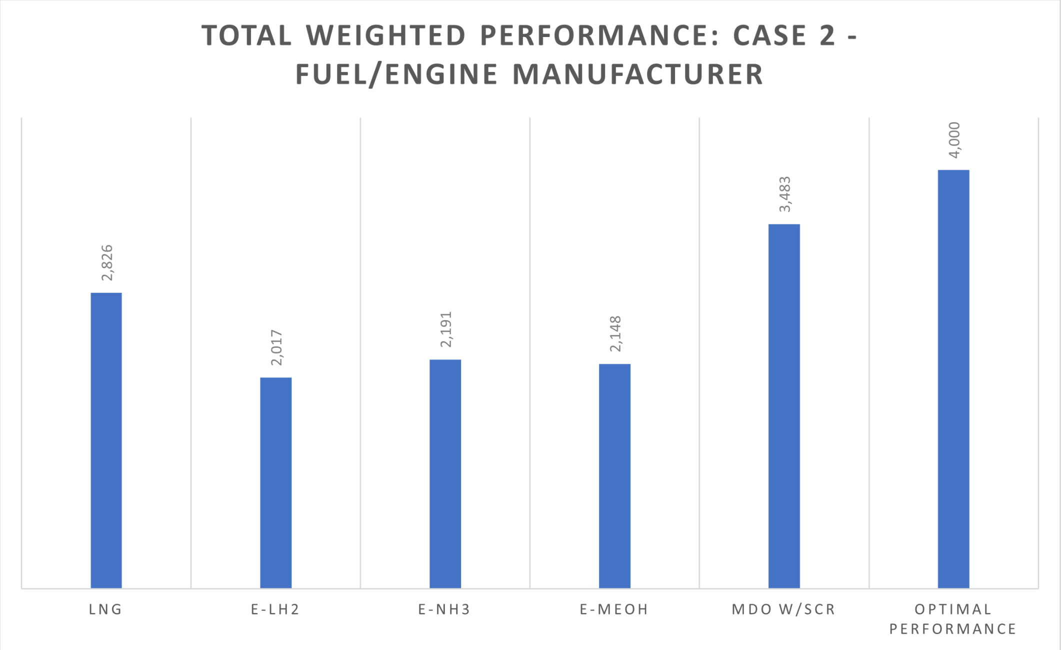

Figure 11.6: Case 2 - Fuel/Engine Manufacturer: Total weighted performance of the alternative fuels implemented in the reference vessel

11.8.3 Case 3: Only including GWP in environmental performance

For the environmental performance, an annual potential impact score is used to rank the different options from 1 to 4. The LCIA method utilized in this thesis weighs the effect of the local pollutants heavy compared to the GHGs. Even though local pollutants like SO_x and NO_x are regulated through legislation. The main concern of the general public seems to be the emissions of GHGs or CO_2-equivalents. Emissions of SO_x and NO_x can be regulated through exhaust gas cleaning, but to reduce CO_2 emissions you have to start with the energy carrier and converter. One reason for the CO_2 focus could be that IMO has gone very public in their goal of reducing GHG emissions until the year 2050, and many different nations expressing similar goals to minimize the increase in global average temperature. For this sensitivity case, the environmental performance is solely based on total yearly Global Warming Potential for both production and operation, see Table 11.11.

Table 11.11: Case 3: Environmental rating based on total yearly GWP for production and operation

	MDO w/SCR	LNG	E-LH$_2$	E-NH$_3$	E-MeOH
Environmental performance	**1**	**1.2**	**3.1**	**3.3**	**4**

Implementing this rating to the decision analysis does not change the fact that LNG and MDO have a more preferable performance than the e-fuels. This is due to the gap between them being too big based on the other criteria, especially the two economic criteria. Because the e-fuels all have similar CO_2 emissions per kWh during production, the annual pilot fuel consumption divides their performance. E-MeOH uses the least amount of pilot fuel and E-LH$_2$ the most. Compared to the rating of the same criteria in the initial decision analysis, the rating is quite similar when only GWP is included. This does not change the ranking. The differences between the three green options are, however, marginal.

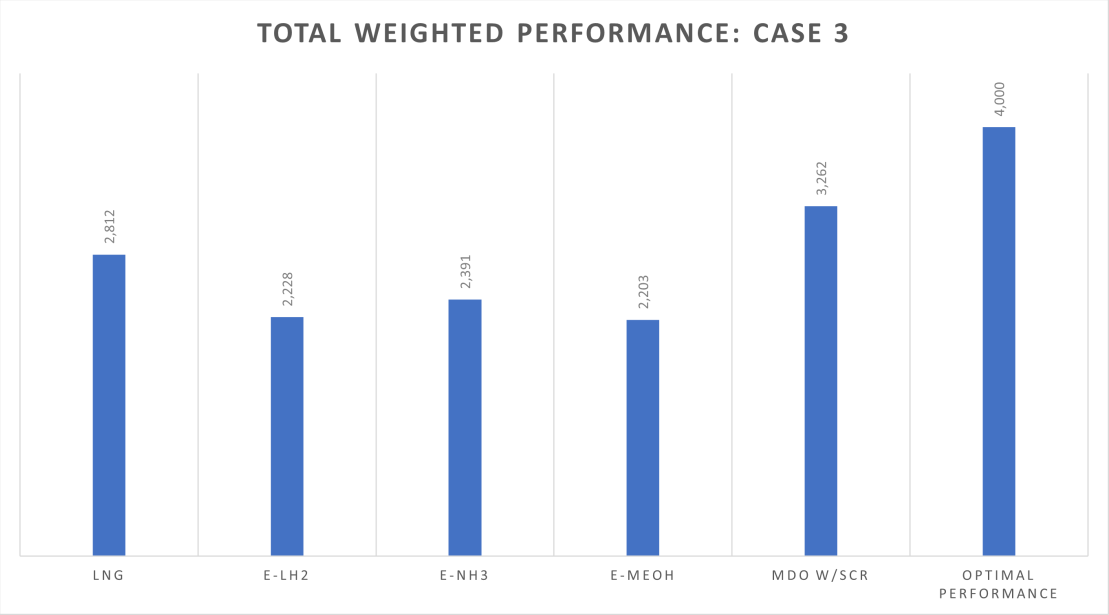

Figure 11.7: Case 3: Total weighted performance of the alternative fuels implemented in the reference vessel

11.8.4 Case 4: A combination of Case 1, Case 2 and Case 3

As a final case, it could be interesting to combine the three cases already assessed by only including GWP in the environmental performance, assuming a lower fuel price for e-fuels and performing the decision analysis for both a shipowner and the authority as stakeholders. See Table 11.12 for the criteria rating for case 4.

Table 11.12: Case 4: Environmental rating based on GWP and VOYEX rating based on lower fuel prices for e-fuels

	MDO w/SCR	LNG	E-LH$_2$	E-NH$_3$	E-MeOH
VOYEX	**3.5**	**4**	**3.2**	**2.9**	**2.2**
Environmental performance	**1**	**1.2**	**3.1**	**3.3**	**4**

For the case of a shipowner as the stakeholder with the values presented in Table 11.12, the ranking of the different options is highly affected. This case increases the overall performance of E-MeOH, ranking it over all e-fuel solutions and being barely outperformed by LNG. Under E-MeOH, we find E-NH$_3$ and E-LH$_2$ in that order.

Now for the same rating, but with criteria weights based on the Authority as the stakeholder, LNG scores the worst followed by MDO and E-LH$_2$, then comes E-NH$_3$ and on the top is E-MeOH. This result is quite similar to the one in case 2.

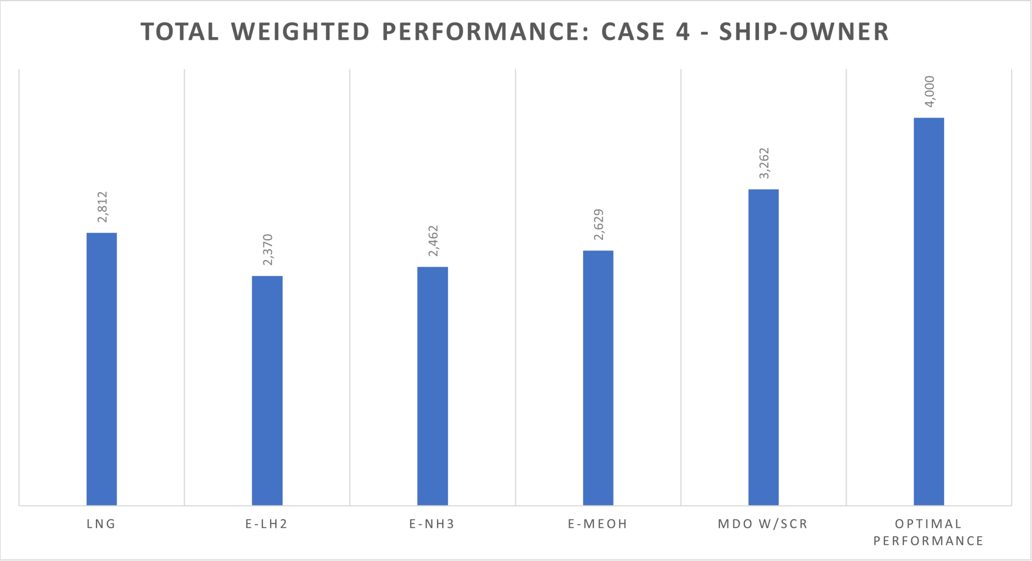

Figure 11.8: Case 4 - Ship-owner: Total weighted performance of the alternative fuels implemented in the reference vessel

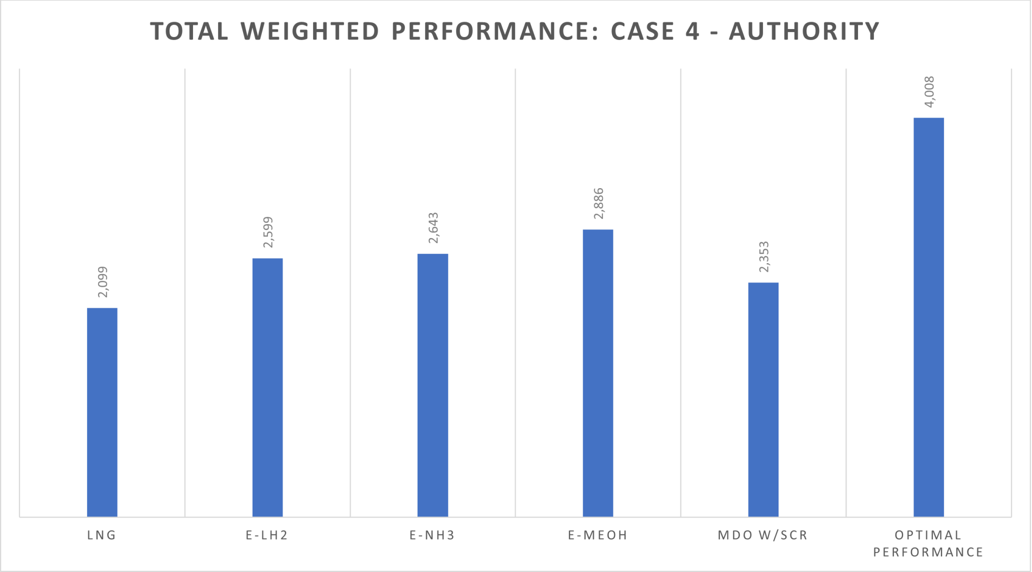

Figure 11.9: Case 4 - Authority: Total weighted performance of the alternative fuels implemented in the reference vessel

From the sensitivity analysis, it is evident that it is crucial to be aware of the assumptions and choices that lay the foundation for the decision analysis. The results are highly sensitive to a change in fuel price and defining criteria weights based on different stakeholder's preferences. In addition, the differences in total weighted performance for both the initial result and for the sensitivity analysis cases are often marginal and go down to the hundredths, especially for the green options. This makes it harder to interpreter the results and to define the options as the best. It is worth mentioning that the sensitivity analysis does not cover changing parameters and assumptions in the Case Study.

Chapter 12

Assessment of Ammonia

Based on the multi-criteria decision analysis results, it is decided to look closer at the implementation of ammonia. This is because MDO and LNG serve as a benchmark in this thesis, and because ammonia performs the best of the green alternatives. However, based on the sensitivity analysis and the overall marginal difference in performance for the green alternatives, all three could be relevant to assess further. Some parameters that impact this decision, in addition to the MCDA, is that based on impressions, it seems like ammonia will have the lowest fuel price of the alternative fuels in the future (Steinshamn, T. S. (2021)). Also, the fuel mix used for this thesis is the ammonia to pilot fuel ratio Wärtsila aims to accomplish from their testing. They have stated that they may achieve a bigger ratio of ammonia, from the R&D. They are also going to look into the possibilities of using hydrogen as pilot fuel. If both the ammonia and hydrogen are green, it would be possible to achieve a zero-emission vessel with an ICE. Lastly, it can be assumed that ammonia could be stored in A-type tanks much more space-efficient than C-type tanks. This could also reduce the required extension, but will not be assessed in this thesis.

In this assessment, the comparisons between ammonia and MDO will be taken further, focusing on the operation, the environmental performance during operation, and the cost of improving the environmental performance. The different ammonia concepts are to be compared with MDO. The concepts are defined based on the fuel mix ratio, see Table 12.1. The only major difference this brings is the tank volume required to meet the endurance requirement of 14 days, resulting in different length extensions.

Table 12.1: Ammonia-to-pilot ratio for the different ammonia concepts

Concept name	Main fuel	Pilot fuel
NH_3 - A	70%	30%
NH_3 - B	90%	10%
NH_3 - C	95%	5%

12.1 Operation

Based on the methods used in the Case Study, the different parameters can be defined for the three concepts. The ammonia is assumed stored in type C LNG tanks, basing the calculated tank volume and extension on the same assumptions as previously in the Case Study. See Table 12.2 for the calculated values. As expected, an increase in the ammonia-to-diesel ratio results in a higher SFC for ammonia, requiring a bigger tank and extension.

Table 12.2: Specific fuel consumption, tank volume and extension for the different ammonia concepts

	NH_3 - A	NH_3 - B	NH_3 - C	Unit
SFC Main Fuel	307.9	395.9	417.9	g/kWh
SFC Pilot Fuel	57.6	19.2	3.6	g/kWh
Required Power Capacity		688,800		kWh
Tank Volume	331	425	449	m3
Extension	8.7	10.6	11.1	m
LOA	75.7	77.6	78.1	m

Based on the estimated differences in power consumption for different length extensions presented in section 10.4, the new average power demands can be estimated. For concept A, the estimated differences for an extension of 8 meters are used. The values for an extension of 10 meters are used for concepts B and C. See Table 12.3 for the resulting power consumption for the general fishing trips.

Table 12.3: Power consumption for the general fishing trips

	NH_3 - A	NH_3 - B	NH_3 - C	Unit
Daily average	48,518	47,931	47,931	kWh
7 day trip	339,624	335,516	335,516	kWh
14 day trip	679,248	671,032	671,032	kWh

Based on the average daily power consumption, it is possible to assess the bunkering intervals for the different concepts. MDO is included as a reference where the maximum capacity of 460 m3 is used. The reference vessel does not necessarily fill the tank maximum during each filling, but it represents the possibilities of the vessel. See Table 12.4 for the maximum bunkering intervals. All three ammonia concepts have some fuel left after a 14-day trip because the power consumption dropped somewhat after the length extension compared to the power requirement, which served as a basis for the tank volume. However, they have to bunker at every return based on the assumption that it lasts 14 days. For the shorter fishing trips, the ammonia concepts have some more flexibility with just above two trips between bunkering. Compared to MDO, it is apparent that implementing ammonia as a fuel makes bunkering three times less flexible and that today's practice would require some modification. For the ammonia concepts, the bunkering becomes more planned, whereas MDO can be more selective of when to bunker based on fuel price. It is worth mentioning that *Libas* recently had its first Blue Whiting trip where it ran on LNG the whole time and returned with a good amount of fuel in the tank. Initially, this was expected to not be feasible and that it would have to run some on diesel to last the whole trip. This illustrates that for the operation and fuel consumption, it is hard to assess if the estimates hold any truth before testing in reality.

Table 12.4: Bunkering interval for the different ammonia concepts implemented in the reference vessel

	NH_3 - A	NH_3 - B	NH_3 - C	MDO	Unit
Full tank endurance	14.2	14.4	14.4	44.8	Days

Based on all of the defined parameters in this section, the annual power and thus fuel consumption can be estimated, see Table 12.5.

Table 12.5: Annual power and fuel consumption for the different ammonia concepts implemented in the reference vessel

	NH_3 - A	NH_3 - B	NH_3 - C	MDO	Unit
Yearly Power Consumption	10,868.0	10,736.5	10,736.5	11,020.8	MWh
Yearly Fuel Consumption:					
Main Fuel	3,346.4	4,250.5	4,486.7	2,069.6	tonne
Pilot Fuel	626.2	206.2	103.1	-	tonne

12.2 Environmental Assessment - Tank-to-Propeller

In the Case Study and MCDA, the total life cycle of the fuel was included in the environmental assessment, resulting in E-NH_3 performing among the best. Because it is established that the production of green ammonia has a low environmental impact compared to some of the other fuels assessed, it is determined to only assess the operation-related emissions, i.e. Tank-to-Propeller (TtP), for this section. This would provide a clearer picture of the possible reduction of the emissions most important for the shipowner. The assessment is based on the same LCIA as for the Case Study, ReCiPe2016H, and the same characterization factors and weightings are used. The emissions for the different concepts are defined to follow the same ratio as the fuel mix, e.g. for concept A, the emissions are 70% from E-NH_3 and 30% from MDO per kWh. All of the results, both at Midpoint and Endpoint, represent the performance over a year based on the annual power consumption previously defined. The resulting different environmental impact scores at Midpoint for the ammonia concepts are illustrated in Figure 12.1, Figure 12.2, Figure 12.3, and Figure 12.4. MDO with SCR is included as a reference.

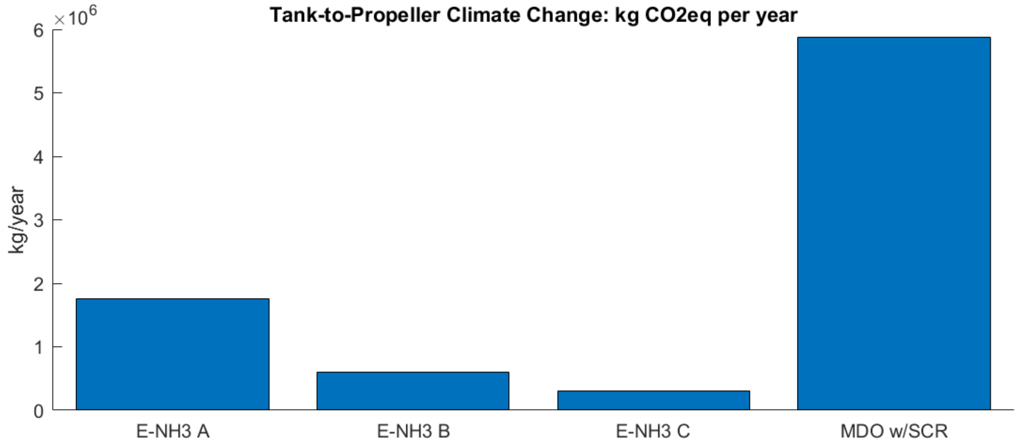

Figure 12.1: ReCiPe2016H Midpoint: Climate Change - Ammonia concepts TtP

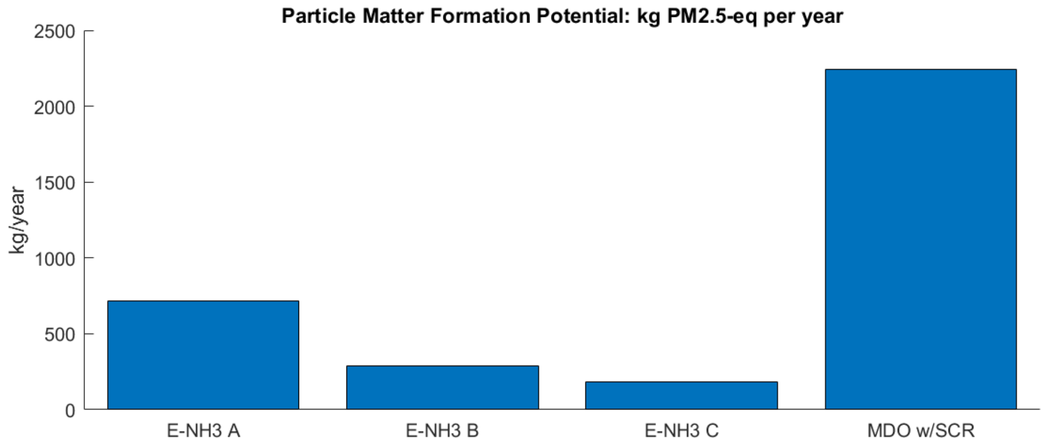

Figure 12.2: ReCiPe2016H Midpoint: Particle Matter Formation Potential - Ammonia concepts TtP

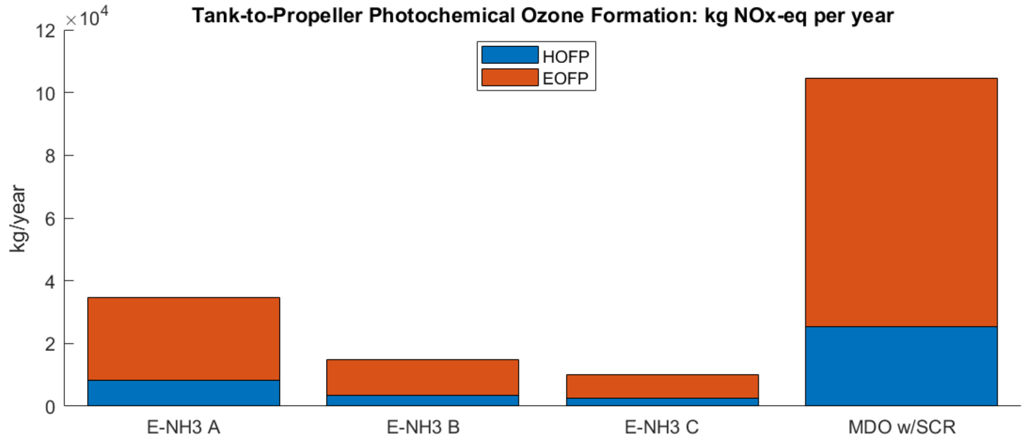

Figure 12.3: ReCiPe2016H Midpoint: Photochemical Ozone Formation - Ammonia concepts TtP

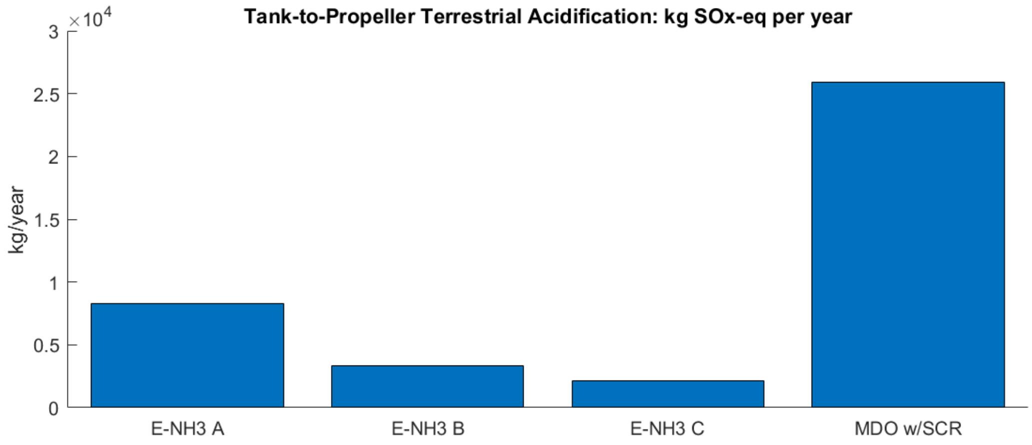

Figure 12.4: ReCiPe2016H Midpoint: Terrestrial Acidification - Ammonia concepts TtP

All four plots follow an expected pattern where MDO performs the worst and the ammonia concepts perform better with an increasing amount of ammonia in the fuel mix. The resulting environmental impact scores at Midpoint are summarized in Table 12.6. The values represent one year of operation.

Table 12.6: ReCiPe2016H Midpoint Summarized: Ammonia concepts - TtP

	NH_3 - A	NH_3 - B	NH_3 - C	MDO	Unit/year
Climate Change	1,754,800	593,000	307,800	5,877,200	kg CO_2-eqv
Particle Matter Formation Potential	700	300	200	2,200	kg $PM_{2.5}$-eqv
Photochemical Ozone Formation	34,600	14,900	10,100	104,500	kg NO_x-eqv
Terrestrial Acidification	8,300	3,300	2,100	25,900	kg SO_x-eqv

To make the results more comparable, the possible reductions compared to MDO are calculated for the impact scores at Midpoint, see Table 12.7. For Climate Change, it is possible to achieve emission reductions approximately equal to the ammonia ratio in the fuel mix for the different concepts. For the three other impact scores at Midpoint, the reduction potential is some percent lower than the ammonia ratio. In the Norwegian Government's action plan for green shipping, it is defined that a zero-emission ship is a ship that reduces the emissions of GHGs by 95% compared to conventional technology (Norwegian Maritime Authority (2019)). This would make it possible to classify concept C, with 95% ammonia and 5% pilot fuel, a zero-emission fishing vessel based on the results. The two other concepts meet more immediate goals of reducing GHG emissions by 50%. As a reference, the average annual emission of CO_2 for a typical passenger vehicle is 4.6 tonnes, according to EPA (2018). Based on this, it is possible to reduce the annual GHG emissions by approximately 900 cars by switching from MDO to concept A. For concept C, the annual reduction represents roughly 1200 cars. Concepts A, B and, C have annual GHG emissions representing 380, 130, and 70 cars, respectively. MDO's annual GHG emissions are equivalent to 1300 cars. For the local pollutants, no required reduction is found to classify a ship as zero-emission.

Table 12.7: Reduction potential for impact scores at Midpoint for the different ammonia concepts compared to MDO w/SCR

	NH_3 - A	NH_3 - B	NH_3 - C	Unit
Climate Change	70.1	89.9	94.8	%
Particle Matter Formation Potential	68.1	86.4	90.9	%
Photochemical Ozone Formation	66.9	85.7	90.3	%
Terrestrial Acidification	68.0	87.3	91.9	%

As for the Case Study, the different impact scores at Midpoint can be translated to Endpoint and finally weighted and normalized to retrieve the potential environmental impact, see Figure 12.5 for the graphical illustration. The performance follows the same pattern as for Midpoint. Climate change affecting human health is the main contributor to the total potential environmental effect.

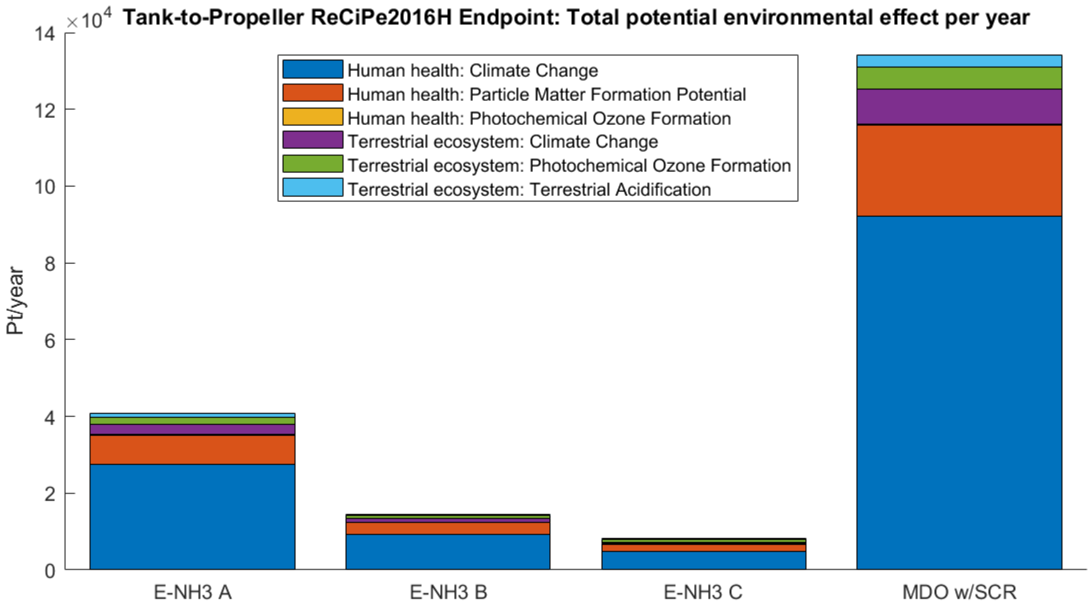

Figure 12.5: ReCiPe2016H: Yearly Potential Environmental Impact - Ammonia TtP

12.3 Financial Analysis

The fuel price for E-NH_3 is higher compared to MDO. By this, a higher reduction of emissions through a higher main fuel amount results in a higher fuel cost. An LCCA is performed for the different concepts to assess how a higher reduction in emissions affects the total cost over the investment duration of the vessel. The CAPEX and OPEX are estimated in the same way for this financial analysis as in the Case Study. For the VOYEX, the values from Scenario 2 in the Case Study are used, see Table 12.8.

Table 12.8: VOYEX related costs for the LCCA

	Cost	Unit
E-NH_3	734	EUR/tonne
MDO	504	EUR/tonne
CO_2	196	EUR/tonne
NO_x	2,750	EUR/tonne

The funding rate of extra investment costs is set to 40% and the investment duration to 15 years. The real interest rate is set equal to the one calculated in the Case Study, 5.68%. The residual value of the vessels after 15 years is set to 10% of the CAPEX. The calculated LCC for the different ammonia concepts with MDO included as a reference can be found in Figure 12.6.

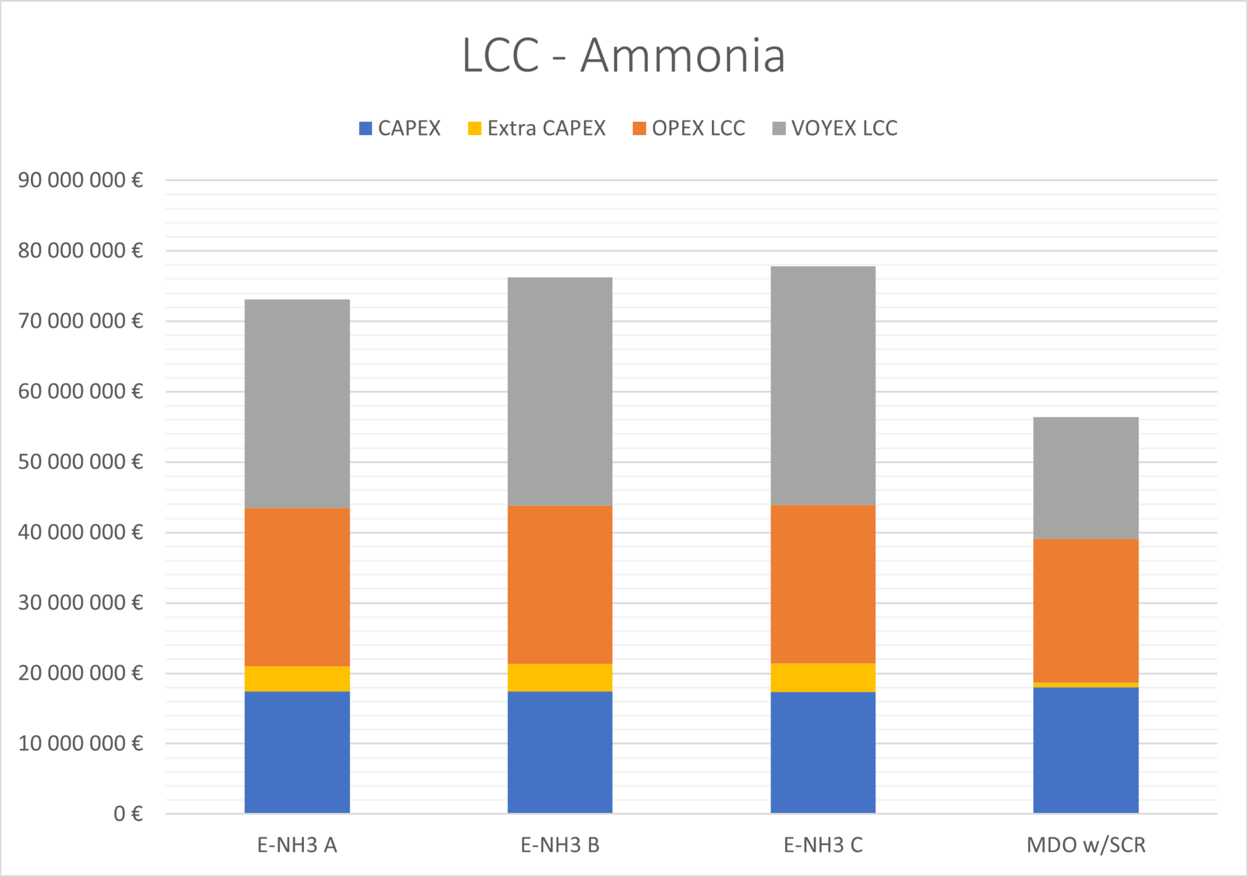

Figure 12.6: Life Cycle Cost for the different ammonia concepts

From the results, it can be seen that the ammonia concepts have a Life Cycle Cost of around 20 million EUROS higher than MDO over 15 years. It can also be seen that it is the VOYEX that causes the big difference in LCC. For the ammonia concepts, the difference in LCC between concepts A and C is 4.7 million EUROS or 315 thousand EUROS per year. This cost difference can be seen as the cost of improving the environmental performance by increasing the ratio of main fuel from concept A to concept C. Because concept C can be defined as zero-emission, it was assessed if exemption from taxation of emission would impact the the results. This had little impact on the LCC, with a total reduction of 340 thousand EURO over 15 years.

12.4 Design Assessment with a Focus on Safety

Based on the information presented in chapter 7 and chapter 8, it is clear that the general safety concept for ammonia as a fuel is very similar to the safety concepts of current regulations for LNG. The general safety concepts can be divided into four main categories; segregation, double barriers, leakage detection, and automatic isolation of leakages. However, for the more specific requirements in these categories, there are some differences. This section covers how the ammonia fuel system affects the ship arrangement based on both the general and the more specific requirements. This assessment is mainly based on Green Shipping Programme et al. (2021) and DNV (2021). Green Shipping Programme et al. (2021) is a safety handbook covering ammonia as a marine fuel. It is developed by Green Shipping Programme, DNV, and, the Norwegian Maritime Authority. DNV (2021) is a rule proposal for ammonia fuelled ship installations based on LNG rules. This means that information retrieved from this is not final and could change in the future.

12.4.1 Fuel Storage

For the storage of ammonia, there are two important focus areas. The first one is to store ammonia without releasing the vapor into the atmosphere. The other is to protect the ammonia fuel installation from external events capable of damaging the tank and cause a release of ammonia.

To store ammonia as liquid, it must either be compressed, refrigerated, or a combination of both. As previously mentioned, it requires a temperature of -33 °C at atmospheric pressure to remain liquid when fully refrigerated and up to 18 bar at 45 °C when fully pressurized. The tank type depends on the storage method. For fully refrigerated ammonia, type A tanks are used, and type C tanks for semi- or fully pressurized. Because venting of tank vapors should be prevented, the tank would require a boil-off gas management system if not designed for the full vapor pressure of ammonia at 18 bar. Type A tanks require secondary barriers, management of leakage scenarios, and the possible emergency venting of fuel gases must therefore be specially considered if this tank type is chosen. The secondary barrier should also be capable of containing all leakages while preventing lowering the temperature of the ship structure to unsafe levels. Compatibility with bunkering facilities concerning pressure and temperature can also impact the choice of the tank if it highly affects the flexibility during operation. The corrosivity of ammonia also creates some requirements for the materials used in the storage tank. If the containment system is made of carbon-manganese steel or nickel steel, the ammonia may cause stress corrosion cracking. Copper or zinc should also be avoided. This applies to all the different components included in the ammonia fuel system.

For the location of the tank, the location must reduce the probability of a leak following a collision or grounding to a minimum. The specific design requirements to protect from this scenario specifies that the tank should be placed at a minimum distance of B/5 or 11.5 meters from the ship side and a minimum of B/15 or 2 meters over the bottom shell plating. The tank should also be protected from mechanical damage, i.e. shielded from exposure to ship and cargo operations. With nets, cranes, wires, and different equipment located all over the deck on a fishing vessel, it is deemed unfeasible to place the tank on deck. Figure 12.7 illustrates how a possible arrangement for the placement of an LH_2 tank in a purse seiner/pelagic trawler. The illustration is retrieved from Thorkildsen (2019), which covers a technical feasibility analysis of using fuel cells with hydrogen as fuel on a purse seiner/pelagic trawler. The illustration is based on *Libas*, capable of running on LNG. It is assumed that a similar placement is feasible for ammonia, given that it is stored in a type C tank.

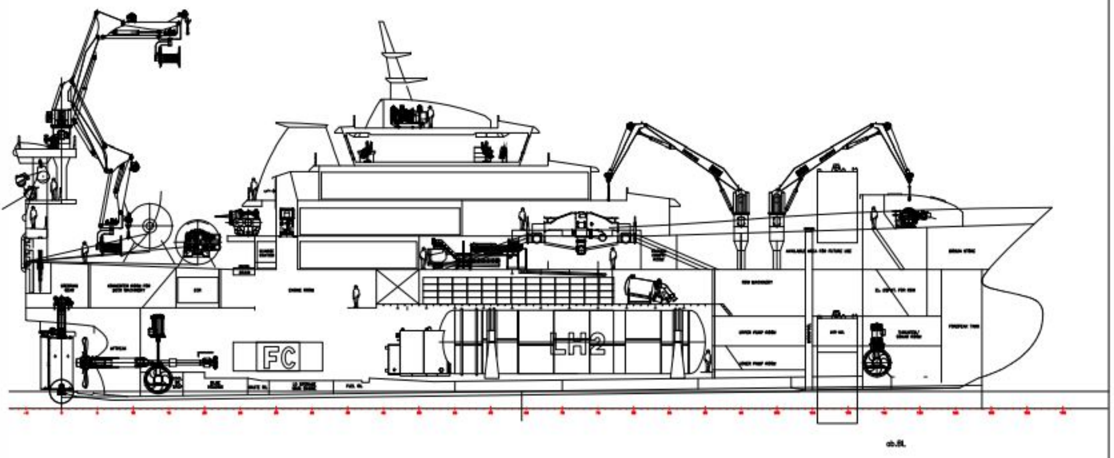

Figure 12.7: Side-view illustration of possible tank placement. Retrieved from Thorkildsen (2019)

12.4.2 Separation of Systems

The main focus of separating the different systems into a tank connection space and a fuel preparation room is to safely contain leakages, to prevent ammonia from spreading to other areas onboard. All tank connections, flanges, and tank valves should be located in the TCS. The fuel preparation room is defined as any space containing pumps, compressors, and/or vaporizers for fuel preparation purposes. These spaces must be gas-tight to prevent possible leaks from reaching other areas in the ship. When gas-tight, they work as a secondary barrier, and the piping inside these spaces does not have to be double-walled, which is practical concerning the different components.

If not accessible directly from the open deck, the TCS and FPR should only be accessible through an airlock. An airlock is a space enclosed by gas-tight bulkheads with two gas-tight doors that are self-closing spaced between. This makes it easier to restore gas tightness should a leakage occur, in addition to easier access compared to the use of a bolted hatch. As mentioned in chapter 7, ammonia is very hygroscopic. To reduce the concentration of ammonia outside the TCS and FPR, water curtains should be arranged outside of the entrance to catch escaping ammonia vapors. For the safety of the personnel, gas masks and filters should be located on the outside of the spaces. Two sets of suitable protective clothing should also be available in the vicinity. Decontamination showers and eyewashes are also required close to the entrances. None of the spaces should be directly adjacent to other rooms with high fire risk.

The ventilation arrangement is important for the TCS and FPR because it should dilute potential leakages in to prevent leaked gas from spreading, ensure that the space can withstand any pressure build-up caused by vaporization of the liquid fuel, and create an under-pressure in the spaces compared to surrounding areas. The ventilation outlets should be located in areas with low risk to harm personnel and where the gas will not spread to other areas in the ship. Another measure to avoid the spread of toxic vapors is by fitting the spaces with inlet and outlet ducts only dedicated to that single space. This arrangement shall have a capacity of at least 30 air changes per hour. A permanent gas detection system is required for both the TCS and FPR. This gas detection system should alert when the concentration of ammonia reaches 150 ppm. When the concentration reaches 350 ppm, all valves required to isolate the leakage should automatically close, and catastrophe ventilation shall automatically start. The capacity defined for catastrophe ventilation is 300 m3/h for each m2 deck area capable of getting wet, but not less than 45 air changes per hour.

12.4.3 Fuel Supply

Similar to both fuel storage and the separation of systems, the main safety focus for the fuel supply is to safely contain and prevent discharges of ammonia during operation. To fulfill the double barrier principle, the ammonia piping should be double-walled to prevent possible leakages from spreading. This requirement is however exempted when the piping is located in the TCS of FPR because these spaces work as a double barrier. A leakage from the main enclosure would increase the pressure in the secondary barrier. To avoid excessive pressure build-up, the secondary enclosures shall be fitted with a single vent pipe led to a safe area in the open air. It can be added that ammonia expands drastically when going from liquid to gaseous state. To avoid an expansion in the pipes leading to operational discharges, the fuel supply system should be designed with a minimum design pressure of 18 bar, corresponding to the vapor pressure for ammonia at 45 C°. If a pipe segment is not designed for this, it shall be fitted with pressure relief valves.

The rules state that for propulsion and power generation using ammonia as the only fuel, the fuel supply system should be designed with redundancy and segregation to avoid losing propulsion should a leakage occur. The dual-fuel engine creates some redundancy because it capable of running on diesel alone. This means that for the given case, it is not required with redundancy and segregation for the fuel supply system, but it should be considered if it is desirable to remain propulsion by ammonia should a leakage occur.

The fuel supply line to the engine shall be equipped with a manually operated stop valve and an automatically operated master fuel valve coupled in series. It should also be fitted with an arrangement used to purge the ammonia from the supply piping after the master fuel valve.

12.4.4 Machinery Space

The main focus area in the machinery space is to reduce the risk of leakage. This is important for the machinery space because personnel is often located here, and it is important for the propulsion of the ship that the room is accessible. The engine room is considered gas safe if all ammonia systems are fitted with secondary barriers. When considered gas safe, the machinery space can be arranged as a conventional one. From this, it is also important that there is no direct access between the machinery space and spaces designed to contain possible leakages like the TCS and FPR, for example.

From a maintenance perspective, it should be possible to safely isolate components located in the machinery space through manual valves and purging.

Based on the assessment thus far a principle diagram for the ammonia fuel system can be created, see Figure 12.8.

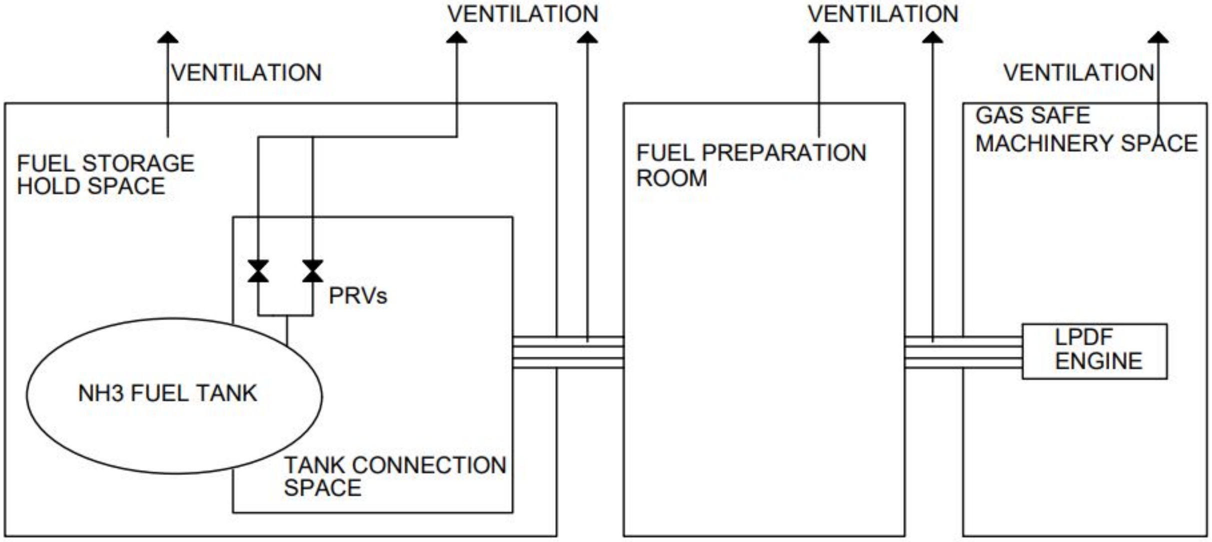

Figure 12.8: Principle diagram for ammonia. Adapted from Green Shipping Programme et al. (2021)

12.4.5 Flammability

Hazardous areas are areas in which an explosive gas atmosphere is or may be expected to be present. To obtain hazardous area classification, a hazardous area classification drawing is required. Hazardous areas are divided into three areas:

- Zone 0 - Area in which an explosive gas atmosphere is present continuously or for long periods
- Zone 1 - Area in which an explosive gas atmosphere is likely to occur during normal operation
- Zone 2 - Area in which an explosive gas atmosphere is not likely to occur during normal operation

Due to the relatively low flammability of ammonia compared to methane and hydrogen, ammonia only constitutes an explosion risk in confined spaces. Thus enclosed spaces with potential for ammonia leakage should be classified as zone 1. This applies to TCS, FPR and, fuel storage hold spaces. There is no need for defining hazardous zones on open deck.

12.4.6 Toxicity

The hazardous area covers only the risk of explosion. It is a bigger concern to limit the risk of exposure to ammonia vapours to people because of its toxicity than of its risk of explosion. The venting of ammonia should be avoided during normal operation. When designing the vent system, arrangements reducing the discharge to open air should be considered even though a total elimination of discharge from the ventilation system is impossible. Because total elimination is impossible, it is required to define toxic zones on open deck where the discharge of ammonia vapor in health-affecting concentrations has a high probability of occurring. These toxic zones are required to be defined in a toxic zone classification drawing where the safety distances from vent mast and ventilation systems with openings are illustrated.

There exist no previous experience in managing the risk of toxic fuels from rules and regulations, but some experience exist for the handling of toxic cargo like ammonia. From the IGC Code and IBC Code some guiding minimum requirements can be defined. According to Green Shipping Programme et al. (2021) the safety distance to ventilation mast outlets should be at least equal to B or 25 m, whichever is less, to the nearest air intake and other non-hazardous spaces. The ventilation mast is dedicated to the pressure relief system in the tank. The ventilation outlets shall be located at least 10 m from ventilation inlets to non-hazardous spaces and at least 4 m above deck. The final required distances is not yet defined for ammonia as fuel.

Purse seiners/pelagic trawlers when engaged in fishing have a lot of personnel performing different tasks required for the operation. Most of them are performed out on deck. If the ventilation of potential fuel leakages are not to harm the personnel, the outlet and inlet placement requires thorough assessment. Mustering stations and lifesaving equipment shall also not be located in toxic zones. It can be expected that the toxic zones will be placed high independent of if the distance requirements become 5 or 20 meters. Figure 12.9 illustrates possible placements areas of the toxic zones, the height does not necessary represent a sufficient safety distance.

Figure 12.9: Potential placements areas of ventilation outlets

Based on the potential placement areas, different safety distances are illustrated in Figure 12.10. One ring represents five meters. It can be seen that some design modifications are required if the safety distance exceeds 5 meters. The aft placement has a lot of operation-related activity making it extra challenging. The two other areas are also often occupied by personnel.

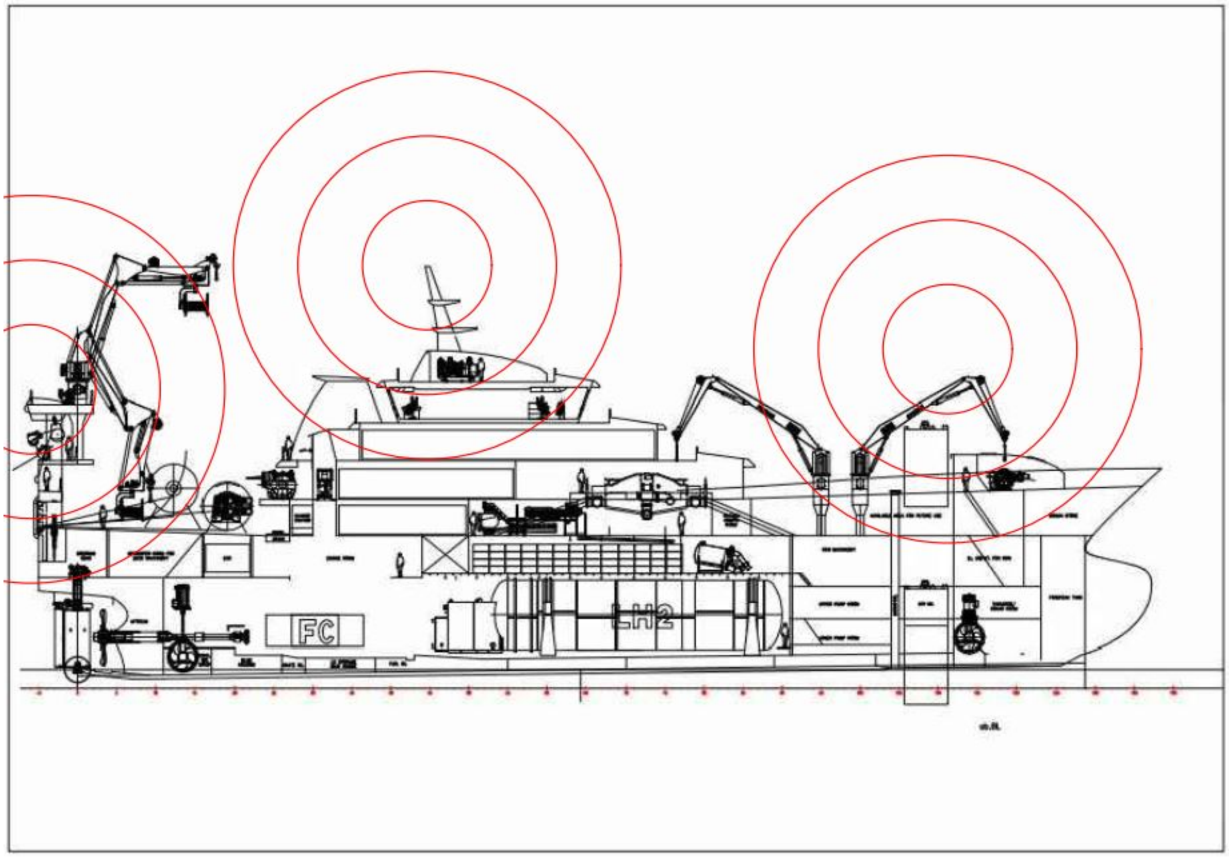

Figure 12.10: Illustration of different safety distances, one ring represent 5 meter. Adapted from Thorkildsen (2019)

Chapter 13

Discussion

13.1 Parameters and Vessel Characteristics

A Case Study was performed to assess the implications the different fuels had on the parameters of the reference vessel based on a general annual operation. The implementation of LNG, LH_2, and NH_3 requires a length extension if the endurance requirement is to be met while maintaining the same fish storing capacity. MeOH can meet the endurance requirement through storage in the reference vessel's conventional tanks. Based on estimates provided by Salt, the length increase was defined to reduce resistance at higher speeds and increase the resistance somewhat at lower speeds. The estimates are calculated with the same deadweight for both the original and the extended vessel. This resulted in lower annual power consumption for the extended vessels because 51% of the annual operation is transit where the wave resistance dominates the total resistance. The assessment of the parameters in the Case Study consists mostly of a qualitative approach, which is sufficient at the level aimed to cover by this thesis. Both the required length extension and change in resistance should be revisited as further work. The implementation of a type C tank will have great repercussions. It would affect the arrangement as everything would require to be placed around the tank room. Both the rearranging and the tank itself impact the center of gravity of the vessel. The stability of the vessel would then require further assessment. In addition, the different fuels have different densities requiring every fuel to be individually assessed. It is, however, worth mentioning that the estimated required extensions are somewhat similar to the extension resulting from implementing LNG in Libas. Extending the hull will impact the hydrodynamics of the vessel in addition. For this thesis, a qualitative approach is used for assessing this change in resistance. Assuming the resistance will change similar to the estimates provided by Salt is deemed an adequate approach for this thesis. However, moving forward, a more thorough study to should be conducted for the reference vessel to ensure a correct estimation of the power consumption.

Both the size of the quotas and the location of the fish varies annually, making it somewhat challenging to define a general annual operation. Defining time in close and remote waters affects the required taxation of emissions. The general annual operation also defines the number of days at sea, consequently affecting the annual power and fuel consumption. To achieve a more accurate estimated power consumption, a knowledge transfer with the vessel owner about their logistics, duration of different species-specific fisheries, annual power consumption, and other relevant information would be helpful. Other shipowners looking to investigate how these results apply to their vessel, should consider how the annual power consumption compares. Preferably the yearly power consumption would be of the same magnitude as for the Case Study.

The method assessing the length extension is mainly based on LNG, as the tank is assumed to be equal for all three fuels. However, LH_2 requires much lower temperatures than the other fuels, and the tank arrangement could be assumed to be more space-demanding than for LNG and ammonia. In addition, it is possible to store ammonia in much more space-efficient type A tanks. This would possibly lead to a shorter required extension. There are several alternative setups of components not assessed in this thesis, mainly due to time limitations. It could be interesting to evaluate how ammonia stored in a type A tank would compare to a tank type C. The former requires less space but requires a more expensive treatment system for boil-off gas. Another possible setup could be how an ICE running on MDO responsible for the propulsion load and a fuel cell running on hydrogen providing power for the hotel loads would perform. This could be an interesting setup if the main goal is to reduce emissions only to some degree and avoid increasing both the investment and fuel cost drastically. This could serve as a short-term alternative given it is capable of reducing GHG emissions by 50%.

The vessel running on LH_2 is defined to only run on diesel when in remote waters during the Blue Whiting fishing trips, affecting the annual MDO consumption. Even though LH_2 has a lower pilot fuel ratio compared to the ammonia solution, the LH_2 vessel has a higher annual consumption of MDO. The higher MDO consumption impacts different aspects of the vessel, both negative and positive. Firstly the environmental performance is worsened due to a higher MDO consumption. The financial performance improves because it requires a smaller tank and uses less LH_2 annually, far more expensive than MDO, i.e. a lower CAPEX and VOYEX than if the vessel was to have an endurance of 14 days in hydrogen mode. Further work could be to investigate how it would perform compared to the other solutions if it ran maximum on hydrogen before switching to MDO during the said fishery. This would improve the environmental performance but drive up the cost.

13.2 Environmental Assessment

The Life Cycle Impact Assessment performed in the Case Study revealed that a substantial reduction in the release of GHGs and local pollutants is possible by implementing green fuels combusted in a dual-fuel ICE for the given reference vessel. The fuel solution ranking is as expected, with all natural gas-based fuels performing worse than LNG and the green fuels and LNG performing better than MDO. As previously mentioned, the LCI is based on values from different LCAs. Even though the different system conditions are summarized in the thesis, it is hard to control how the authors have defined values regarding the calculation. This makes it challenging to assess how the different LCAs compare to each other.

Both green ammonia and green methanol are among the top performers regarding environmental performance, at both Midpoint and Endpoint. As previously stated, none of the emission values during production of E-MeOH is based on an existing LCA. Based on qualitative assumptions, the production emission value for CO_2 is estimated. The fact that this value is based on relevant articles makes it usable as a reference for now. What also strengthens the estimation is that the value is similar to that of E-NH_3 and E-LH_2. All three have somewhat similar processes and could be expected to have emissions of the same magnitude. From the results in the environmental assessment, it was also clear that the emissions of GHGs have the biggest impact on performance. The rest of the production emission values for E-MeOH are assumed similar to E-NH_3. Some of the emission values during production for E-NH_3 are not found in any LCAs and are assumed equal to E-LH_2. Some of the emission values for E-MeOH are thus equal to those for E-LH_2. To improve the validity of the LCI and consequently the results from the environmental assessment, an LCA of natural gas-based ammonia, green ammonia, and green methanol should be conducted with similar system conditions and parameters to the one performed for LNG, LH_2, and natural gas-based methanol. Based on this, it is important to be somewhat critical of the result and use it more as an indication. Batteries are not accounted for in this LCI. Batteries will have an impact on the environmental performance as both production and the recycling of batteries will lead to emissions.

Based on a public impression, it is the emissions of GHG that are the main concern with relation to the environment. Everyone from private persons to businesses and governments aims to reduce their release of said emissions. The LCIA method ReCiPe 2016 weighs local pollutants heavily compared to GHGs when calculating the total potential environmental effect. This does not seem to reflect the public opinion at first. The environmental flows of GHGs at Midpoint are, however, of greater magnitude than the local pollutants. From the illustration of the total potential environmental effect, it can be seen that the emissions of GHG that affect human health have the highest share by far. In the end, the total environmental performance gives the emission of GHGs the contribution that reflects that of public concern.

The environmental impact at both Midpoint and Endpoint is included in the assessment. This is due to the higher degree of relation to the emission flows at Midpoint and the relative environmental effect the different emission flows have at Endpoint. This makes it possible to compare the more specific emission flows, e.g. CO_2-eqv., for the fuels at Midpoint and how the fuels compare on a total environmental impact basis. It is worth mentioning that the values at Midpoint follow a more standard calculation method and is more academically recognized when assessing the environmental performance of processes than the Endpoint method. This is mainly because several different LCIA methods exist, providing several possible conclusions regarding the total environmental impact. For non-experts in this field, it is, however, hard to interpreter the Midpoint values concerning what is a good or bad performance in addition to the relative importance of the different Midpoint values. Based on this, the weighted and normalized Endpoint values are used quantitatively in this thesis.

Methods used in LCA studies are originally developed for assessing land-based industrial processes (Ellingsen and Aanondsen (2006)). Adapting these to fishing applications would improve the accuracy of the environmental impact assessment concerning the operation of the fishing vessel. The topics with poorly covered indicators for impacts are over-fishing, local pollutants, antifouling, and seafloor ecosystem disturbance (Ellingsen and Aanondsen (2006)). The last impact is less relevant for a purse seiner/pelagic trawler as they operate mid-water. Moving forward, it is recommended to improve these impact indicators to improve the environmental assessment of the fishing operation.

Defining the environmental performance per unit of fish delivered, either kg or tonne, was considered to generalize the results and make them easier to compare to other vessels. Because the environmental performance was defined based on a general annual operation and quotas, it was deemed that the generalization would not achieve a sufficient certainty. This would be more relevant if each species-specific fisheries were assessed. The emissions of CO_2-eqv. could for example be defined as CO_2-eqv. per tonne of Mackerel.

13.3 Financial analysis

The financial feasibility for the different solutions has been assessed through a Life Cycle Cost Analysis in this thesis. To perform this analysis, the CAPEX, OPEX, and VOYEX were investigated with a mix of a qualitative and quantitative approach. The extra investment cost and the annual fuel cost were found to be very different for the different solutions. The fuels requiring both length extensions and type C tanks were among the more costly concerning the CAPEX. For the fuel costs, the green fuels have a substantially higher expense compared to LNG and MDO. The LCCA revealed far less competitive Life Cycle Costs for the green fuels compared to that of MDO and LNG, both for today's scenario and for the future where the emission taxes increases and green fuel prices decrease according to the estimations of LR and UMAS (2020). This analysis is performed with a constant real interest rate and fuel price. The real interest rate is hard to estimate without knowing the future economic situation and risks. In reality, the fuel price will vary based on supply and demand, location and future rules, and regulations. The vessel uses spot prices and chooses bunkering spots based on marginal profit in a realistic operation.

From the LCCA, it is clear that the fuel price is a limiting factor for phasing in green fuels in fisheries and the maritime sector in general. The extra fuel cost for alternative fuels exceeds the additional investment cost early in the vessel's lifetime. In addition, it is possible to retrieve a substantial amount of funding for the extra investment cost today. Based on this, a further financial assessment was carried out to assess the average required fuel price for the different solutions to break even after 10 years. The quotas and fish price is assumed constant, resulting in an average annual revenue. This assessment revealed big gaps between the predicted fuel prices and the fuel prices required for the solutions to be financially feasible. Different future possibilities could reduce this gap. Local production utilizing low electricity prices combined with technological maturing of the production methods would lower the different fuel prices and impacting the VOYEX. The fuel prices used in this thesis are not estimated for local production in Norway but more globally. It could be expected that the estimation would be somewhat lower if this was the case. Another possible reduction measure could be involvement by the Government, either in the form of establishing some sort of funding system or in the form of incentives. This thesis is not to speculate how a funding arrangement should be regulated, but the gap reveals a big limiting factor for making fishing vessels greener. With the general public having an increased concern for the environment, one possibility could be paying more for ”green” fish. The requirement for a fish to be green could be requiring it was caught by a vessel with an emission reduction of a given percent compared to that of a standard solution. This would provide the green vessels with a higher income and thus reducing the gap. This could very well be an idealization and not possible to introduce, but a somewhat similar pattern is seen for shipping. There are examples of several companies willing to pay extra for green transportation of their goods recently. It can be expected that going forward, this demand will increase, and similar trends could possibly occur in the fishing industry.

13.4 Multi-Criteria Decision Analysis

A multi-criteria decision analysis from the perspective of a shipowner was performed and revealed that more traditional solutions like MDO with SCR technology and LNG are favorable compared to green fuels. Mainly due to their lower VOYEX and CAPEX, in addition to a more reliable supply of fuel. A sensitivity analysis was performed to assess how the different criteria and stakeholders affected the results. Only from an Governmental perspective, with a heavy focus on environmental performance, did the ranking change with the green fuels performing best. This implies a contrast between the two stakeholders. At the end of the day, it is however the shipowners that make the final decision favoring the financial aspect at the cost of environmental performance if required of them. The Government can only try to influence, through different measures, to make the green solutions more financial sound compared to the traditional solutions. This influencing is, however, a delicate matter as it should not drive anyone out of business. Based on the MCDA, future measures like an increased CO_2 tax do not seem to be adequate. With the Paris Agreement and the reduction goals of both Norway and IMO, it is deemed unsafe to bet on traditional solutions for the future, despite the results. It is a big gamble to put all eggs in one basket and not having the possibility of switching to greener fuels in the future. One possible solution is making vessels for LNG that are ammonia-ready. This notation means that all requirements for ammonia are taken into consideration in the design process. Because ammonia can be stored in type C tanks, only some minor tweaks are required for the dual-fuel engine. This would, however, result in a twice as low endurance based on the lower energy density for ammonia. This solution is a way of diversifying the vessel with LNG as a short-term solution, and should the fuel price of ammonia drop to a financially feasible level, it is relatively easy to switch.

The sensitivity analysis revealed that two different scenarios could lead to E-MeOH performing better than E-NH_3. The defined fuel price reduction to 800 EUR/tonne for E-MeOH would bring it above ammonia in the MCDA ranking. Roughly estimated, the ranking changes when E-MeOH is reduced to under 930 EUR/tonne from a shipowners perspective. The other scenario is when the Government is the stakeholder, weighting the environmental performance highest. Despite these findings, ammonia is still chosen to investigate further for several reasons. The reduction in price for E-MeOH is qualitatively assumed, and could possibly not be an accurate prediction. Methanol has a much lower extra investment cost compared to ammonia when ammonia is assumed stored in type C tanks. Storing ammonia in type A tanks could reduce the extra investment cost related to ammonia. The possibility of designing ammonia-ready vessels using LNG at first is also an advantage for ammonia.

Further work should include performing a survey, much like the one performed by Hansson et al. (2019), assessing what criteria Norwegian maritime stakeholders emphasize, in addition to their respective weighing. One could assume that answers from Swedish maritime stakeholders would be similar, but performing a survey would ensure proper criteria and weights reflecting the situation in Norway are applied. Additionally, it would be easier to define a more precise weighting for the different stakeholders.

13.5 Assessment of Ammonia

Based on the MCDA, it was determined to further assess ammonia. This assessment is similar to the Case Study but with three different ammonia concepts. The concepts are defined based on different ammonia and pilot fuel ratio possibilities in the future. Only a type C tank was considered for the assessment. Moving forward, it would be interesting to assess how a type A tank would compare for this Case Study. Today's operation pattern would require some changes as the ammonia concepts would require bunkering more frequently than a traditional vessel. The environmental assessment focuses only on Tank-to-Propeller emissions, and it is found possible to reduce the emissions of GHGs by 70% and 95% for concepts A and B, respectively. By using a car with an annual average emission of 4.6 tonnes of CO_2, this equals a reduction of 900 and 1200 cars. For the total environmental impact at Endpoint, the reduction potential is equally high. Reducing the GHG emissions by 95% instead of 70% comes, however, with a cost of 4.7 million EURO over 15 years. This assessment does not take into account the possible N_2O slip. For ammonia to be a feasible solution in the future, this mustn't become a problem as it is one of the most potent GHGs, much stronger than CO_2.

The design assessment concerning safety was carried out with a mix of qualitative and quantitative approaches because the regulations for ammonia are yet to be defined finally. The proposed rules used in this thesis are probably to undergo many more revisions before the final class regulations for ammonia are defined. The assessment does however highlight the most important safety barriers required to ensure a safe operation, which in general can be defined as applying the single failure criterion for different components in the ammonia fuel system. Much of the same practice used for LNG can be used for ammonia with some minor tweaks. The greatest change is the requirements for ventilation and more strict safety distances and toxic zones based on ammonia's toxicity. Most fishing operations are performed on deck, and a thorough assessment of the placement of ventilation outlets is required to ensure no exposure to personnel. Other than ventilation, the single failure criterion is fulfilled through segregation of systems, double barriers, detection of leakages, and isolation of leakages. This assessment highlights how these safety concepts can be implemented. When more specific regulations are defined in the future, the design assessment can be taken one step further through concept designs and preliminary arrangements. In addition to implementing safety in the design, it must be implemented in the daily operation. Fishing vessels and fishermen have no experience with ammonia as fuel, requiring proper training and education to ensure a safe operation.

Chapter 14

Conclusion and Further Work

14.1 Conclusion

Purse seiners/pelagic trawlers are power-demanding vessels with a widespread operational area. This establishes both a high endurance range- and power requirement if a similar operation is to be kept, making the implementation of alternative energy carriers more challenging. The Case Study assessing the implementation of the different alternative energy carriers in a purse seiner/pelagic trawler revealed a correlation between a good environmental performance and a high life cycle cost. The environmental performance from a cradle-to-grave perspective was best for the green energy carriers, with E-MeOH performing the best. However, for the Life-Cycle Cost Analysis, E-MeOH performed the worst. The calculated LCC for E-NH_3 and E-LH_2 is also high relative to LNG and MDO. It is the fuel price that makes the green solutions unfeasible from a financial perspective.

There is a clear difference in the ranking of the fuel solutions assessed in this thesis based on the stakeholder. When considering a set of criteria covering the aspects of sustainability and weighting them in a multi-criteria decision analysis from a shipowner and a governmental perspective, the results follow the same pattern as for the environmental and financial performance in the Case Study. Shipowners heavily weigh the financial performance, favoring more traditional fuels like MDO and LNG. On the other hand, the Government is much more worried about the environmental performance favoring green fuels. This highlights the limiting factor for a green transition in the fishing industry, which is the financial aspect as shipowners are responsible for ordering the majority of new ships. Even though a shipowner would favor traditional solutions because of the financial performance, it is a big risk to bet on pure traditional solutions going forward. Global warming is on the agenda worldwide, and with an expected investment duration of 15-20 years for new ships, it is unwise to invest in solutions not capable of meeting upcoming reduction goals set by both the Norwegian Government and IMO.

Based on the findings, green ammonia is found to be the most relevant of the green alternatives. Implementing ammonia will require much more frequent bunkering, removing some of the flexibility related to more traditional fuels with higher energy densities. If an ammonia ratio of 95% is achieved in the fuel mix, it is possible to define the vessel as a zero emission vessel. However, increasing the ammonia ratio also increases the life cycle cost because more ammonia is used. It then becomes a trade-off between financial and environmental performance. Based on the timeline of IMO and Norway's reduction goals, and the current technology maturity, a lower ammonia ratio, e.g. the 70-to-30 mix, is favorable and more realistic shortly, with a zero-emission fishing vessel being a future solution when technology development drives costs down.

From a safety aspect, it is crucial to avoid leakages of ammonia and to minimize consequences should a leakage occur. To ensure a safe implementation of ammonia as fuel, many of the same safety principles used for LNG can be applied; segregation of systems, double barriers, detection of leakages, and isolation of leakages. The main difference is the toxicity of ammonia, imposing stricter regulations for ventilation and the definition of toxic zones on deck to ensure safe operation for personnel.

To summarize, implementing green fuels makes sense from an environmental perspective, but it is not financially feasible due to a much higher fuel cost. Maturing of technology and the establishing of smaller local production facilities in Norway could reduce the fuel price, consequently increasing the realization probability of green fishing vessels. With ammonia performing the best of the green alternatives in this thesis, a way of combating the poor financial performance is to design the vessel ammonia-ready. Operating on LNG would reduce emissions to some extent shortly while maintaining a good financial operation. The vessel would also be capable of using ammonia as a drop-in fuel and achieving emission reductions complying with the Government's goal for 2030, should the price drop to a sufficiently low level. This alternative solution would lower the investment risk compared to a traditional LNG vessel while only slightly increasing the extra investment cost. One challenge is the reduced endurance by changing a specific volume of LNG with ammonia.

14.2 Further Work

The assessment of the implementation of the different fuels in the Case Study is performed based on LNG tanks with a qualitative approach. Further work should include individual assessment of the required extension, resistance, and stability. Additionally, a more precise operational profile and insight into logistics would improve the assessment.

As mentioned in the discussion, a proper LCA for natural gas-based ammonia, green ammonia, and green methanol should be performed if the environmental performance of these fuels is to be assessed in greater detail. It would then be possible to either support or contradict the findings in this thesis. Preferably, all fuels assessed should be included in the same LCA to ensure equal parameters and assumptions. In addition, the LCA method should be adapted to assess fishing applications more accurate. Improving the impact indicators over-fishing, local pollutants, anti-fouling, and seafloor ecosystem disturbance would help to improve the accurately.

Based on time limitations, the estimation of the CAPEX is performed qualitatively, with some quantified values. Going forward, the required components for the fuel systems should be quantified in a more detailed manner and more specific costs retrieved if possible. This would make for a more accurate extra investment cost compared to the traditional solution.

Economy plays a major part in the feasibility of implementing alternative fuels in fishing vessels, especially the fuel cost. By this, it would be important to further assess how smaller local production facilities in Norway would affect the fuel price and consequently how this impacts the performance of the fuel solutions. Preferably, the fuel prices would be estimated for one or several dedicated bunkering spots, fitting to the operation of the reference vessel.

A survey assessing what criteria are important, and their relative importance, for Norwegian maritime stakeholders, would increase the robustness of the multi-criteria decision analysis and should be conducted going forward.

The multi-criteria decision analysis covers the definition of sustainability to some extent. Expanding the scope to better cover sustainability would require more interdisciplinary work, resulting in a more accurate assessment of the fuels. This would make it possible to make a more sound decision concerning the energy carrier when a new fishing vessel is to be planned.

With ammonia concluded to be the best alternative of the green fuel solutions, a more comprehensive study should be conducted assessing this implementation. This study should cover the implementation of both type C and type A tanks, how this affects the arrangement in detail, and the possible required length extension. A change of main dimensions in addition to the introduction of new components like the tank would require an assessment of both the stability and the resistance. In addition, the implementation of the safety principles in the design ensuring a safe operation should be further assessed.

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Appendix

A CO2-calculations for E-MeOH

Assumptions:

- η_{process} = 0.7
- LHV = 5.5 kWh/kg
- Daily MeOH production: 300 000 kg/day
- Daily CO2 used for production: 450 000 kg/day
- CO2-emissions from wind power: 14 kg/MWh (Gilbert et al. (2018))
- CO2-emissions from capture: 0.3 kg CO2/kg CO2 captured
- Steam for the distillation process generated by heat recovery from the reactor similar to how CRI on Island solves it.
- No transport of CO2 or MeOH. Everything on site

Calculations:

$$\text{Power usage per kg MeOH} = \frac{\text{LHV}}{\eta_{\text{process}}} = \frac{5.5\text{kWh/kg}}{0.7} = 7.86\text{kWh/kg MeOH} \tag{14.1}$$

$$\text{Daily power usage} = 7.86\text{kWh/kg} \cdot 300000\text{kg/day} = 2357143\text{kWh/day} \tag{14.2}$$

$$\text{CO2 from wind power} = 14\text{kg/MWh} \cdot 2357.143\text{MWh/day} = 33000\text{kg CO2/day} \tag{14.3}$$

$$\text{CO2 from CO2 capture} = 0.3\text{kg/kg} \cdot 450000\text{kg/day} = 135000\text{kg CO2/day} \tag{14.4}$$

$$\text{Net CO2-emissions} = 33000\text{kg/day} + 90000\text{kg/day} = 168000\text{kg CO2/day} \tag{14.5}$$

$$\text{Specific CO2-emissions} = \frac{168000\text{kg CO2/day}}{300000\text{kg MeOH/day}} = 0.56\text{kg CO2/kg MeOH} \approx 100\text{g CO2/kWh} \tag{14.6}$$

B Fishing Voyages Statistics

Table 14.1: Landing statistics for Harvest

	Trawl	**Purse Seine**	**Total**	**Norwegian Economical Zone**	**EU Zone**
Blue Whiting	4	0	4	0	4
Mackerel	0	6	6	0	6
NVG-herring	3	2	5	5	0
North Sea Herring	4	3	7	4.5	2.5
Sandeel	6	0	6	6	0
Total 2019	**17**	**11**	**28**	**15.5**	**11.5**
Blue Whiting	4	0	4	0	4
Mackerel	0	10	10	1	9
NVG-herring	1	4	5	5	0
North Sea Herring	1	8	9	6	3
Sandeel	4	0	4	4	0
Total 2018	**10**	**22**	**32**	**16**	**16**

C Defining Vessel Parameters

C.1 Calculating SFC

Defining the energy density in kWh/kg:

$$\text{Energy density} = \frac{Q_{HV}}{3600} \quad [kWh/kg] \tag{14.7}$$

It is then possible to calculate the SFC at 100% efficiency:

$$SFC_{1.0} = \frac{1000}{\text{Energy density}} \quad [g/kWh] \tag{14.8}$$

Lastly the SFC can be calculated based on the real efficiency:

$$SFC = \frac{SFC_{1.0}}{\eta} \quad [g/kWh] \tag{14.9}$$

Fuel type	LNG	LH2	NH3	MeOH	MDO
Energy density [kJ/kg]	50800	120000	18600	19500	42600
Energy density [kWh/kg]	14.1	33.333	5.167	5.417	11.8
SFC at 100% eff.	70.8	30.000	193.5	184.6	84.5
Efficiency	0.5	0.42	0.44	0.44	0.45
Amount pilot fuel	1%	20%	30%	8%	-
SFC, main fuel	140.3	57.1	307.9	386.0	187.8
SFC, pilot fuel	1.7	40.2	57.6	15.4	-

C.2 Tank Size

Energy required [kWh]

The resulting weight for the required energy can be calculated as follows:

$$\text{Weight} = \frac{\text{Energy required} \cdot SFC}{1000} \quad [kg] \tag{14.10}$$

The resulting volume based on the weight can be calculated as follows:

$$\text{Volume} = \frac{\text{Weight}}{\rho} \quad [m3] \tag{14.11}$$

Based on a filling capacity of 5% the required volume can be calculated by:

$$\text{Required volume} = \frac{\text{Volume}}{0.95} \tag{14.12}$$

Fuel Type	LNG	LH2	NH3	Methanol	MDO
Energy	688800	319915	688800	688800	688800
Density	422.6	70.8	675	794	900
Weight	96649	18281	212094	265886	129352
Req. Volume	241	272	331	335	144

D Calculating Power and Fuel Consumption

D.1 Defining New Power Demands

The differences in resistance due to different extensions are defined as follows:

Extension	6 meters	8 meters	10 meters
Steaming (14 kn)	-3%	-5%	-9%
Trawling	1%	3%	5%
Searching (9-10 kn)	0%	0%	0 %
Purse net shooting	0%	1%	2%

This only affects the power demand for propulsion. Ammonia and hydrogen requires an extension of around 8 meters and LNG around 6. The new propulsion power demands are defined as follows:

Mode	**Percentage**	**LNG**	**LH2**	**NH3**
Searching	12%	1000	1000	1000
Steaming	51%	1649	1615	1615
Trawling Norway Pout	9%	1515	1545	1545
Trawling Blue Whiting	9%	2626	2678	2678
Trawling Sandeel	5%	2020	2060	2060
Purse Seining	5%	1700	1717	1717
Average demand		1520	1513	1513

Thus the different power demands are defined as follows:

	LNG	LH2	NH3	MeOH	MDO
Propulsion demand [kWh]	1520	1513	1513	1541	1541
Equipment demand [kWh]	509	509	509	509	509
Total average demand [kWh]	2029	2022	2022	2050	2050
Daily power demand [kWh/day]	48 688	48 518	48 518	49200	49200
7 days demand [kWh]	340 818	339 624	339 624	344 400	344 400
14 days demand [kWh]	681 636	679 248	679 248	688 800	688 800

D.2 Defining 100% Diesel Operation for Hydrogen vessel

The hydrogen fuelled vessel will run its dual fuel engine 100% on diesel when entering remote waters during its Blue Whiting fishing trips. Every year the vessel is defined to perform four of these trips.

- Total blue whiting duration: $4 \cdot 14\text{days} = 56\text{days}$
- Close waters defined as 250 nm.
- Steaming speed of 14 knots.
- Steaming in close waters both when leaving and returning.
- Time in close waters during blue whiting fisheries: $(4 \cdot 2 \cdot 250/14)/24 = 5.95\text{days}$

The hydrogen fuelled vessel will run on hydrogen 6 days of 56 of the blue whiting fishery and 50 days on 100% diesel. This is around 20% of the yearly operation.

E Scipt: ReCiPe2016 Calculation and Plot

Listing 14.1: RecipeFUEL.m

```
function [strRanked] = ReCiPeFUEL
%Calculates the environmental perforamce of
%LNG,HYDROGEN,AMMONIA,METHANOL,MDO

EnergyConsumed  = [10906184;10867960;10867960;11020800;11020800];

%LNG,HYDROGEN,AMMONIA,METHANOL BRUNED IN A DF ICE
%MDO BURNED IN AN ICE

%Import emissions from the fuels (g/kWh)
fid = 'ReCiPe2016.xlsx';
CH4_op = xlsread(fid,'B4:B11');
CH4_pr = xlsread(fid,'C4:C11');
N2O_op = xlsread(fid,'D4:D11');
N2O_pr = xlsread(fid,'E4:E11');
SOx_op = xlsread(fid,'F4:F11');
SOx_pr = xlsread(fid,'G4:G11');
NOx_op = xlsread(fid,'H4:H11');
NOx_pr = xlsread(fid,'I4:I11');
PM_op  = xlsread(fid,'J4:J11');
PM_pr  = xlsread(fid,'K4:K11');
CO2_op = xlsread(fid,'L4:L11');
CO2_pr = xlsread(fid,'M4:M11');

Emissions = [CH4_op,CH4_pr,N2O_op,N2O_pr,SOx_op,SOx_pr, NOx_op,NOx_pr,...
    PM_op,PM_pr,CO2_op,CO2_pr];
CalcEmissions = zeros(8,12);

%LNG
for i = 1:1:length(Emissions(1,:))
    CalcEmissions(1,i) = EnergyConsumed(1)*Emissions(1,i)*0.986 ...
        + EnergyConsumed(1)*Emissions(8,i)*0.014;

%LH2 - 100% MDO during Blue Whiting included
    CalcEmissions(2,i) = (EnergyConsumed(2)*Emissions(2,i)*0.63...
        + EnergyConsumed(2)*Emissions(8,i)*0.37);
    CalcEmissions(3,i) = (EnergyConsumed(2)*Emissions(3,i)*0.63...
        + EnergyConsumed(2)*Emissions(8,i)*0.37);
%Ammonia
    CalcEmissions(4,i) = EnergyConsumed(3)*Emissions(4,i)*0.7 ...
        + EnergyConsumed(3)*Emissions(8,i)*0.3;
    CalcEmissions(5,i) = EnergyConsumed(3)*Emissions(5,i)*0.7 ...
        + EnergyConsumed(3)*Emissions(8,i)*0.3;
%Methanol
    CalcEmissions(6,i) = EnergyConsumed(4)*Emissions(6,i)*0.92 ...
        + EnergyConsumed(4)*Emissions(8,i)*0.08;
    CalcEmissions(7,i) = EnergyConsumed(4)*Emissions(7,i)*0.92 ...
        + EnergyConsumed(4)*Emissions(8,i)*0.08;
%MDO
    CalcEmissions(8,i) = EnergyConsumed(5)*Emissions(8,i);
end
```

```
GWP_op = zeros(8,1);
GWP_pr = zeros(8,1);
PMFP_op = zeros(8,1);
PMFP_pr = zeros(8,1);
HOFP_op = zeros(8,1);
HOFP_pr = zeros(8,1);
EOFP_op = zeros(8,1);
EOFP_pr = zeros(8,1);
TA_op = zeros(8,1);
TA_pr = zeros(8,1);


for i = 1:1:length(GWP_op(:,1))
    GWP_op(i,1) = (CalcEmissions(i,1)*34 + ...
        CalcEmissions(i,3)*298 + ...
        CalcEmissions(i,11)*1)/1000;
    GWP_pr(i,1) = (CalcEmissions(i,2)*34 + ...
        CalcEmissions(i,4)*298 + ...
        CalcEmissions(i,12)*1)/1000;
    PMFP_op(i,1) = (CalcEmissions(i,7)*0.06 + ...
        CalcEmissions(i,9)*0.34 + ...
        CalcEmissions(i,5)*0.05)/1000;
    PMFP_pr(i,1) = (CalcEmissions(i,8)*0.06 + ...
        CalcEmissions(i,10)*0.34 + ...
        CalcEmissions(i,6)*0.05)/1000;
    HOFP_op(i,1) = (CalcEmissions(i,7)*1.03)/1000;
    HOFP_pr(i,1) = (CalcEmissions(i,8)*1.03)/1000;
    EOFP_op(i,1) = (CalcEmissions(i,7)*3.24)/1000;
    EOFP_pr(i,1) = (CalcEmissions(i,8)*3.24)/1000;
    TA_op(i,1) = (CalcEmissions(i,7)*0.73 + ...
        CalcEmissions(i,5)*2.28)/1000;
    TA_pr(i,1) = (CalcEmissions(i,8)*0.73 + ...
        CalcEmissions(i,6)*2.28)/1000;
end

CC = zeros(16,1);
PMFP = zeros(16,1);
HOFP = zeros(16,1);
EOFP = zeros(16,1);
TA = zeros(16,1);
for i = 1:1:8
    CC(1+(i-1)*2,1) = GWP_op(i,1);
    CC(i*2,1) = GWP_pr(i,1);
    PMFP(1+(i-1)*2,1) = PMFP_op(i,1);
    PMFP(i*2,1) = PMFP_pr(i,1);
    HOFP(1+(i-1)*2,1) = HOFP_op(i,1);
    HOFP(i*2,1) = HOFP_pr(i,1);
    EOFP(1+(i-1)*2,1) = EOFP_op(i,1);
    EOFP(i*2,1) = EOFP_pr(i,1);
    TA(1+(i-1)*2,1) = TA_op(i,1);
    TA(i*2,1) = TA_pr(i,1);
end

%Plot CO2-eqv
x = CC;
fig7 = figure;
hold on
```

```
str={'LNG','NG-LH2','E-LH2','NG-NH3','E-NH3','NG-MeOH','E-MeOH','MDO w/SCR'};
labels = {'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';...
    'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.'};
set(gca,'YTick',1.5:2:15.5)
hB = barh(x);
xtips1 = hB(1).XEndPoints;
ytips1 = hB(1).YEndPoints;
labels1 = string(labels);
text(ytips1,xtips1,labels1,'HorizontalAlignment','left',...
    'VerticalAlignment','middle')
hAx=gca;
hAx.YTickLabel=str;
xlabel('kg/year')
title('Climate Change: kg CO2eq per year')
%saveas(fig7, 'CC.png')
hold off

%Plot PM2.5-eq
y2 = PMFP;
fig8 = figure;
hold on
str={'LNG','NG-LH2','E-LH2','NG-NH3','E-NH3','NG-MeOH','E-MeOH','MDO w/SCR'};
labels = {'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';...
    'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.'};
set(gca,'YTick',1.5:2:15.5)
hB = barh(y2);
xtips1 = hB(1).XEndPoints;
ytips1 = hB(1).YEndPoints;
labels1 = string(labels);
text(ytips1,xtips1,labels1,'HorizontalAlignment','left',...
    'VerticalAlignment','middle')
hAx=gca;
hAx.YTickLabel=str;
xlabel('kg/year')
title('Particle Matter Formation Potential: kg PM2.5-eq per year')
%saveas(fig8, 'PMFP.png')
hold off

%Plot NOx-eqv
y3 = [HOFP,EOFP];
fig9 = figure;
hold on
str={'LNG','NG-LH2','E-LH2','NG-NH3','E-NH3','NG-MeOH','E-MeOH','MDO w/SCR'};
labels = {'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';...
    'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.'};
set(gca,'YTick',1.5:2:15.5)
hB = barh(y3,'stacked');
xtips1 = hB(1).XEndPoints;
ytips1 = hB(2).YEndPoints;
labels1 = string(labels);
text(ytips1,xtips1,labels1,'HorizontalAlignment','left',...
    'VerticalAlignment','middle')
hAx=gca;
hAx.YTickLabel=str;
legend('HOFP'...
    ,'EOFP')
xlabel('kg/year')
```

```
title('Photochemical Ozone Formation: kg NOx-eq per year')
%saveas(fig9, 'POF.png')
hold off

%Plot SOx-eq
y4 = TA;
fig10 = figure;
hold on
str={'LNG','NG-LH2','E-LH2','NG-NH3','E-NH3','NG-MeOH','E-MeOH','MDO w/SCR'};
labels = {'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';...
    'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.'};
set(gca,'YTick',1.5:2:15.5)
hB = barh(y4);
xtips1 = hB(1).XEndPoints;
ytips1 = hB(1).YEndPoints;
labels1 = string(labels);
text(ytips1,xtips1,labels1,'HorizontalAlignment','left',...
    'VerticalAlignment','middle')
hAx=gca;
hAx.YTickLabel=str;
xlabel('kg/year')
title('Terrestrial Acidification: kg SOx-eq per year')
%saveas(fig10, 'TA.png')
hold off

CC_he = zeros(16,1);
CC_te = zeros(16,1);

%Midpoint to endpoint, normalization and weighting
CC_he = CC * 9.3E-07*16840;
CC_te = CC * 2.8E-09*558400;
PMFP = PMFP * 6.29E-04*16840;
HOFP = HOFP * 9.1E-07*16840;
EOFP = EOFP * 1.29E-07*558400;
TA = TA * 2.12E-07*558400;

%Potential environmental effect
Pt = zeros(8,1);
for i = 1:8
    Pt(i,1) = CC_he(i+(i-1),1)+CC_he(2*i,1)...
        +CC_te(i+(i-1),1)+CC_te(2*i,1)...
        +PMFP(i+(i-1),1)+PMFP(2*i,1)...
        +HOFP(i+(i-1),1)+HOFP(2*i,1)...
        +EOFP(i+(i-1),1)+EOFP(2*i,1)...
        +TA(i+(i-1),1)+TA(2*i,1);
    i = i+1;
end

FuelNr = [1;2;3;4;5;6;7;8];

Tot = [FuelNr,Pt];

Ranked = sortrows(Tot,2,'ascend');
strRanked = string(Ranked);

for i = 1:length(FuelNr(:,1))
    if Ranked(i,1) == 1
```

```
        strRanked(i,1) = 'LNG';
    elseif Ranked(i,1) == 2
        strRanked(i,1) = 'NG-LH2';
    elseif Ranked(i,1) == 3
        strRanked(i,1) = 'E-LH2';
    elseif Ranked(i,1) == 4
        strRanked(i,1) = 'NG-NH3';
    elseif Ranked(i,1) == 5
        strRanked(i,1) = 'E-NH3';
    elseif Ranked(i,1) == 6
        strRanked(i,1) = 'NG-MeOH';
    elseif Ranked(i,1) == 7
        strRanked(i,1) = 'E-MeOH';
    elseif Ranked(i,1) == 8
        strRanked(i,1) = 'MDO w/SCR';
    end
end


%Plot total environmental perfoamnce
y = [CC_he,PMFP,HOFP,CC_te,EOFP,TA];
fig11 = figure;
hold on
str={'LNG','NG-LH2','E-LH2','NG-NH3','E-NH3','NG-MeOH','E-MeOH','MDO w/SCR'};
labels = {'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';...
    'Prod.';'Oper.';'Prod.';'Oper.';'Prod.';'Oper.';'Prod.'};
set(gca,'YTick',1.5:2:15.5)
hB = barh(y,'stacked');
xtips1 = hB(1).XEndPoints;
ytips1 = hB(6).YEndPoints;
labels1 = string(labels);
text(ytips1,xtips1,labels1,'HorizontalAlignment','left',...
    'VerticalAlignment','middle')
hAx=gca;
hAx.YTickLabel=str;
xlabel('Pt/year')
legend('Human health: Climate Change','Human health: Particle Matter Formation Potential'...
,'Human health: Photochemical Ozone Formation'   ,'Terrestrial ecosystem: Climate Change'...
,'Terrestrial ecosystem: Photochemical Ozone Formation','Terrestrial ecosystem: Terrestrial ...
Acidification', 'Location','northeast')
title('ReCiPe2016H Endpoint: Total potential environmental effect per year')
%saveas(fig11, 'Pt.png')
hold off
```

F Fish Price Statistics

Table 14.2: Yearly average fish prices [EUR/tonne] for Harvest (Fiskeridirektoratet (N.D.))

	2017	2018	2019	Average
Blue Whiting	147.2	208.8	238.2	198.1
Mackerel	1004.4	1346.5	1654.4	1335.1
NVG-herring	455.2	442.7	410.1	436.0
North-sea herring	464.9	395.1	567.7	475.9
Sandeel	160.5	219.7	239.7	224.6

Table 14.3: Yearly average fish prices [EUR/tonne] for sale from fishermen. (SSB (2021))

	2012	2013	2014	2015	2016	2017	2018	Average
Blue Whiting	227.0	190.1	140.7	183.3	261.9	140.7	208.6	225.4
Mackerel	711.0	842.0	676.1	813.8	1122.3	920.5	1283.3	1061.5
Herring	565.5	464.6	457.8	576.2	676.1	422.9	417.1	596.7
Sandeel	200.8	207.6	164.9	191.1	279.4	156.2	219.2	236.5

G AHP

	VOYEX	Extra CAPEX	Environmental performance	Reliable supply of fuel	Infrastructure	Safety
VOYEX	1.00	2.00	3.00	3.00	5.00	3.00
Extra CAPEX	0.50	1.00	2.00	2.00	4.00	2.00
Environmental performance	0.33	0.50	1.00	1.00	3.00	1.00
Reliable supply of fuel	0.33	0.50	1.00	1.00	3.00	1.00
Infrastructure	0.20	0.25	0.33	0.33	1.00	0.33
Safety	0.33	0.50	1.00	1.00	3.00	1.00

Consistency check:

- $\gamma_{\text{max}} = 6.0562$
- Consistency Index = 0.011
- Consistency Ratio = 0.009
- The pairwise comparison matrix is consistent because $0.009 < 0.1$

Criteria	Weights
VOYEX	0.356
Extra CAPEX	0.221
Environmental performance	0.124
Reliable supply of fuel	0.124
Infrastructure	0.050
Safety	0.124

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