LIFE CYCLE ASSESMENT OF

Marine propulsion systems

asplan viak

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EXECUTIVE SUMMARY

BACKGROUND

At the same time as the Norwegian Government aims for continued development for ocean industries, Norway has committed to reducing its greenhouse gas (GHG) emissions. Both national and international goals have been set for emission reductions for the maritime sector. The development and adoption of new and emerging marine fuels and energy carriers may offer GHG emission reduction potentials for the Norwegian ocean industry, but because emissions arise both upstream and downstream of the use phase, a life cycle perspective is required to obtain a complete picture of the GHG emissions. Addressing this issue, NCE Maritime CleanTech commissioned Asplan Viak AS to do a comparative life cycle assessment (LCA) study of a range of marine propulsion systems relying on different fuels and energy carriers.

This report estimates and compares the life cycle GHG emissions of a range of propulsion system technologies. Through three case studies, various propulsion systems for a platform supply vessel, a chemical tanker, and an express boat are considered. The study considers both conventional fuels and internal combustion engines as well as new and emerging alternatives such as ammonia as a combustion fuel and electrification through the use of energy carriers in batteries and fuel cells.

Two wide categories of propulsion technologies were considered in the three case studies: combustion-based propulsion systems and electric propulsion systems. The cradle-to-grave GHG emissions were calculated for a given number of years of operation and considered the most relevant components as well as fuels and energy carriers.

MAIN FINDINGS

When consolidating the findings of the three case studies we find that currently, there is not *one* ideal propulsion system alternative in terms of GHG emissions. Across the different case studies, we find that certain propulsion systems may offer GHG emission benefits for one application and operational profile, but disadvantages in another. The main findings for the considered propulsion system configurations are summarized below. Note that the summarized results consider the life cycle emissions of the propulsion systems including components such as engines, batteries, and fuel cells as well as fuels and energy carriers, rather than solely the fuels and energy carriers.

COMBUSTION-BASED PROPULSION SYSTEMS

Marine fossil fuels such as MGO and LS-HFO are used in internal combustion engines. Propulsion systems relying on these two fossil fuels have similar life cycle GHG emissions. While marine diesel oil (MDO) and regular heavy fuel oil (HFO) were not considered specifically in the study, these fuels have similar fuel cycle emission factors and consequently life cycle GHG emissions as MGO and LS-HFO. To reduce GHG emissions, it is desirable to replace combustion of fossil fuels in internal combustion engines with propulsion systems that offer lower life cycle emissions.

Biodiesel is a blend of fatty acid methyl esters (FAME) and fossil diesel and is used in internal combustion engines. FAME blending cannot be in high concentrations without substantial risks for fuel quality, engine operation, exhaust emissions and infrastructure. In Europe, maximum 7% v/v FAME is allowed in diesel fuel and 5% v/v in the U.S. In the current study, biodiesel was considered with 5 % v/v FAME and 95 % v/v fossil diesel. Because fossil diesel makes up the majority of biodiesel and because it has a higher fuel cycle emission factor than marine fuels such as MGO and LS-HFO, propulsion systems using biodiesel were found to have higher life cycle emissions compared to propulsion systems relying on MGO and LS-HFO. Therefore, propulsion systems relying on current blending rates of biodiesel may not be a good alternative for the marine transport sector. Note that in road transport, however, biodiesel replaces fossil diesel and as such, biodiesel offers GHG benefits for road transport.

Hydrotreated vegetable oil (HVO) is a drop-in fuel that can be used in diesel engines either without or with minor modifications. HVO is commonly referred to as renewable diesel and is produced via hydroprocessing of oils and fats. The fuel cycle emission factor of HVO depends primarily on the feedstocks used to produce the fuel and may vary considerably. When advanced (waste-products) feedstocks are used, HVO may offer substantial life cycle emission reductions compared to fossil fuels. If crop-based feedstocks are used, emissions are typically higher and there is a risk of emissions stemming from indirect land use change (ILUC). While ILUC emissions are uncertain, both with respect to whether they occur or not and how significant they might be, studies indicate that the fuel cycle emissions including ILUC may be as high, or even higher, than that of fossil fuels. Note that HVO availability may be somewhat limited and more expensive than regular marine fuels. Consequently, one may not expect HVO to replace conventional marine fuels for all applications.

Liquid ammonia (L-NH_3) as combustion fuel in internal combustion engines has received increasing attention as it does not emit GHG emissions during complete combustion and is often referred to as a so-called “zero-emission” fuel. However, when considering the complete fuel cycle of ammonia, we find that ammonia is not necessarily a less GHG emitting fuel than fossil alternatives; the life cycle emissions of the ammonia combustion propulsion system vary widely depending on the ammonia production pathway. For ammonia and hydrogen, green, blue and grey production pathways were considered. A green production pathway is based on electricity, blue is based on hydrocarbons with carbon capture and storage, and grey is based on hydrocarbons without carbon capture and storage. We find that green ammonia, regardless of whether Norwegian or Nordic electricity is assumed, may offer GHG emission reductions compared to fossil fuel alternatives. The emission reduction is substantially lower when Norwegian electricity (98 % renewables) is used than when the Nordic electricity (about 60 % renewables) is used. Blue ammonia results in similar emissions as conventional fossil fuels used in marine applications. Finally, we find that grey ammonia increases the life cycle emissions compared to conventional fossil fuels. Note challenges with complete combustion is a major concern for the ammonia combustion fuel propulsion system as incomplete ammonia combustion may produce emissions of the highly potent GHG nitrous oxide (N_2O), which were not considered in the analysis. Our findings highlight that the ammonia is not a “zero-emission” combustion fuel and that life cycle GHG emissions of the ammonia combustion propulsion system are highly dependent on the ammonia production pathways.

Liquified natural gas (LNG) is a fossil fuel that can be combusted in different types of engines, here we considered LNG combustion in three internal combustion engines: dual fuel Otto cycle 4-stroke, spark ignition Otto cycle 4-stroke, and dual fuel Diesel cycle 2-stroke. The considered engine types suffer from different rates of methane slip. As methane is a potent GHG, methane slip is highly undesirable. In our study, we find that methane slips severely compromised potential GHG benefits of LNG compared to conventional marine fuels. Compared to conventional marine fuels, we found that the considered LNG alternatives for the platform supply vessel resulted in higher GHG emissions, while a relatively modest GHG reduction was obtained for the chemical tanker.

Liquified biomethane (LBM) is liquified upgraded biogas that can be combusted in different types of engines. Here, we considered the same engines as for LNG. As different feedstocks and production pathways may be used to produce LBM, its fuel cycle emission factor may vary. As LBM is primarily produced from advanced feedstocks (mainly bio-waste) it has a low fuel cycle emission factor, even when methane slip is considered. We find that LBM offers GHG benefits both compared to its fossil counterpart LNG and the more conventional fossil fuels used for marine applications.

ELECTRIC PROPULSION SYSTEMS

Li-ion batteries may be used in hybridized or fully electric propulsion systems. Fully battery-powered marine applications are somewhat limited by the current state of the technology. Propulsion systems relying only on batteries require much larger battery packs compared to those using auxiliary batteries. Because there are considerable emissions associated with the production of Li-ion batteries, fully battery-powered propulsion systems have much higher production emissions than fossil or fuel cell propulsion systems. Even so, the fully-battery powered express boat propulsion system obtained substantial life cycle GHG emission reductions compared to propulsion systems relying on fossil fuels. Note that the GHG benefit of the fully battery-powered express boat propulsion system may not be harvested under all circumstances as the high production emissions place constraints on the electricity used for charging. Both the Norwegian production mix and the Nordic consumption mix provided substantial life cycle benefits for the fully battery-powered express boat propulsion system.

When used as an auxiliary battery, either in a hybridized configuration in combination with fossil fuels or fuel cells, a much smaller battery pack is used. Thus, the production emissions are not particularly high for the auxiliary battery. We found that for a hybridized platform supply vessel, battery use provided significant GHG emission reductions compared to the fossil fuel alternatives.

Ammonia solid oxide fuel cell (SOFC) is a fuel cell using ammonia as an energy carrier. The advantage of using ammonia in a fuel cell, rather in a combustion engine, is that the fuel cell has a higher theoretical conversion efficiency than the combustion engine. Furthermore, the potential issue of nitrous oxide emissions is avoided as the fuel cell is not relying on combustion. We find that ammonia fuel cell propulsion system offers advantages compared to the fossil fuel alternatives, regardless of ammonia production pathway. Green ammonia provides substantial GHG advantages compared to blue and grey ammonia. As such, our findings indicate that ammonia is better used in fuel cell than in a combustion engine. Note that this latter finding is highly dependent on the energy conversion efficiencies of both the ammonia fuel cell and the combustion engine.

Hydrogen proton exchange membrane fuel cell (PEMFC) is a fuel cell using either liquid or compressed gaseous hydrogen as an energy carrier. Whether the hydrogen fuel cell alternatives provide a GHG benefit depends to a large extent on the hydrogen production pathway. Our results indicate that grey hydrogen may increase or decrease the life cycle GHG emissions compared to conventional alternatives depending on the vessel type and its operational profile. Blue hydrogen (SMR w. CCS) in PEMFCs provide lower life cycle GHG emissions compared to MGO. Interestingly, we find that using blue hydrogen used in PEMFCs also provide lower life cycle emissions than LNG use in both the platform supply vessel and the chemical tanker (LNG was not considered for the express boat). This finding indicates that for marine propulsion systems, using LNG to produce blue hydrogen may be a better application than using LNG for combustion. Note that this finding does not necessarily hold true for grey hydrogen; for the chemical tanker, we find that propulsion systems relying on liquid or compressed hydrogen in PEMFCs had higher life cycle emissions compared to the propulsion system relying on LNG.

CONCLUSION

The life cycle perspective offered by the LCA method is crucial to provide a holistic emission profile of the various propulsion system alternatives. Through the life cycle perspective, we find that under some conditions so-called "zero-emission" alternatives may have higher total life cycle GHG emissions compared to conventional propulsion systems relying on fossil fuels.

For new and emerging fuels and energy carriers such as ammonia, biofuels, hydrogen, and electricity, decision makers should carefully evaluate the realistic availability of low-emissions production pathways in the location of the intended vessel operation to ensure GHG benefits. Furthermore, the operational profile and application should also be considered as these may affect suitability from a

GHG emission reduction perspective. Failing to account for availability, operational profile, and application, well-intended decisions may result in undesirable outcomes that may increase the overall GHG emissions.

While there are important uncertainties and limitations associated with the analysis, an overall picture of the GHG profile of a wide range of marine propulsion systems is provided. Furthermore, the preliminary results provide useful insights and highlight important benefits and challenges pertaining to the GHG emissions of various marine propulsion system technologies. The LCA study demonstrates that significant GHG emission reductions may be obtained for marine propulsion systems, and ultimately the transport sector, but its realization and optimization require informed and deliberate decision making.

PREFACE

This report is produced by Asplan Viak AS commissioned by NCE Maritime CleanTech. The report considers greenhouse gas emissions of propulsion systems for express boats, platform supply vessels, and chemical tankers. The analysis will provide early insights into greenhouse gas emissions associated with a range of propulsion systems at different stages of technology readiness levels.

The analysis and report were prepared by Linda Ager-Wick Ellingsen and John Ingar Jenssen. The project was done in cooperation with NCE Maritime CleanTech represented by Hege Økland and Tore Boge. In addition, relevant industry actors, such as Norled, Brødrene Aa, Eidesvik, Corvus Energy, ZEM Energy, Yara, and Protech provided data and information for different parts of the analysis.

Trondheim, 26.11.2020

Linda Ager-Wick Ellingsen
Project manager

Michael M. Jenssen
Quality assurance

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ABBREVIATIONS

AC	Alternating current
AE	Auxiliary engine
CCS	Carbon capture and storage
C-H_2	Compressed hydrogen gas
CO_2-eq	Carbon dioxide equivalent
DC	Direct current
DF	Dual fuel
DWT	Dead weight tonnage
FAME	Fatty acid methyl esters
GHG	Greenhouse gas
HFO	Heavy fuel oil
HVO	Hydrotreated vegetable oil
IMO	The International Maritime Organization
ILUC	Indirect land use change
LBM	Liquified biomethane
LCA	Life cycle assessment
Li-ion	Lithium-ion
LHV	Lower heating value
L-H_2	Liquid hydrogen
LNG	Liquified natural gas
L-NH_3	Liquid ammonia
LS-HFO	Low sulphur heavy fuel oil
MDO	Marine diesel oil
MGO	Marine gasoil
NTP	National Transport Plan
PEMFC	Proton exchange membrane fuel cells
PSV	Platform supply vessel
SECAs	Sulphur Emission Control Areas
SFOC	Specific fuel oil consumption
SI	Spark ignition
SMR	Steam methane reformation
SOFC	Solid oxide fuel cell
WTT	Well-to-tank

1. INTRODUCTION

1.1. Background and context

Based on longstanding ocean traditions Norway is currently one of the world's largest and most advanced seafaring nations. The Norwegian Government aims for continued development of the ocean industries while stimulating research, innovation, and technological development in order to see new industries emerge with the goal of positioning Norway as one of the world's leading ocean economies ('The ocean nation of Norway', 2018).

At the same time, Norway was among the first countries to ratify the Paris Agreement. Through the ratification of the agreement, Norway has committed to working with the EU to reduce greenhouse gas (GHG) emissions by at least 40 % by 2030 compared to 1990 levels (Environment, 2020). Further, Norway was among the first countries to submit a strengthened target under the Paris Agreement. Norway's new and strengthened target is to reduce the emissions with at least 50% by 2030 compared to 1990 levels.

Both national and international goals have been set for emission reductions for the maritime sector. According to the current National Transport Plan (NTP), the Government aims for use of biofuels or so-called *"low- or zero emission vessels"* in 40% of all short sea shipping (Det Kongelige Samferdselsdepartement, 2018). Furthermore, the Government wants to ensure that *"low- or zero emission solutions"* are employed in all new ferries that are part of the national road system, and wants to contribute to using *"low- or zero emission solutions"* for county municipal ferries and express boats (Det Kongelige Samferdselsdepartement, 2018). In the Green Shipping Action Plan, the Norwegian government has stated that emission for inland shipping shall be reduced by 50% within 2030 (Departementene, 2019). Furthermore, the International Maritime Organization (IMO) has a global strategy to reduce GHG emissions by 50 % by 2050 (compared to 2008 levels). In a broader perspective, this is key to reaching the Paris agreements challenge of reducing CO_2 emissions by 80 – 95 % (compared to 1990 levels) by 2050.

The development and adoption of new and emerging marine fuels, energy carriers, and propulsion system technologies may offer GHG emission reduction potentials for the Norwegian ocean industry. But because emissions arise both upstream and downstream of the use phase, a life cycle perspective is required to obtain a complete picture of the GHG emissions and to support informed decision making. Addressing this issue, NCE Maritime CleanTech commissioned Asplan Viak AS to do a comparative life cycle assessment (LCA) study of a range of marine propulsion systems.

NCE Maritime CleanTech wanted to consider a range of different marine propulsion systems for three case studies. The three case studies were: (1) platform supply vessel (PSV), (2) chemical tanker, and (3) express boat. Case 1 is largely based on the propulsion system of an existing PSV, while Cases 2 and 3 consider propulsion systems for a fictitious express boat and a chemical tanker, respectively.

Both conventional and emerging alternatives were considered for combustion engines and electric technologies. As the vessel types considered in the analysis differ both in terms of applications and operational profiles, NCE Maritime CleanTech defined various fuels and propulsion systems for the different case studies.

To estimate and compare the life cycle GHG emissions of the various marine propulsion systems, Asplan Viak did an attributional LCA where emissions were ascribed to the studied system (interested readers can read more about the LCA method in Appendix A – LCA method and procedure). In this study, we focus our attention on the global warming potential of GHG emissions, expressed in terms of metric ton carbon dioxide equivalents (ton CO_2-eq). The cradle-to-grave GHG emissions were calculated for a given number of years of operation and considered the most relevant propulsion system components as well as fuels and energy carriers.

The study considers both conventional fuels and combustion engines as well as new and emerging fuels, energy carriers, and energy conversion technologies. Because the various technology options are at different technology readiness levels, ranging from lab scale to commercially available, uncertainties associated with the results must be expected. The variation in technology readiness level holds true for the energy conversion technologies used onboard the vessels as well as for the production of the new and emerging fuels, such as biofuels, ammonia, and hydrogen, where different production pathways are available. Even so, the preliminary results will provide insightful information and highlight important aspect pertaining to the life cycle GHG emissions of both conventional and emerging propulsion system technologies.

1.2. Report structure

The study considers three cases in total. The current report considers primarily Cases 1 and 2 regarding propulsion systems for a PSV and a chemical tanker, respectively. While Case 3 regarding the express boat propulsion systems was considered in a preceding report (Asplan Viak, 2020), the current report includes a summary of the findings for Case 3. As such, the current report may be read as a stand-alone document for all three case studies.

This report is organized into seven main chapters. This introductory chapter establishes the background and motivation for the report and formulates the overarching aim. Chapters 2 – 4 describe the three case studies. Chapter 5 provides an overview of the emission factors used for the propulsion system components as well as the fuels and energy carriers. Chapter 6 presents the results of the three case studies. Finally, Chapter 7 discusses the findings and concludes the study.

2. CASE 1: PLATFORM SUPPLY VESSEL

Case 1 considers a PSV. PSVs are designed for supplying offshore drilling rigs and production platforms with necessary equipment, stores, and drilling consumables (Wärtsilä). Initially, these vessels mainly used variable speed motor drives and fixed pitch propellers. Today, they mostly deploy variable speed thrusters and they are increasingly being equipped with hybrid diesel-mechanical and diesel-electric propulsion (MAN AG, 2016).

2.1. Case study description - PSV

Data and information about Viking Energy served as a starting point for the LCA of PSVs. Viking Energy was originally delivered with a diesel-electric propulsion system using both liquified natural gas (LNG) and marine gasoil (MGO). The vessel was the world's first LNG-fuelled PSV. The system was later hybridized with a Li-ion battery and will additionally be equipped with an ammonia solid oxide fuel cell (SOFC) system in 2023. Further details about the vessel is provided in the text below.

Viking Energy provides supply materials to Equinor North Sea platforms. It can carry 1 300 m^3 of fuel oil, 2 000 m^3 of water ballast or drill water, 1 100 m^3 of potable water, 200 m^3 of methanol, 800 $m^3$of brine, 900 m^3 of liquid mud, and 450 m^3 of dry bulk (*Platform supply vessel VIKING ENERGY*).

When delivered in 2003, Viking Energy was equipped with four Wärtsilä 6R32DF engines with a total installed power of 8 040 kW. The 4-stroke medium speed dual fuel (DF) engines run simultaneously on LNG and MGO. In gas mode, the engine operates according to the lean-burn Otto process. Ignition is obtained by injecting a small quantity (less than 1 % of the fuel energy requirement at nominal load) of a pilot fuel (MGO) directly into the combustion chamber (*Wärtsilä LNG-fuelled engines for offshore vessels*). In MGO mode, the engine operates on a diesel cycle. The studied PSV employs MGO primarily when used as a pilot fuel or if LNG is not available. The LNG is stored in a large stainless-steel tank in the middle of the vessel.

Each of the DF engines is connected to a generator. The generator converts the mechanical energy provided by the engine to electrical energy. The four generator sets (gensets) are connected by a closed bus to an AC grid. The original diesel-electric genset propulsion system is illustrated in Figure 2.

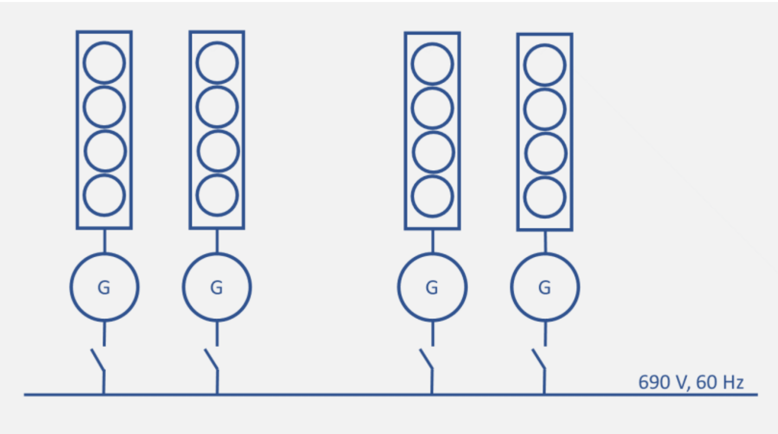


Figure 1 Diesel-electric configuration of the original vessel.

In 2016, the PSV was hybridized when it was equipped with a 653 kWh Li-ion battery. The Li-ion battery is charged with electricity generated from the gensets onboard the vessel and can provide electricity for the grid instantaneously. From the battery, the current is directed to an inverter that converts the electric energy in the form of DC to AC. A transformer controls the voltage sent to the AC grid. The hybridized diesel-electric propulsion system is shown in Figure 3.

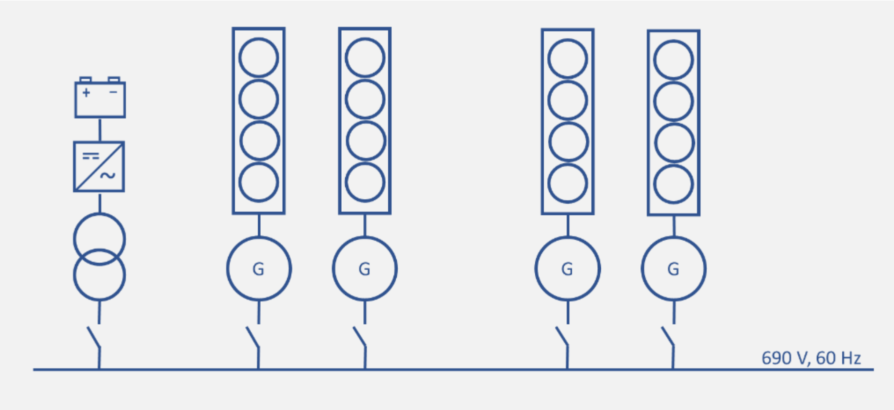


Figure 2 Battery hybridized diesel-electric configuration adapted in 2016.

The batteries serve as an alternative to spinning reserve and backup power, as well as improving the efficiency of remaining diesel engines through peak shaving and load levelling. During dynamic positioning, a PSV must have redundant generators running in case one fails. Consequently, the generators run on low load levels for which they are not optimized, resulting in high specific fuel oil consumption (SFOC). As the battery can provide instantaneous supply of electricity, it can replace the use of spare generators which results in higher (and more efficient) engine load levels, thereby reducing the SFOC.

Batteries can also act as an enabler for fuel cells. From 2023, the propulsion system will be equipped with three ammonia SOFCs with a total installed power of approximately 2 000 kW. The future propulsion system is depicted in Figure 4.

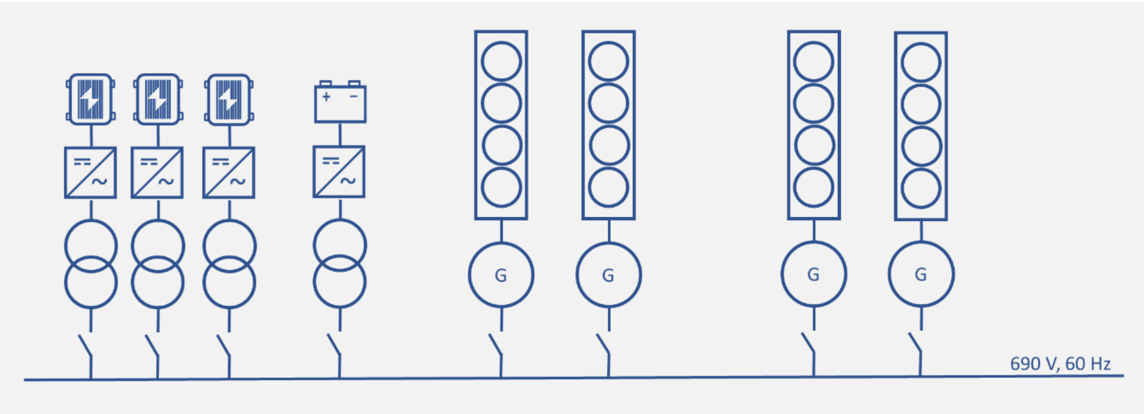


Figure 3 Hybridized propulsion system with ammonia SOFC, Li-ion battery, and DF engines planned for adoption in 2023.

The ammonia SOFC is expected to supply about 70-80 % of the energy that comes from LNG and MGO today.

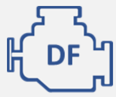
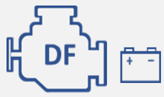
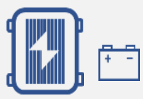
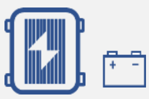
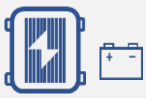
2.2. Propulsion system scenarios – PSV

The LCA study intends to assess the described fuels and energy carriers and propulsion system above as well as alternative electric propulsion systems. In the study, ten main scenarios will be considered. In Scenarios 1 – 3, MGO, biodiesel (5 % v/v fatty acid methyl esters (FAME) + 95 % v/v diesel), and liquid ammonia are considered separately in a diesel-cycle internal combustion engine. Scenarios 4 and 5 consider LNG and liquified biomethane (LBM) in an Otto-cycle internal combustion engine, respectively. Scenario 6 considers the original configuration of Viking Energy, where LNG and MGO are used in a DF internal combustion engine. Scenario 7 considers the battery-hybridized system of Viking Energy, where a Li-ion battery is added to the propulsion system. Scenario 8 an ammonia SOFC propulsion system with an auxiliary Li-ion battery. Scenarios 9 and 10 consider a proton exchange membrane fuel cell (PEMFC) propulsion system with an auxiliary Li-ion battery, where Scenario 9 evaluates liquid hydrogen and Scenario 10 considers compressed gaseous hydrogen.

Furthermore, four production pathways will be considered for production of compressed gaseous hydrogen (C-H_2), liquid hydrogen (L-H_2), and liquid ammonia (L-NH_3). These include two so-called green production pathways where production is based on electricity from the Norwegian production mix and the Nordic consumption mix (the difference between these two electricity mixes are described in Appendix C – Fuel cycle emission factors). In addition, so-called blue and grey production pathways relying on hydrogen produced through steam methane reformation (SMR) with and without carbon capture and storage (CCS), respectively, were considered. For simplicity, the four production pathways will hereafter simply be referred to as Green (Norwegian), Green (Nordic), Blue, and Grey. Liquid ammonia will be considered both for combustion in a diesel-cycle internal combustion engine and in a SOFC.

A summary of the ten propulsion system scenarios considered in the LCA of the PSV are shown in Table 2.

Table 1 Summary of the various propulsion system scenarios considered in the LCA of the PSV

Scenario number and fuel description	Energy conversion technologies	
1. MGO 2. Biodiesel (5 % v/v FAME) 3. Liquid ammonia • Green (Norwegian) • Green (Nordic) • Blue • Grey	Internal combustion engine with diesel-cycle	
4. LNG 5. LBM	Internal combustion engine with Otto-cycle	
6. LNG/MGO	Dual fuel internal combustion engine with Otto-cycle (LNG) and diesel-cycle (MGO)	
7. Hybridized LNG/MGO	Dual fuel internal combustion engine with Otto-cycle (LNG) and diesel-cycle (MGO) and auxiliary Li-ion battery	
8. SOFC using liquid ammonia • Green (Norwegian) • Green (Nordic) • Blue • Grey	Ammonia SOFC and auxiliary Li-ion battery	L-NH_3 
9. PEMFC with liquid hydrogen • Green (Norwegian) • Green (Nordic) • Blue • Grey	Liquid hydrogen PEMFC and auxiliary Li-ion battery	L-H_2 
10. PEMFC with compressed hydrogen • Green (Norwegian) • Green (Nordic) • Blue • Grey	Compressed hydrogen PEMFC and auxiliary Li-ion battery	C-H_2 

Note that using ammonia in conventional internal combustion engines is challenging due to its poor fuel properties and specially designed engines are required (Korean Register, 2020). To overcome the high minimum ignition energy, ammonia requires an ignition plug if used in a spark ignition engine or a pilot fuel for ignition in a compression ignition engine. For simplicity, the analysis assumed that ammonia is used in a diesel-cycle engine without the addition of a pilot fuel in a compression engine because the pilot fuel use is likely to be small compared to the ammonia use.

2.3. Analysed propulsion system components – PSV

The LCA study considers the following propulsion system components: gensets with skid, battery, fuel cells, power converters for the battery and fuel cells, additional cables required for battery and fuel cells, and fuel tanks for ammonia, LNG/LBM, and liquid and compressed hydrogen. The components are further described in the text below.

2.3.1. Gensets

The four gensets consist of the DF engines, generators, and skids. One genset weighs about 70 ton in total. As a simplification, it was assumed that all gensets, regardless of whether the engine was a pure Otto- or diesel-cycle or DF engine, weighed and consisted of the same materials. In reality, engines may differ somewhat in terms of both weight and materials.

2.3.2. Li-ion battery

The Li-ion battery was installed onboard Viking Energy in 2016. The battery has a nominal capacity of 653 kWh. Note that the battery is required for propulsion systems relying on the fuel cells (Scenarios 8 – 10).

2.3.3. SOFC

It was assumed that a 3 000 kW SOFC will be used in conjunction with a Li-ion battery. It is further assumed that the SOFC is replacing the fossil fuel use and that the Li-ion battery is used as in the current Viking Energy. It was further assumed that the fuel cell energy efficiency was 70 % for the SOFC. The 70 % energy efficiency is in line with what the developer expects for the mature fuel cell. Further, it is expected that the mature fuel cell will have a usable lifetime of 60 000 hours. As such, one replacement of the fuel cell stacks was assumed in the analysis. Note that in the short term, an efficiency of 60 % and a usable lifetime of 20 000 hours are expected. Uncertainty aspect with respect to both usable lifetime and efficiency will be considered in the discussion (sub-section 7.2).

2.3.4. PEMFC

As an alternative to the ammonia SOFC, hydrogen PEMFCs with both liquid and compressed hydrogen were considered. It was also assumed that an approximately 3 500 kW PEMFC can replace the vessel's fossil fuel use. The higher power rating of the PEMFC compared to the SOFC is a consequence of the assumed 60 % efficiency of the PEMFC. It was further assumed that similar to the SOFC, the PEMFC stacks required one replacement.

2.3.5. Fuel tanks

It was assumed that the MGO tank may also be used for biodiesel. The tank is an integral part of the vessel and as such, it was not modelled separately.

For Scenarios 4 – 7, it was assumed that one cryogenic tank with a fuel capacity of 220 m^3 was required for LNG (or LBM) storage, which is the size of the LNG fuel tank onboard Viking Energy. It was assumed that this was a double lined tank made of stainless-steel.

As a simplification, similar tanks were assumed for the propulsion systems relying on ammonia (Scenario 3 and 8). The tank volumes of these were estimated based on relevant considerations, such as share of annual energy use, fuel density, energy efficiency. Note that the fuel tank requirements for fuel cell scenarios (8 – 10) were based upon energy use in Scenario 7, while fuel tank requirement for the ammonia combustion scenario (3) was based on Scenario 6.

For Scenario 3, it was assumed that the fuel tank would be 2.0 times larger compared to the existing LNG tank, accounting for the higher volume requirement of ammonia compared to LNG. Note that these estimates assume equal engine efficiency as the LNG engine, which must be considered as optimistic for ammonia combustion. For Scenario 8, it was estimated that the tank would be approximately the same size as the LNG tank. Recall that this estimate not only accounts for the higher volume requirement of ammonia versus LNG but also the higher energy conversion efficiency of the SOFC propulsion system and the lower fuel demand due to the battery.

For Scenario 9 considering liquid hydrogen, it was estimated that 1.7 times the tank volume of LNG was required. It was assumed that the cryogenic hydrogen tanks were made in a similar manner as the hydrogen tanks for compressed hydrogen, but that the liquid hydrogen tanks additionally contained a steel liner.

For Scenario 10 it was estimated that a volume of about 5.2 compared to LNG volume was required for storing the compressed hydrogen. The estimated volume equals 1 730 individual carbon fibre composite fuel tanks of the type assumed for the express boat. The composite fuels tanks have an aluminium-alloy tank lined internally with plastic lining and wrapped externally in a protective layer of composite carbon fibre.

It was assumed that fuel tanks for ammonia and hydrogen will be placed on deck and will consequently not take up any under-deck storage space.

2.3.6. Additional cables

Extra cabling is required for creating a battery-hybridized propulsion system (Maritime Battery Forum, 2016). Additional cable requirements for the hybridization (Scenario 7) were based on a previous study considering the environmental cost-benefit of hybridization (Maritime Battery Forum, 2016). Additional cable requirements for fuel cells (Scenarios 8 – 10) were roughly approximated by assuming three times as much for the fuel cell unit as for the battery. Potential energy losses in the cables were not considered in the analysis

2.3.7. Power converters for batteries and fuel cells

Both the battery and the fuel cells require power converters to provide AC current at the right voltage. From the electrochemical devices, the current is directed to an inverter that converts the electric energy in the form of direct current (DC) to alternating current (AC). A transformer controls the voltage sent to the AC grid.

Because the fuel cells considered for the PSV (Case 1) has a similar power rating as the fuel cells in the express boat (Case 3), the power converter requirements for the PSV were assumed to be the same as for the express boat. For the battery in the PSV, it was assumed that power converter requirements were proportionally less compared to the requirement for the express boat.

2.3.8. Excluded components

Common components in the propulsion system (e.g., integrated fuel tanks, shafts, emergency genset, thrusters, etc.) were not considered. Onshore infrastructure required for the various propulsion systems were not considered in the analysis. Thus, potential establishment of onshore fuel storage tanks or mooring systems were not considered. While onshore fuel tanks suitable for MGO and biodiesel are already available, onshore storage tanks for hydrogen and ammonia would probably have to be established should technologies relying on these be realized for the route. Maintenance was not considered.

2.4. Operational profile - PSV

The PSV has a range of different operational modes. The energy use and duration of the operational modes vary significantly. Rather than providing one energy estimate based on the various operational modes, an energy estimate was calculated for each of the operational modes. The more detailed energy estimates enable more accurate results compared to an overall energy estimate.

Based on data from 01.01.2012 - 31.12.2018 (except 2016), an average operational profile was estimated with respect to how much time the vessel spends in each mode. Because the battery was installed in 2016, the time spent in different operational modes may not be representative for an average year. Thus, 2016 data were excluded from the calculation of the average operational profile. Eight main operational modes were reported for the PSV:

- Dynamic positioning
- Harbour
- Mobilization
- Standby
- Transit in economical speed
- Transit high
- Waiting on weather
- Uncategorized

Mobilization and uncategorized were excluded from the data set. Mobilization was excluded as it was only registered for a very few hours in 2013 and 2014 (0.04 % of total hours in the considered time period). Because the vessel hardly spends any time in this mode, it was considered as not being part of the regular operation. Uncategorized was excluded as the associated activities (yard stay, technical downtime, and shifting alongside) are also not considered as regular PSV operation and because the hours spent in these activities may vary significantly per year.

Based on the six considered operational modes, we find that on average the vessel is in operation 8 558 hours per year. The average number of hours and share of time spent in the seven operational modes is presented in Figure 5.

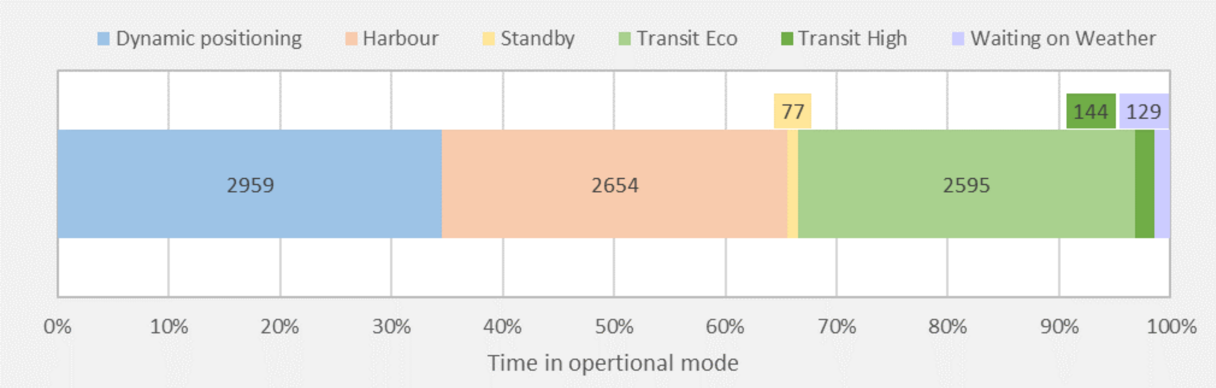


Figure 4 Average operational profile with hours spent in different operational modes

Based on the average time spent in the six operational modes, the vessel spends 96 % in three modes: dynamic positioning (35 %), harbour (31 %), and transit in economical speed (30 %). The vessel spends significantly less time in standby (0.9%), high speed (1.7 %), and waiting on weather (1.5 %).

2.5. Fuels use – PSV

This section estimates the use of fuels in the time periods 2012 – 2015 (Scenario 6) and 2017 – 2018 (Scenario 7) in sub-section 3.5.1 and 3.5.2.

2.5.1. Fuel during 2012 – 2015 (Scenario 6)

Data from the time period 01.01.2012 – 31.12.2015 were used to obtain an overview of the fuel use for the different operational modes for Viking Energy – representative for Scenario 6. The distribution between LNG and MGO among the operational modes are provided in Figure 6. In the figure, darker colour shades denote LNG while lighter shades denote MGO.

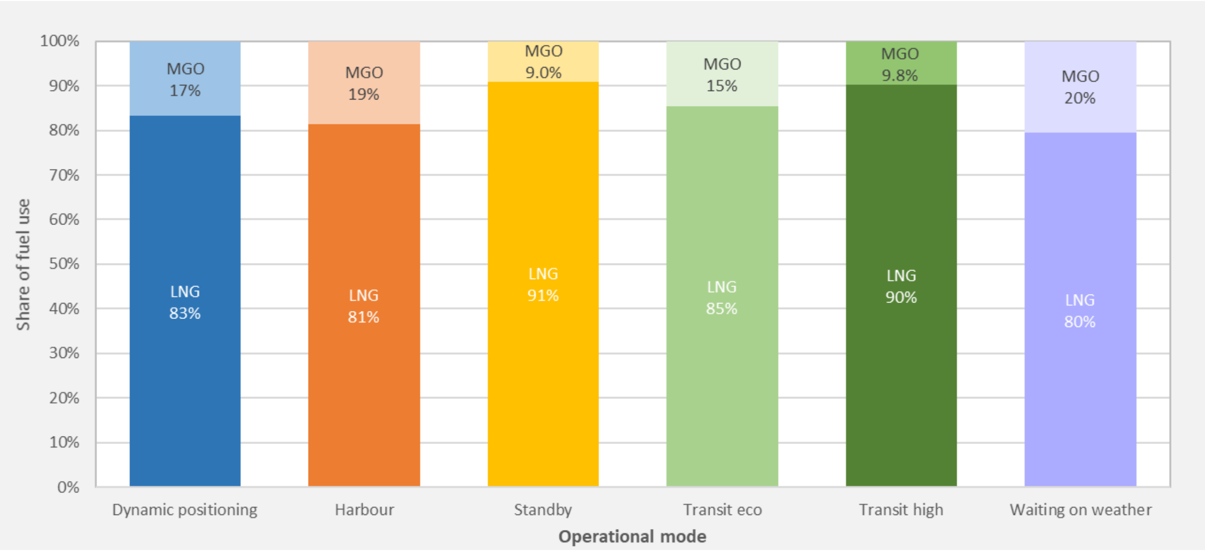


Figure 5 Average distribution of fuel use for the different operational modes for Viking Energy in 2012 – 2015

The average fuel use for 2012 – 2015 confirms that the vessel primarily relied on LNG most of the time.

2.5.2. Fuel use during 2017 – 2018 (Scenario 7)

Data from the time period 01.01.2017 – 31.12.2018 were used to obtain an overview of the fuel use for the different operational modes for the battery-hybridized Viking Energy - representative for Scenario 7. In the figure, darker colour shades denote LNG while lighter shades denote MGO.

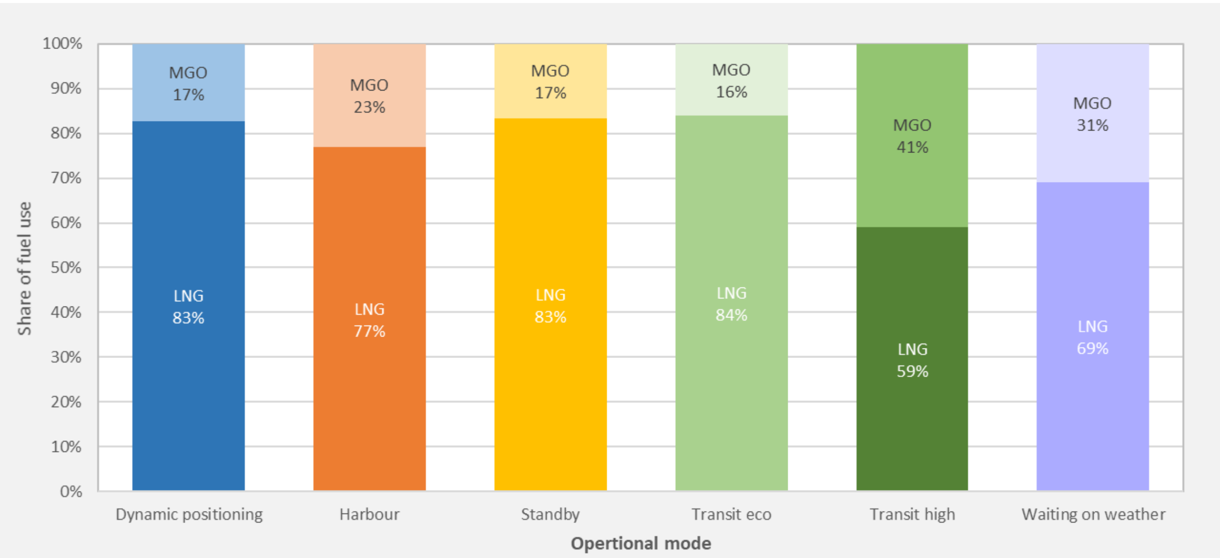


Figure 6 Average distribution of fuel use for the different operational modes for Viking Energy in 2017 – 2018

The shares of LNG and MGO changed somewhat when going from a pure fossil fuel operation to a battery-hybridized operation. The most significant change in fuel use was found in transit high.

2.5.3. Annual average fuel consumption – Scenario 6 & 7

Based on the average yearly hour of operation, operational mode time shares, and fuel use shares, the annual average fuel consumption was calculated for Scenario 6 and Scenario 7. Figure 8 presents the annual average fuel consumption per LNG and MGO and operational mode for Scenario 6 and Scenario 7. In the figure, darker colour shades denote LNG while lighter shades denote MGO.

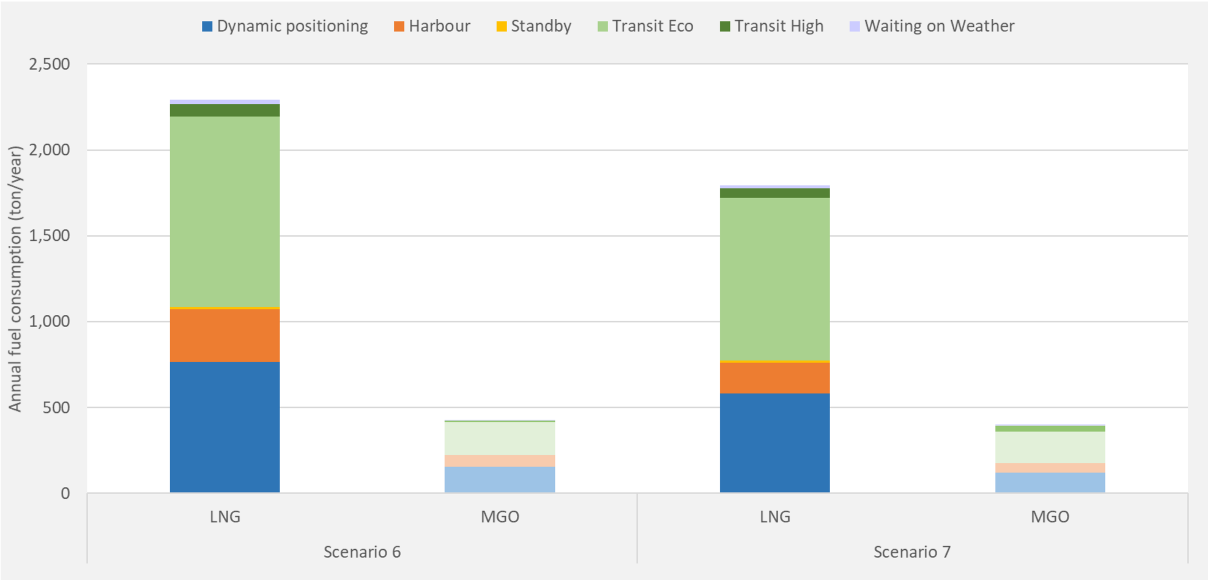


Figure 7 Average annual consumption per fuel and operational mode

The total average fuel consumption is 2 722 ton/year in Scenario 6 (original propulsion system) and 2 197 ton/year in Scenario 7 (hybridized propulsion system). Thus, the total fuel consumption is 19 % lower for Scenario 7 compared to Scenario 6. LNG use was reduced by 22 %, going from 2 292 ton/year in Scenario 6 to 1 793 ton/year in Scenario 7. MGO use was reduced by 6.0 %, going from 429 ton/year in Scenario 6 to 404 ton/year in Scenario 7.

Fuel reductions were significant in the three most time and fuel consuming operations: dynamic positioning, harbour, and transit in economical speed. During dynamic positioning the battery is used as a spinning reserve, enabling the use of only one engine rather than two. As an engine operating alone will operate at a higher engine load, the engine efficiency is higher and the SFOC is lower. In the operational phase total (LNG and MGO) fuel use was reduced by 24 %. Compared to the other operational modes, the vessel has low fuel use per hour when it is in harbour. Even so, a 38 % total fuel reduction was obtained in harbour as battery use replaces burning fuels at low engine loads. Perhaps more unexpectedly, battery use also leads to a 13 % fuel reduction in transit in economical speed.

The interested reader can find the estimated SFOC as well as the engine efficiency for the DF engine in Appendix D – Specific fuel oil consumption.

2.5.4. Estimated total fuel consumption – Scenarios 1 – 10

Fuel use for Scenarios 1 – 5 and 8 – 10 were respectively based on the fuel use (kg) in 2012 – 2015 (Scenario 6) and 2017 – 2018 (Scenario 7), energy conversion efficiencies of engines and fuel cells (including converters), and the lower heating value (LHV) measured in MJ/kg. The assumed LHVs used in this report are provided in Table 3.

Table 2 Lower heating values used to convert fuel use

Fuel	MGO	Biodiesel	Ammonia	LNG	LBM	Hydrogen	LS-HFO
Lower heating value (MJ/kg)	42.7	42.8	18.6	49.2	50.0	120	41.8

Because Scenarios 1 – 5 and 8 – 10 were based on Scenario 6 and 7, respectively, different approaches were required to calculate consumption of fuels and energy carriers. As a simplification, it was assumed that the weight difference in propulsion systems itself did not affect the fuel use. In reality, the difference in weight will affect the fuel use somewhat.

It was assumed that all combustion engines have the same SFOC and efficiency profile and consequently, the fuel consumption in Scenarios 1 – 5 was simply converted to the various combustion fuels by using the LHV of the respective fuels. Note that at current, ammonia combustion engines are not commercialized and the assumption of an equal efficiency as MGO is rather simplistic and optimistic but was nonetheless adopted for the sake of facilitating a comparison.

In comparison to the combustion engine alternatives, estimating the consumption of energy carriers in Scenarios 8 – 10 was more complicated as the higher energy efficiency of the fully electric propulsion system had to be considered. To estimate the consumption of ammonia and hydrogen for the fuel cell scenarios, we had to establish the energy conversion efficiencies in the engines and the fuel cells as well as the converters. Because Scenarios 8 – 10 build on Scenario 7, the fuel consumption in Scenario 7 served as a starting point. To account for energy conversion losses in the engine, the average engine efficiency for each of the six operational modes were established. The average energy efficiency was based on the average engine load of maximum continuous rating. We relied on average engine loads for Viking Energy. Both the average engine loads and engine efficiencies estimated for the different operational modes are provided in Table 3.

Table 3 Estimated average engine efficiency estimated for each operational mode in Scenario 7

Operational mode	Dynamic positioning	Harbour	Standby	Transit Eco	Transit High	Waiting on Weather
Engine load of maximum continuous rating	48%	23%	34%	70%	75%	50%
Engine efficiency	41 %	31 %	36 %	45 %	46 %	41 %

For both fuel cells, it was assumed that the converters and the fuel cells were operating under a constant efficiency, and that the converter was operating at an efficiency of 96 %, the SOFC 70 %, and the PEMFC 60 %.

It is worth remarking that while the SOFC will replace about 70 – 80 % of the energy coming from LNG and MGO on Viking Energy currently (Scenario 7), the study assumed that the ammonia SOFC and hydrogen PEMFC will fully replace the energy that comes from combustion of LNG and MGO.

Figure 9 reports the estimated total fuel use in terms of weight measured in metric ton per operational mode per year. As in the previous figures, darker colour shades denote LNG while lighter shades denote MGO. In addition, upward diagonal stripes denote biofuel (biodiesel and LBM), downward diagonal stripes denote ammonia in the combustion engine (Scenario 3) and SOFC (Scenario 8), and vertical stripes denote hydrogen (Scenario 9 & 10).

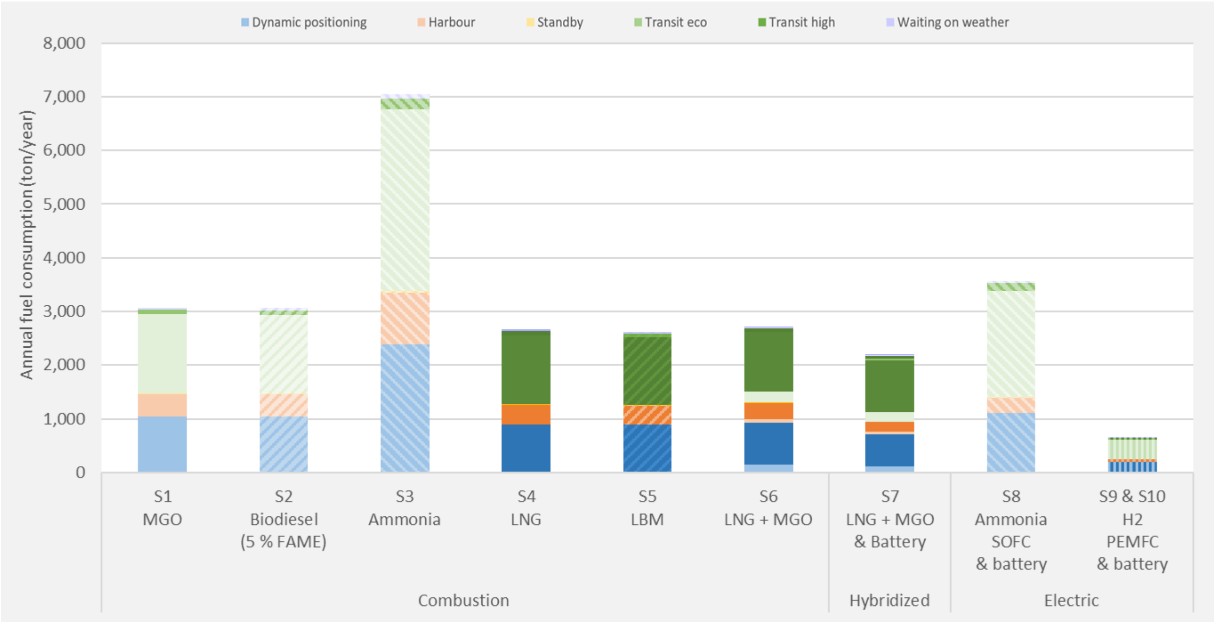


Figure 8 Total annual fuel or energy carrier use per operational mode in terms of weight

Figure 9 reports the estimated fuel consumption over the course of a year. Scenario 1 and 2 consume about the same amount of fuel in terms of weight because MGO and biodiesel have a similar LHV. In contrast, the weight of ammonia in Scenario 3 would be significantly heavier as it has a low LHV. Scenarios 4 and 5 relying solely on LNG or LBM, respectively, would require slightly less fuel weight with the highest LHVs of the considered fuels. In comparison to Scenarios 4 and 5, the original vessel (Scenario 6) relying on LNG and MGO requires somewhat more fuel in terms of weight because MGO has a lower LHV compared to LNG. The battery-hybridized vessel (Scenario 7) uses less fuel in terms of weight as the battery enabled fuel reductions (a more detailed comparison of fuel use between Scenario 6 and 7 was given in Figure 8). In Scenario 8, the vessel has replaced its LNG and MGO fuel use in favour of ammonia in an SOFC. Consequently, the SOFC vessel requires ammonia, which leads to higher fuel weight as ammonia has significantly lower LHV than LNG and MGO. Because the SOFC has higher efficiency than the internal combustion engine and because the vessel is also equipped with an auxiliary battery, less ammonia is required in Scenario 8 compared to Scenario 3. In Scenarios 9 and 10, the hybridized vessels use liquid and compressed gas hydrogen in a PEMFC, respectively. While the PEMFC has lower efficiency (60 %) than the SOFC (70 %), hydrogen has a much higher LHV (120 MJ/kg) than ammonia (18.6 MJ/kg), resulting in comparatively lower weight.

3. CASE 2: CHEMICAL TANKER VESSEL

Case 2 considers a chemical tanker. Chemical tankers are cargo ships constructed or adapted and used for the carriage of any liquid chemicals in bulk (Wärtsilä). Compared to PSVs, chemical tankers have a much simpler operational profile as they spend most of their time in transit.

3.1. Case study description – chemical tanker

The case study considers a fictitious medium range chemical tanker with a capacity of approximately 50 000 deadweight tons (DWT). It was assumed that the tanker is a modern vessel with an installed engine power of about 8 000 kW. Two broad propulsion system categories were evaluated for the chemical tanker: internal combustion engines and fuel cell electric. The propulsion system scenarios are described in the next sub-chapter.

3.2. Propulsion system scenarios – chemical tanker

In total, nine main scenarios were considered for the chemical tanker, but for the ammonia and hydrogen scenarios, four fuel production pathways were considered. Table 4 provides a summary of the various propulsion system scenarios considered in the LCA of the tanker.

Table 4 Summary of the various propulsion system scenarios considered in the LCA of the chemical tanker.

Scenario number and fuel description	Energy conversion technologies	
1. MGO 2. Biodiesel (5 % FAME) 3. Liquid ammonia • Green (Norwegian) • Green (Nordic) • Blue • Grey 4. LS-HFO (low sulphur HFO, 1 % S)	Internal combustion engine with main and auxiliary engine on diesel-cycle	Diesel Diesel
5. LNG 6. LBM	Internal combustion engine with main engine on diesel-cycle and auxiliary engine on Otto-cycle	Diesel Otto
7. SOFC with liquid ammonia • Green (Norwegian) • Green (Nordic) • Blue • Grey	Ammonia SOFC and auxiliary Li-ion battery	L-NH_3
8. PEMFC with liquid hydrogen • Green (Norwegian) • Green (Nordic) • Blue • Grey	Liquid hydrogen PEMFC and auxiliary Li-ion battery	L-H_2
9. PEMFC with compressed hydrogen • Green (Norwegian) • Green (Nordic) • Blue • Grey	Compressed hydrogen PEMFC and auxiliary Li-ion battery	C-H_2

Note that for Scenario 4, it was assumed that low sulphur heavy fuel oil (LS-HFO) was used. Because the ship is using LS-HFO, there is no scrubber system for the main engine. This contrasts with the current international ship fleet where a significant number of ships use scrubber technology to reduce SO_2 emissions in order to meet local air pollution regulations in Sulphur Emission Control Areas (SECAs), see Figure 10. However, the LCA study considers a modern vessel using LS-HFO where this technology is unnecessary. Thus, scrubber systems were not considered for any of the propulsion scenarios.

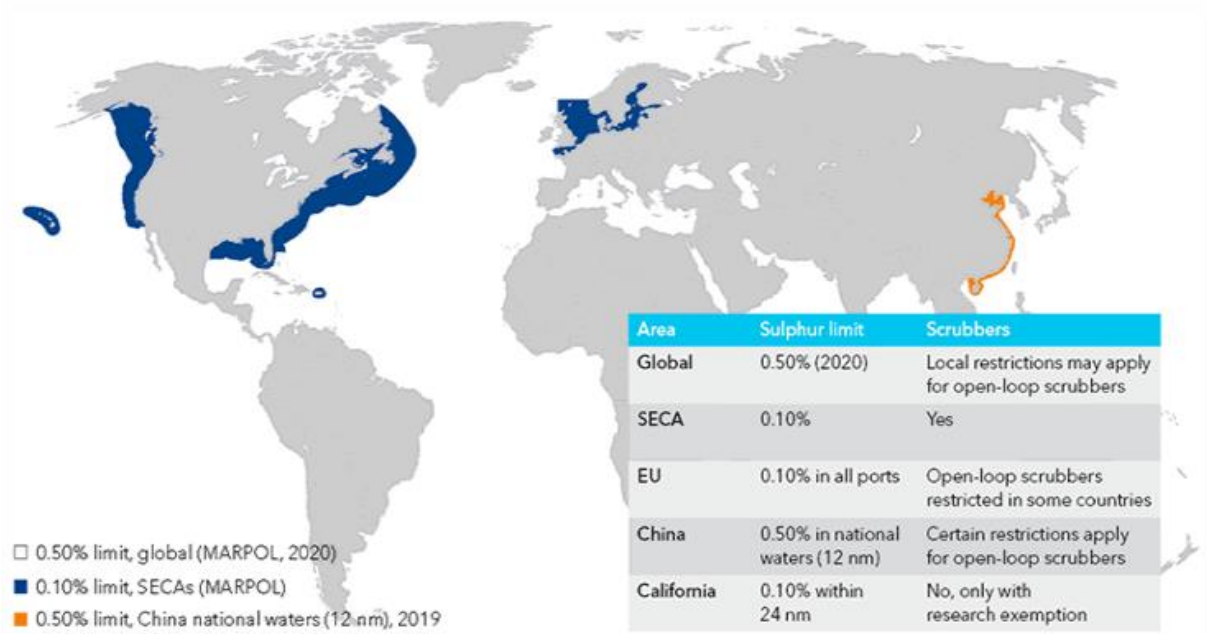


Figure 9 Local air pollution regulation in SECAs. Figure from (DNV-GL, 2019).

3.3. Analysed propulsion system components – chemical tanker

The LCA study considers the following propulsion system components: internal combustion engine, boilers (only for the combustion engine scenarios), fuel cells and auxiliary battery, power converters for the fuel cells and battery, additional cables required for fuel cells and battery, and fuel tanks.

3.3.1. Internal combustion engine

It was assumed that the vessel has an installed engine power of about approximately 8 000 kW. As a simplification, it was assumed that all gensets, regardless of whether the engine was a pure Otto- or diesel-cycle or DF engine, weighed and consisted of the same materials. In reality, engines may differ somewhat in terms of both weight and materials.

3.3.2. Boilers

The demand for internal heating of the hotelling part of the ship is covered by an exhaust boiler extracting heat from the exhaust when the main engine is utilized. However, when at bay, main engine is at standstill, thus not providing heat and additional boilers are applied for heating. The exhaust boiler is extracted from calculations in scenarios with fuel cells as they do not provide hot exhaust.

3.3.3. Fuel cells and battery

It was assumed that the SOFC and the PEMFC had a power rating of 6 000 kW and 7 000 kW, respectively, and that the required auxiliary battery had a nominal capacity of about 2 600 kWh. As for the PSV, it was assumed that the fuel cell energy efficiency was 70 % for the SOFC and 60 % for the PEMFC. For the chemical vessel, it was estimated that four cell stack replacements were required for both the SOFC and PEMFC. No replacement of the battery was assumed.

3.3.4. Power converters and cables
The power converter and cabling requirements were assumed to be about three times larger than that for the PSV. The power converter was assumed to have a constant energy efficiency of 96 %, potential losses in the cables were not considered.

3.3.5. Fuel tanks
It was assumed that fuel tanks for MGO and LS-HFO (Scenarios 1 and 4, respectively) can also be used for biodiesel (Scenario 2). It was further assumed that these are integrated parts of the vessel design. As such, these tanks were not modelled specifically.

Double lined cryogenic tanks made of stainless-steel were assumed for liquid ammonia for combustion (Scenario 3) and SOFCs (Scenario 7), LNG (Scenario 5), LBM (Scenario 6), and liquid hydrogen (Scenario 8). Note that it was assumed that the double lined hydrogen tanks for liquid hydrogen were made in a similar manner as the hydrogen tanks for compressed hydrogen, but that the liquid hydrogen tanks additionally contained a steel liner. Composite fuel tanks were assumed for compressed hydrogen (Scenario 9). The composite fuels tanks have an aluminium-alloy tank lined internally with plastic lining and wrapped externally in a protective layer of composite carbon fibre.

It was assumed that fuel tanks for ammonia, LNG, LBM, and hydrogen will be placed on deck and will consequently not take up any internal storage space.

3.3.6. Excluded components
Common components in the propulsion system (e.g., integrated fuel tanks, shafts, emergency genset, thrusters, etc.) were not considered. Onshore infrastructure and maintenance were not considered in the analysis.

3.4. Operational profile – chemical tanker
Chemical tankers typically spend time in only three operational modes: cruising, manoeuvring, and hotelling at berth. While various sources report the time spent in the various operational modes, we based our estimate calculations on a Finnish study that applies AIS tracking to render average time spent in different operational modes for various vessel types (Jalkanen, Johansson and Kukkonen, 2016). Regarding time spent in the three operational modes, the Finnish study reports the following information for chemical tankers:

- 53 % of the time in cruising mode
- 3 % of the time in manoeuvring mode
- 44 % of the time hotelling at berth

The above data indicate that cruising and hotelling (in harbour) are the two main operating modes and for simplicity, we consider only fuel use during cruising and while in harbour.

Based on the above information from the Finnish study and expected operational hours from a shipowner, we find that the average yearly time spent during cruising and in harbour are 4 465 hours and 3 959 hours, respectively.

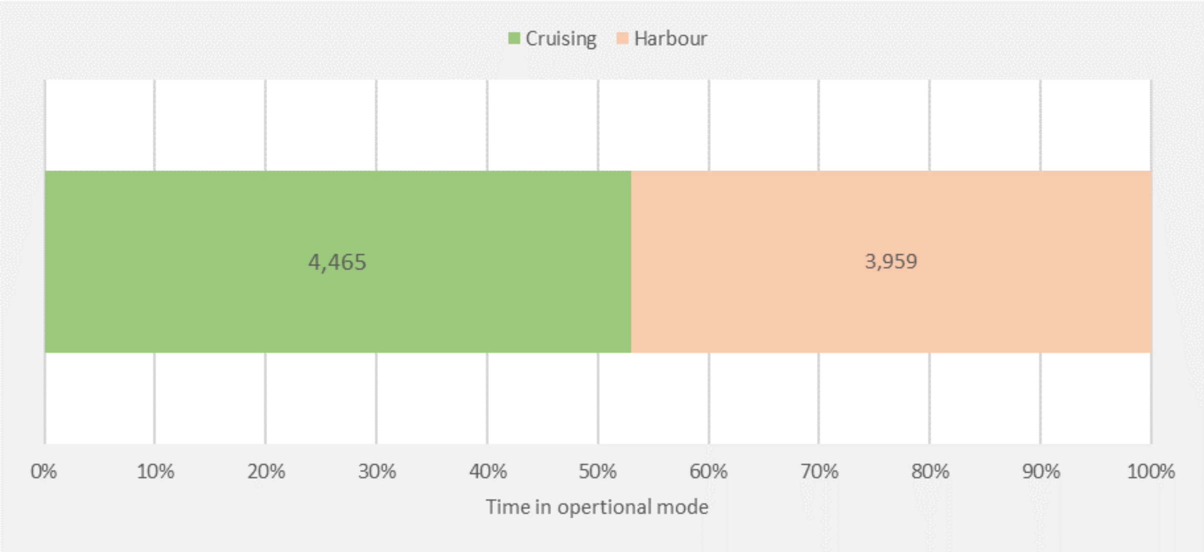


Figure 10 Estimated operational profile with hours spent in different operational modes

Both the main engine (ME) and the auxiliary engines (AE) are in use during cruising, while only the AE are in use while in harbour. In the next sub-chapter, the fuel use of each engine types and operational modes are estimated.

3.5. Fuel use – chemical tanker

Because both the ME and the AE run during cruising, one must determine how much fuel use stems from each of these to estimate the separate fuel use by the ME and the AE. According to the Finnish study, 71 % of the fuel during operation is used by the ME, while the remaining 29 % is used by the AE and boilers (Jalkanen, Johansson and Kukkonen, 2016). Using the ME fuel use as a starting point, we estimated the division of fuel use of the AE during cruising and in harbour.

Based on the estimated power output and time in operational modes, one can estimate the total annual energy demand at shaft by the ME and the AE. The ME power output at shaft was taken from the data sheet of an ME used in a modern chemical tanker and was found to be 5 083 kW (at the design speed of 14 knots). By multiplying the annual power output at shaft by the annual time spent in cruising, the total annual energy demand at shaft was estimated for the ME. As specific data was not available for the AE, literature values were used instead. For the particular size and vessel type, Scarbrough *et al.* (2017) reports that the average AE power output at shaft during cruising is 550 kW (boiler use is 0 kW). By multiplying this number by the total annual hours in cruising, one gets the total annual AE energy demand at shaft while in cruising.

The total ME annual energy demand at shaft was divided by 71 % to obtain the vessel's total annual energy demand at shaft. Subsequently, the total annual energy demand at shaft of the ME was subtracted from the total annual energy demand at shaft to calculate the total annual energy demand at shaft by the AE. This number was again subtracted by the annual AE energy demand at shaft while cruising to obtain the AE energy demand at shaft while in harbour.

The abovementioned energy calculations were all performed at the shaft, which does not include the engine efficiency. Thus, to get the total energy use of the ME and AE, we must consider the engine efficiencies. The energy efficiency of the ME at 14 knots was 55.6% (with an SFOC of 155 g/kWh) for the considered engine.

According to a report published by the European Environment Agency, tankers typically operate at 60 % of maximum continuous rate (MCR) when they are hotelling (Trozzi and Lauretis, 2019). Extrapolation of data for the AE provides an energy efficiency of 35 % (240 g/kWh) while in harbour.

Based on an estimated MCR of 45 %, we estimated an energy efficiency of 31 % (270 g/kWh) during cruising.

Based on the above calculations, the annual fuel consumption was estimated for a generic modern chemical tanker. The fuel consumption of the generic chemical tanker is presented in Figure 12.

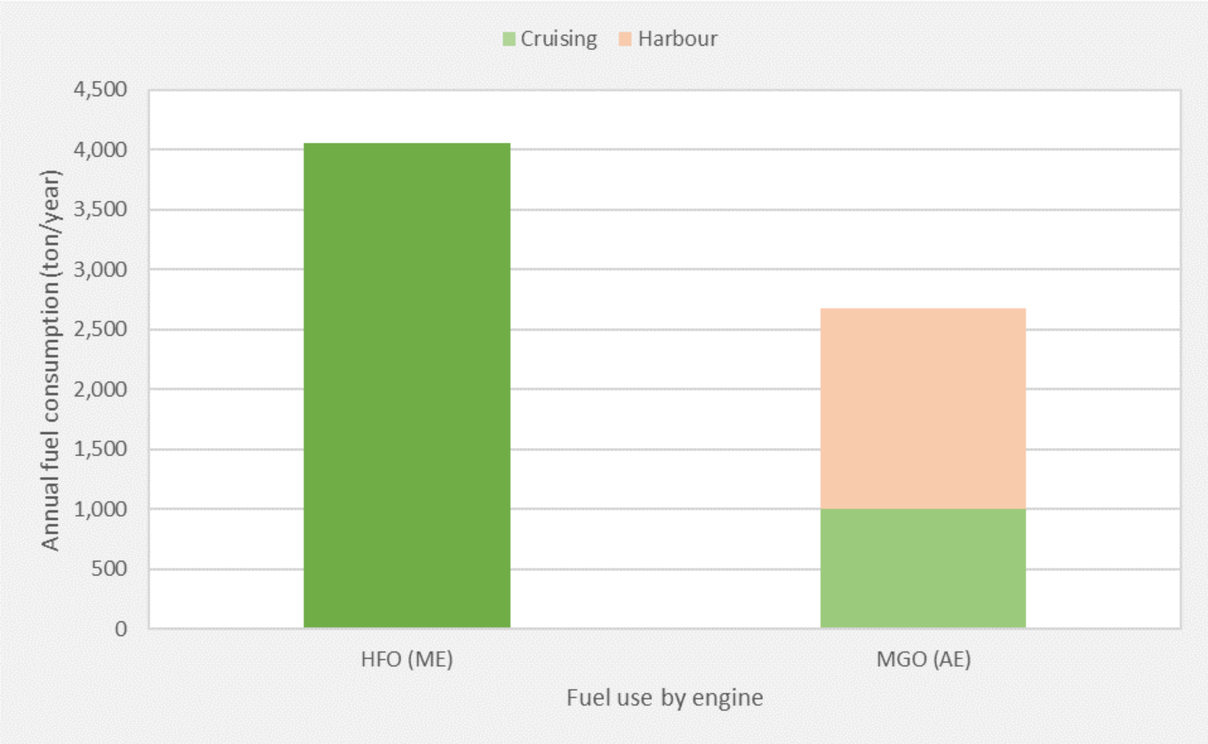


Figure 11 Estimated annual fuel consumption of LS-HFO and MGO for a generic modern chemical tanker

Based on the calculation, we find that a generic modern chemical tanker consumes about 6 700 tons of fuels for cruising and hotelling annually. The ME fuelled on HFO uses about 60 % of the total consumption. The AE fuelled on MGO uses about 15 % of the total fuel consumption for cruising and 25 % for hotelling while in harbour.

3.5.1. Estimated total fuel consumption – Scenarios 1 – 9

Based on the estimated generic fuel consumption of LS-HFO and MGO, the fuel consumption for the nine different fuel and propulsion system scenarios were considered. As in Case 1, it was assumed that the difference in weight did not affect the fuel consumption. Note that this is a simplistic approach as the difference in weight will affect the fuel use in reality (this is discussed in sub-chapter 7.3 considering limitations of the study). Also similar to Case 1, it was assumed that all combustion engines have the same SFOC and efficiency profile. It was further assumed that the SOFC and the PEMFC were operating under a constant efficiency of 70 % and 60 %, respectively. As a simplifying measure, additional energy (from the fuels cell or land current) required to charge the batteries was assumed to be negligible and therefore not explicitly considered. The LHVs presented in Table 2 were used to calculate the fuel consumption in terms of weight. Figure 13 reports the estimated total fuel consumption in terms of weight per operational mode per year.

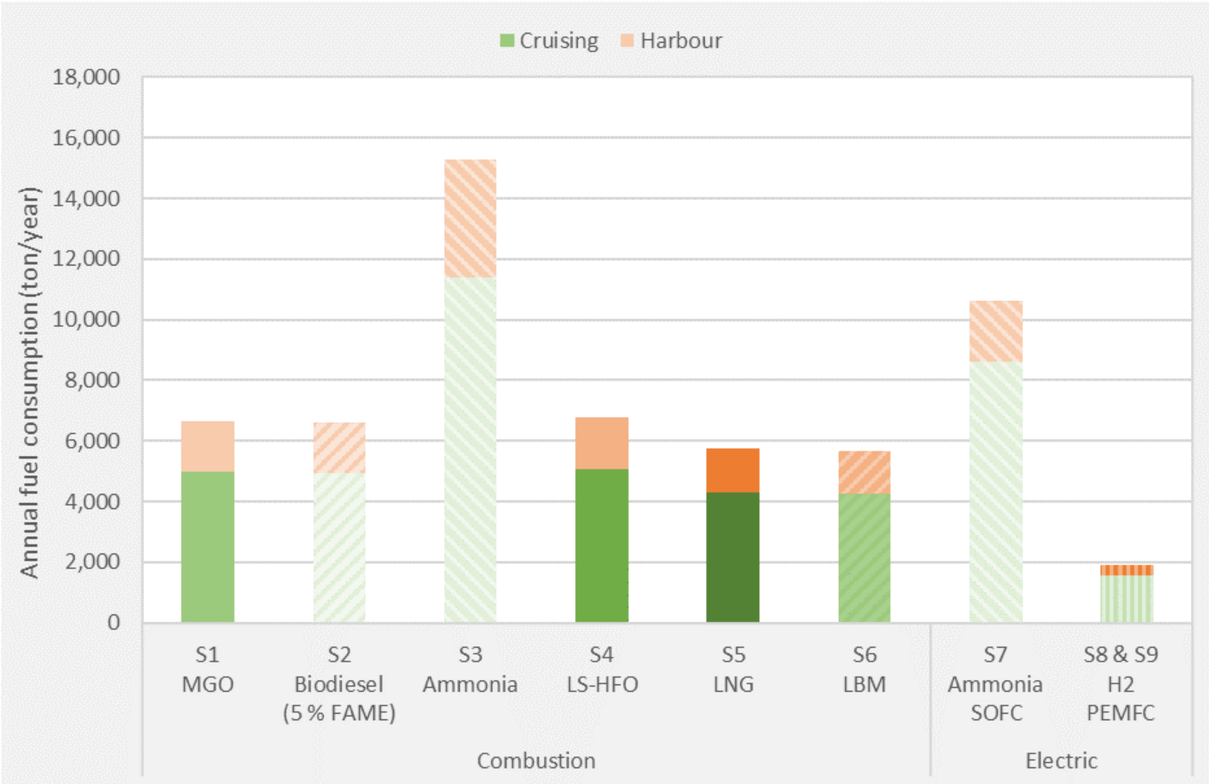


Figure 12: Total use of fuel per operational mode in terms of weight

The annual average fuel consumption varies among the different scenarios. The weight of the fuels is fairly similar for MGO, biodiesel, LS-HFO, LNG, and LBM. In contrast, the propulsion systems relying on ammonia are significantly higher due to the low LHV of ammonia. As ammonia FC has a higher fuel efficiency than the ammonia combustion engine, less ammonia is required in Scenario 7 compared to Scenario 3. Because hydrogen has a very high LHV compared to the other fuel alternatives, Scenario 8 (L-H_2) and Scenario 9 (C- H_2) have the lowest fuel weight of the considered fuels.

Fuel volume is also an interesting aspect that should be considered when comparing different fuel alternatives. To consider this aspect, the fuel volume for the different scenarios was considered. While values of fuel tank volumes may be found in the literature, the assumptions behind these estimates are unknown. To be consistent with the system boundaries and assumptions of our study, we made our own calculations regarding the fuel tank storage volume. The fuel tank storage volume for HFO and MGO of a chemical tanker was used as a starting point. The shipowner reports that one of their vessels have fuel tanks that can hold 2 120 m^3 of HFO and 570 m^3 of MGO, but that they are only permitted to fill the fuel tanks up to 98 % of tank capacity. The usable fuel tank storage volume is equivalent to about 43 % of the estimated annual average fuel consumption. As the considered fuel tank is deemed to be abnormally large by the shipowner, the shipowner suggested that half the fuel tank size should lay the foundation for the analysis.

By assuming that the fuel tanks should hold about 21 % of their annual fuel use, the fuel tank storage volumes were estimated. Recall that the fuel consumption estimates incorporated the efficiency of the onboard energy conversion in the engines and fuel cells and as such, the estimated fuel volume also incorporates this efficiency. By considering the differences in efficiencies of the powering units, we have assured that the ship will be able to perform the same amount of operations and length of sailing with the alternative fuels or energy carriers. Figure 14 presents the estimated fuel volumes (left axis; columns) as well as the fuel weights (right axis; circles). Note that the estimate solely considers the volume required for storing the fuel without potential volume requirements for tank insulator.

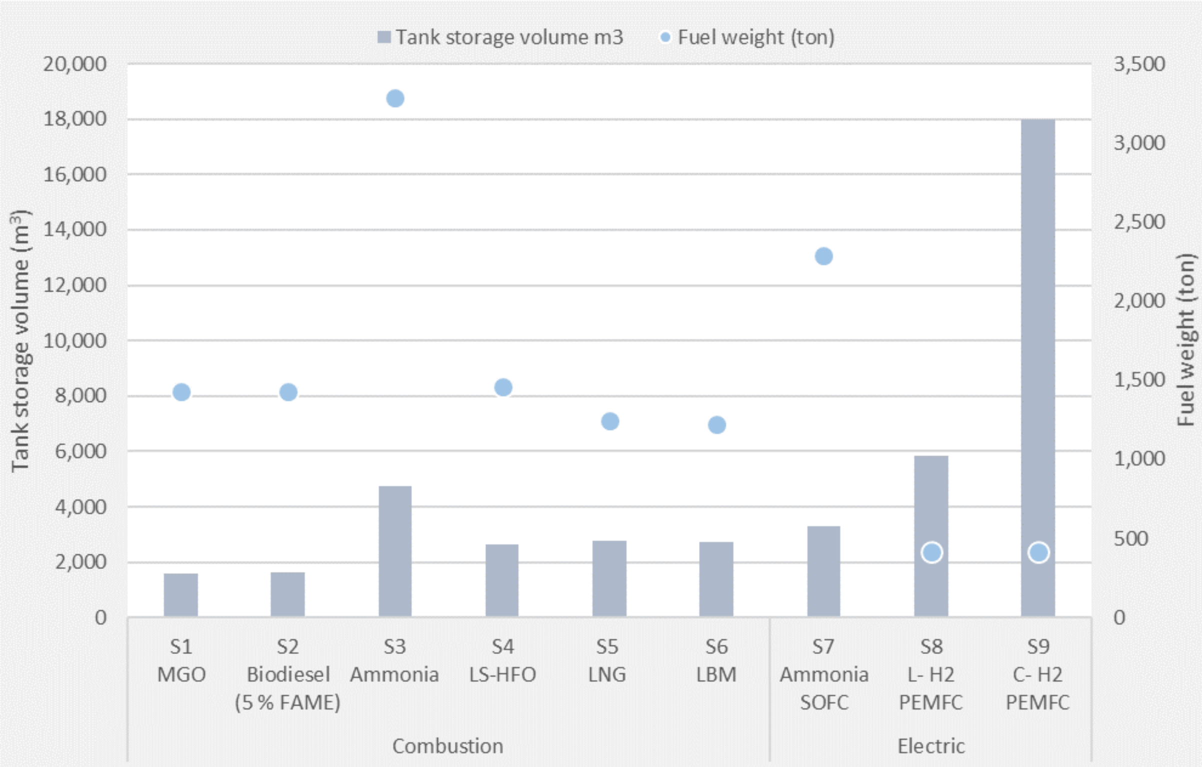


Figure 13 Estimated fuel volume and weight for the chemical tanker scenarios. Note that the efficiencies of energy conversion are incorporated in the estimates, while the additional volume required for a potential insulator is not considered.

When considering the fuel volume, the ranking in preferability differs from that of fuel weight. Here, we find that particularly hydrogen is a much less attractive option compared to conventional combustion fuels such as MGO and HFO. Compressed hydrogen is a particularly unattractive alternative when fuel volume is considered. Because the energy conversion efficiency of ammonia (Scenarios 3 and 7) are particularly uncertain, the estimated fuel volume of ammonia is associated with uncertainty. Both estimates are likely to be optimistic and actual fuel volumes will probably be higher, at least until the technologies mature.

4. CASE 3: EXPRESS BOAT – SUMMARY

Case 3 considered propulsion system alternatives for a fictitious express boat. The study is described in a separate report (Asplan Viak, 2020). In the current report, only a brief summary of the study and results is provided.

4.1. Case study description – express boat

The case study considers an express boat that operates the 150 nautical mile route between Bergen and Selje. The route takes about 4.5 hours each way. In this case study, the propulsion system of a fictitious carbon-fibre catamaran servicing the route is analysed. The boat makes one round-way trip every day, with a two-hour layover in Selje. The route is shown in the blue line in Figure 14.

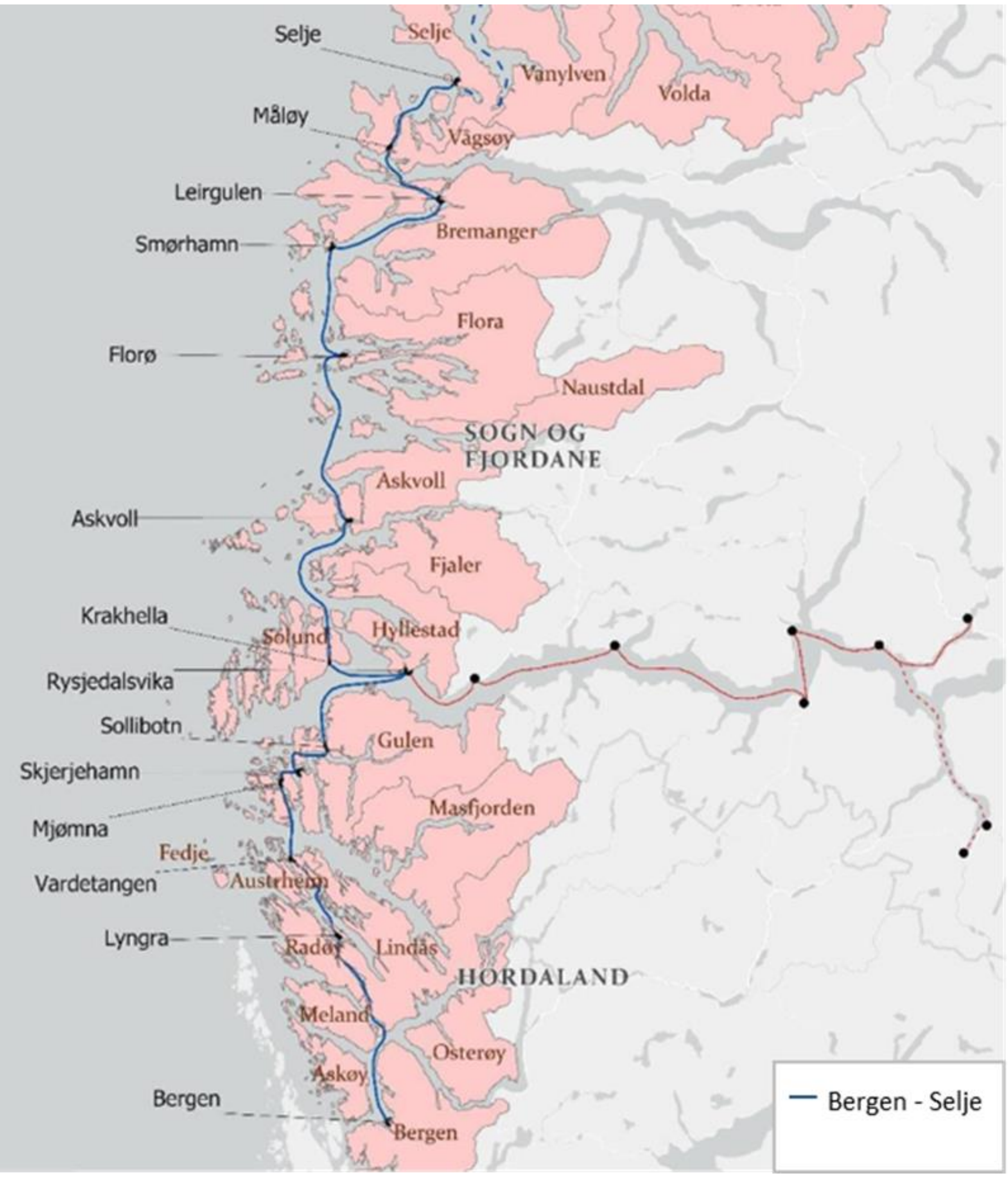


Figure 14 The route between Bergen and Selje. Figure is taken from COWI (2019).

The cradle-to-grave GHG emissions were calculated for a 10-year period of operation and considered the most relevant propulsion system components as well as fuels and energy carriers. The functional unit of the studied propulsion systems is thus set to the service life of ten years. It was assumed that all propulsion systems provide the same passenger capacity. The analysis was carried out as an attributional LCA where emissions were ascribed to the studied system.

4.2. Propulsion system scenarios – express boat

Two wide categories of propulsion technologies were considered for the express boat: internal combustion engine and electric motor. In the preceding report, 15 different express boat propulsion system alternatives were considered. Here, we have updated three of the ammonia production pathways considered in the preceding report as well as added a production pathway for both ammonia and hydrogen, so that a total of 18 alternatives are considered. The alternatives are summarized in Table 5.

Table 5 Overview of considered propulsion system alternatives for the express boat

Alternative	Fuel/energy storage description	Propulsion technology
MGO	Marine gasoil	Combustion
Biodiesel	Biodiesel blend (5% v/v FAME and 95% v/v diesel)	Combustion
HVO (without ILUC)	Hydrotreated vegetable oil (a drop-in biofuel) where any potential indirect land use change emissions are not considered	Combustion
HVO (with ILUC)	Hydrotreated vegetable oil (a drop-in biofuel) where potential indirect land use change emissions are considered	Combustion
Green ammonia (Norwegian)*	Liquid ammonia produced using electricity based on the Norwegian production mix	Combustion
Green ammonia (Nordic)*	Liquid ammonia produced using electricity based on the Nordic consumptions mix	Combustion
Blue ammonia*	Liquid ammonia based on hydrogen produced through steam methane reformation with carbon capture and storage	Combustion
Grey ammonia+	Liquid ammonia based on hydrogen produced through steam methane reformation	Combustion
Battery (Nordic)	Nordic electricity mix, for charging Li-ion battery	Electric
Battery (Norwegian)	Norwegian electricity mix, for charging Li-ion battery	Electric
Green L-H_2 (Nordic)	Liquid hydrogen produced through electrolysis using the Nordic electricity mix, for use in PEMFC	Electric
Green L-H_2 (Norwegian)	Liquid hydrogen produced through electrolysis using the Norwegian electricity mix, for use in PEMFC	Electric
Blue L-H_2	Liquid hydrogen from steam methane reformation with carbon capture and storage, for use in PEMFC	Electric
Grey L-H_2+	Liquid hydrogen from steam methane reformation, for use in PEMFC	Electric
Green C-H_2 (Nordic)	Compressed hydrogen produced through electrolysis using the Nordic electricity mix, for use in PEMFC	Electric
Green C-H_2 (Norwegian)	Compressed hydrogen produced through electrolysis using the Norwegian electricity mix, for use in PEMFC	Electric
Blue C-H_2	Compressed hydrogen from steam methane reformation with carbon capture and storage, for use in PEMFC	Electric
Grey C-H_2+	Liquid hydrogen from steam methane reformation, for use in PEMFC	Electric

*These ammonia production pathways have been modified compared to the preceding report
+These production pathways have been added reflect grey production pathways

4.3. Analysed propulsion system components – express boat

The analysis considered the production and disposal of onboard fuel tanks, combustion engines, batteries, fuel cells, power converters, and electric motors.

While common propulsion components used in both propulsion technologies, such as the shaft, gear box, and propeller, were not modelled in the analysis, the energy efficiencies of these components were considered when estimating the total propulsive efficiency. Onshore infrastructure required for the various propulsion systems were not considered in the analysis. Thus, potential establishment of onshore fuel storage tanks or mooring systems were not considered. While onshore fuel tanks suitable for MGO, biodiesel and HVO are already available, onshore storage tanks for hydrogen and ammonia would probably have to be established should technologies relying on these be realized for the route. Maintenance was not considered.

4.4. Energy use – express boat

Table 6 summarizes the total energy demand in terms of kWh per round-trip for the various propulsion systems. In the analysis, it was assumed that the boat makes one daily round-trip during the ten years of operation.

Table 6 Round-trip energy demand

		Combustion		Electric	
		Fossil/biofuel	Ammonia	Battery	PEMFC
Round-trip energy use	kWh	46 669	53 883	33 758	35 954

Note that these energy estimates consider the difference in weight as well as energy conversion efficiencies among the various propulsion systems.

In the analysis, it was assumed that the combustion engine used for MGO, biodiesel, and HVO was operating at a constant efficiency of 40 %, while it was assumed that the ammonia combustion engine was operating at a lower constant efficiency of 35 %. The lower efficiency was assumed due to the difficulties in completely combusting ammonia inside the combustion chamber (Korean Register, 2020). The uncertainty regarding the ammonia engine efficiency is considered in sub-chapter 7.2.

5. EMISSION FACTORS

This chapter offers an overview of the emission factors used in the analysis. Sub-chapter 5.1 provides an overview of the emission factors associated with production and disposal of various components while sub-chapter 5.2 provides an overview of emission factors associated with the various fuels and energy carriers.

5.1. Propulsion system components

In the current report, emission factors for the internal combustion engine, skid, boilers, auxiliary Li-battery, SOFC, fuels tanks for LNG, ammonia, and liquid hydrogen, and cables were established. Further information about these emission factors can be found in Appendix B – Emission factors for propulsion systems. The emissions factors for the remaining components were established in the preceding report and can be found there (Asplan Viak, 2020).

Table 7 presents the production (cradle-to-gate) and disposal emission factors associated with the various propulsion system components.

Table 7 Summary of production and disposal emission factors for components

Component	Production emission factor (kg CO_2-eq/kg)	Disposal emission factor (kg CO_2-eq/kg)
Combustion engine	5.4	0.7
Electric motor (generator)	7.1	0.7
Skid	3.7	0.7
Boilers	7.1	0.7
Auxiliary Li-ion battery (PSV & chemical tanker)	11.5	0.9
Li-ion battery (express boat)	15.7	0.9
SOFC	67.3	1.4
PEMFC	10.8	0.5
Cryogenic tank (LNG, LBM, and L-NH_3)	6.4	0.7
Carbon fibre composite fuel tanks (C-H_2)	21.0	1.7
Cryogenic tank (L-H_2)	17.1	1.7
Cables	23.8	0.5
Power converters	4.4	0.3

While the cryogenic tanks have a lower emission factor per kg than the composite fuels tanks, the cryogenic tanks are considerably heavier. Thus, per tank, the cryogenic tank has higher production and disposal emissions than the composite fuel tanks.

5.2. Fuels and energy carriers

The total use phase emissions were estimated based on the fuel cycle emission factor and the estimated energy use. The fuel cycle emissions include well-to-tank (WTT) and utilization. For fuels, utilization includes combustion, and for LNG and LBM it also includes methane slip. As such, the fuel cycle emission factors consider the entire supply chain of the fuels and energy carriers at each stage from energy resource extraction, production, distribution, and utilization. This ensures consistent system boundaries whether it is fossil fuels, biofuels, ammonia, electricity, or hydrogen.

This study relies partly on fuel cycle emission factors from the preceding LCA study considering propulsion system alternatives for express boats and can be found in that report (Asplan Viak, 2020). As the preceding study did not consider LS-HFO, LNG, or LBM, the current study establishes the fuel cycle emission factors for these fuels. In addition, updates for ammonia fuels and grey hydrogen has been added. See Appendix C – Fuel cycle emission factorsfor details.

Arguably, expressing fuel cycle emission factors in terms of emissions per engine output (g CO2-eq/kWh) provides a more useful comparison for a diverse range of fuels (Gilbert et al., 2020). However, it is not the purpose of the current study to compare the emission factors of various fuels, but rather to provide a holistic emission profile of various propulsion system alternatives. Therefore, the fuel cycle emissions presented here do not allow for comparison. Furthermore, the energy use estimates incorporate the SFOC of the various engines and scenarios. Thus, it was considered more useful to report the fuel cycle emission factors in terms of emissions per energy content (g CO_2-eq/MJ).

Table 8 provides a summary of the fuel cycle emission factors used for the various fuels in the analysis. For the sake of transparency, the table distinguishes between WTT and utilization. All emissions factors are measured in terms of g CO_2-eq/MJ.

Table 8 Fuel cycle emission factors for considered fuels and energy carriers. Note that the emission factors are not to be used for comparison of fuels and energy carriers as energy conversion efficiency is not considered.

Fuel or energy carrier	WTT	Utilization g CO_2-eq/MJ	Total fuel cycle
MGO	12.0	74.4	86.4
LS-HFO	11.5	75.7	87.2
Biodiesel	19.8	69.8	89.6
HVO (without ILUC)	24.4		24.4
HVO (with ILUC)	41.6		41.6
Green ammonia (Norwegian*)	11.6		11.6
Green ammonia (Nordic)	60.2		60.2
Blue ammonia	78.7		78.7
Grey ammonia	104.3		104.3
LNG in 2-stroke DF diesel-cycle (ME, tanker)	19.4	56.3	75.7
LNG in 4-stroke SI Otto-cycle (AE, tanker; PSV)	19.4	68.9	88.3
LNG in 4-stroke DF Otto-cycle (PSV)	19.4	71.7	91.1
LBM in 2-stroke DF diesel-cycle (ME, tanker)	27.4	1.2	28.6
LBM in 4-stroke SI Otto-cycle (AE, tanker; PSV)	27.4	13.8	41.2
LBM in 4-stroke DF Otto-cycle (PSV)	27.4	16.6	44.0
Electricity (Norwegian*)	5.9		5.9
Electricity (Nordic)	31.1		31.1
Green liquid hydrogen (Norwegian*)	11.3		11.3
Green liquid hydrogen (Nordic)	57.8		57.8
Blue liquid hydrogen	55.7		55.7
Grey liquid hydrogen	132.7		132.7
Green compressed hydrogen (Norwegian*)	10.6		10.6
Green compressed hydrogen (Nordic)	51.0		51.0
Blue compressed hydrogen	35.0		35.0
Grey compressed hydrogen	103.9		103.9

*Because the Norwegian electricity mix is based on 98% renewable energy sources (primarily hydropower), it may be viewed as representative for renewable electricity.

Note that the ammonia production pathways considered in the current report vary somewhat from the preceding report as data availability increased. While the preceding report only considered electricity for the hydrogen production, the current report considers electricity for the entire ammonia production. As such, the current report distinguishes between green (with both Norwegian and Nordic electricity), blue, and grey ammonia. Information about how the WTT emission factors were established is specified in Appendix C – Fuel cycle emission factors.

The fuel cycle emission factors for LNG and LBM vary depending on the methane slip for a given engine. As the report considers methane slip from a 2-stroke DF diesel-cycle engine, a 4-stroke DF Otto-cycle engine, and a 4-stroke SI Otto-cycle engine, three different fuel cycle emission factors were estimated for both LNG and LBM. Details about the fuel cycle emission factor including assumptions regarding methane slip during fuel combustion can be found in Appendix C – Fuel cycle emission factors.

It is also worth pointing out that utilization of biofuels, ammonia, and hydrogen yields no GHG emissions. The combustion of biofuels is offset by the renewable credit given to biofuels as the CO_2 emitted during combustion is considered to equal the CO_2 absorbed during plant growth, assumed to provide a net zero impact. Note that methane slip was included for LBM. Complete combustion of ammonia does not produce GHG emissions, neither does use of ammonia or hydrogen in fuel cells. As a simplification, it was assumed that ammonia was completely combusted. However, one should be aware that incomplete combustion of ammonia is a challenge that potentially leads to emission of the potent GHG nitrous oxide (N_2O). High uncertainty and data unavailability prevented evaluation of potential nitrous oxide emissions.

The fuel cycle emission factors and the estimated energy use was used to estimate the total life cycle GHG emissions over a given time period for each of the vessel types. The operating time periods were set to 10 years for the express boat and the PSV, while for the tanker it was set to 25 years. The energy use for the PSV, tanker vessels, express boat, were presented in section 2.5, 3.5, and 4.4 respectively. Recall that the estimated energy use inherently accounts for the efficiency of the engine and electrochemical devices (battery, fuel cells) and power converters.

6. RESULTS

This chapter presents the cradle-to-gate GHG emissions of the three case studies. Sub-chapter 6.1 presents the results of the PSV (Case 1), 6.2 the results of the chemical tanker (Case 2), and 6.3 briefly considers the result of the express boat (Case 3). Results for the PSV and express boat are estimated based on a 10-year operating period, while the results for the chemical tanker is estimated based on a 25-year operating period.

6.1. Case 1: PSV

The life cycle emissions were estimated based on a 10-year operating period. Figure 15 presents the overall life cycle GHG emissions, while Figure 16 takes a closer look at use phase emissions broken down in terms of operational mode.

6.1.1. Total life cycle emissions

The total GHG emissions from a 10-year time period of operation were estimated for each of the 10 scenarios. Figure 15 reports the GHG emissions divided between production (charcoal), use phase (green), and disposal (yellow). Note that four production pathways were considered for both ammonia and hydrogen, and the result of all of these pathways have been indicated in the figure; use phase emissions based on green (Norwegian) production pathways were denoted by a green colour in the stacked column, while the total life cycle emissions relying on the green (Nordic) production pathways were denoted by a green circle, blue production pathways with a blue circle, and grey production pathways by a grey circle.

Figure 15 Total GHG emissions over a 10-year operating time period for the PSV scenarios.

For all scenarios, the use phase emissions are the major source of life cycle emissions. In contrast, the emissions associated with production and disposal of the propulsion system components are very small. Even though a greater degree of electrification generally results in higher production and disposal emissions, these scenarios have lower total life cycle GHG emissions compared to the fossil fuel alternatives. Another general finding is that fuel and energy carrier alternatives relying on renewables offer emission reduction potential compared to fossil alternatives.

As MGO represents a conventionally fuelled PSV, results from the other scenarios will be compared to Scenario 1. Recall that the MGO fuel use was based on the original powertrain configuration of Viking Energy with a DF 4-stroke engine relying on LNG in Otto cycle and MGO in diesel cycle.

Use of biodiesel (Scenario 2) has slightly higher emissions than MGO (Scenario 1). As the fuel use (in tons) were fairly similar, the difference stems primarily from the assumed fuel cycle emission factors for the two fuels; biodiesel has a higher fuel cycle emission factor than MGO because diesel, the main fuel in biodiesel (95 % v/v), has a higher fuel cycle emission factor than MGO. Diesel has a higher fuel cycle emission factor as it is further refined than MGO. Because the share of FAME is so low (5 % v/v) it is not enough to compensate for the higher emission factor of diesel.

For the use of ammonia in a combustion engine (Scenario 3), the life cycle emissions stem solely from upstream emissions as complete combustion of ammonia does not result in GHG emissions. As seen in the figure, the life cycle emissions depend strongly on the ammonia production pathway. The study considered four different production pathways for ammonia. Green (Norwegian) ammonia yields by far the lowest ammonia emissions of the four considered pathways. Green (Nordic) offers a 28 % GHG emission reduction compared to MGO. Blue ammonia offers somewhat lower GHG emission compared to MGO, but keep in mind that the emission estimate assumed similar energy conversion efficiency for the MGO and ammonia engines, complete ammonia combustion, and the heavier fuel weight of ammonia compared to MGO is not accounted for. As such, blue ammonia may not offer emission reductions compared to MGO. Use of grey ammonia results in an increase of GHG emissions compared to MGO.

Use of LNG (Scenario 4) in a SI Otto engine results in somewhat higher life cycle GHG emissions compared to MGO (Scenario 1). Based on the general perception that LNG is a cleaner fuel than MGO, the higher GHG emissions of the LNG scenario is perhaps a bit surprising. In line with data from SINTEF Ocean, methane slip of 2.7 % was assumed for the 4-stroke SI Otto cycle engine (Lindstad, 2019), which increased the use phase emissions by 18 % compared to if it had not been included. Note that details about the estimation of methane slip can be found in Appendix C – Fuel cycle emission factors.

Use of LBM (Scenario 5) in a SI Otto engine offers lower life cycle emissions compared to MGO (Scenario 1). While the release of carbon during combustion is assumed to equal the stored carbon during the growth phase of the plant, release of methane stemming from incomplete combustion should be considered. The current study assumes a 2.7 % methane slip during operation for LBM (same as LNG). Compared to the MGO-fuelled vessel (Scenario 1), LBM offers an impact reduction of 52 %. Note that there is uncertainty associated with the estimated GHG emissions as WTT emission factors for LBM is affected by a number of factors, such as feedstock, production route, and methane content.

Use of LNG and MGO in a DF engine (Scenario 6) represents Viking Energy from 2003 to 2015 and has about 5.2 % higher life cycle GHG emissions compared to the MGO-fuelled vessel (Scenario 1). Again, the life cycle emission is perhaps a bit higher than expected compared to the general perception that LNG offers GHG emission reduction. A methane slip of 3.3 % was assumed for the DF engine on an Otto cycle. Had methane slip not been considered, the original Viking Energy (Scenario 6) would have offered 11 % lower emissions than a regular MGO-fuelled PSV (Scenario 1).

The battery hybridized propulsion system (Scenario 7) represents Viking Energy from 2016 to 2022 and offers 15 % lower emissions than the conventional MGO propulsion system (Scenario 1). Furthermore, the hybridized propulsion system (Scenario 7) has 19 % lower life cycle emissions compared to the original propulsion system (Scenario 6). The additional emissions associated with production and disposal of the battery and power converters are dwarfed by the emission saving during the use phase.

Scenario 8 considers an ammonia SOFC. The emission reduction will depend on the production pathway for ammonia. Compared to the conventional MGO-fuelled propulsion system (Scenario 1), ammonia SOFC (Scenario 8) may offer 37 – 90 % emission reductions. Compared to the current hybridized propulsion system (Scenario 7), the ammonia SOFC (Scenario 8) may offer 26 – 89 % emission reductions with the evaluated ammonia production pathways.

As an alternative to the ammonia SOFC (Scenario 8), hydrogen PEMFCs may be used either with liquid hydrogen (Scenario 9) or compressed gaseous hydrogen (Scenario 10). As for ammonia, the hydrogen production pathway plays an important role in the life cycle emissions for both liquid hydrogen (Scenario 9) and compressed hydrogen (Scenario 10). Notice that there are some differences in the emission profile between Scenario 9 and 10 that are caused by the hydrogen WTT emission factors. For liquid blue hydrogen production and green (Nordic) electrolysis, the emission factors are 55.7 and 57.8 g CO_2-eq/MJ, respectively. The emission factors for compressed hydrogen from blue and green (Nordic) are 35.0 and 51.0 g CO_2-eq/MJ, respectively. As such, the emission factors for liquid blue hydrogen and green (Nordic) are relatively similar, while this is not the case for compressed hydrogen. The difference arises primarily because CCS is applied to the production of the gaseous hydrogen, before transformation to compressed or liquid hydrogen. Note that the CCS process removes about 85% of the carbon content, and that the liquification process is significantly more energy demanding than the compression process. As a result, the liquid blue hydrogen is estimated to have a similar emission factor as liquid green (Nordic) hydrogen. In addition, there is an interesting difference in ranking between green (Nordic) and blue hydrogen and ammonia. While green (Nordic) ammonia performs better than blue ammonia, blue hydrogen performs better than green (Nordic) hydrogen. The main reason why these two energy carriers do not follow the same pattern is because the CCS process removes about 85 % of the GHG emissions in hydrogen production (Prussi *et al.*, 2020), while implementing CCS to ammonia production removes only about a 25% of the GHG emissions (Al-Breiki and Bicer, 2021).

The difference in production emissions due to propulsion systems between Scenario 8, 9, and 10 is also worth commenting on. While the production of the SOFC results in higher emissions than the PEMFCs, the ammonia fuel tanks have lower emissions than the hydrogen fuel tanks. This trade-off in emission profiles results in lower production emissions for the ammonia SOFC (Scenario 8) and liquid hydrogen PEMFC (Scenario 9) compared to the compressed hydrogen PEMFC propulsion system (Scenario 10). The higher production emission of Scenario 10 is primarily due to compressed hydrogen taking up a higher volume and requiring more fuel tanks. Furthermore, the compressed hydrogen is assumed stored in fuel tanks made of carbon fibre composite, which have a high emission factor, all of this resulting in high fuel tank emissions.

6.1.2. Use phase emissions per operational mode

By taking a closer look at the use phase emissions per operational mode of the various scenarios, further insights as to how the differences arise are provided. Figure 16 reports the use phase emissions per operational mode for all scenarios. In this figure, the only the lowest (Norwegian green) and highest (grey) results are shown for the ammonia and hydrogen production pathways.

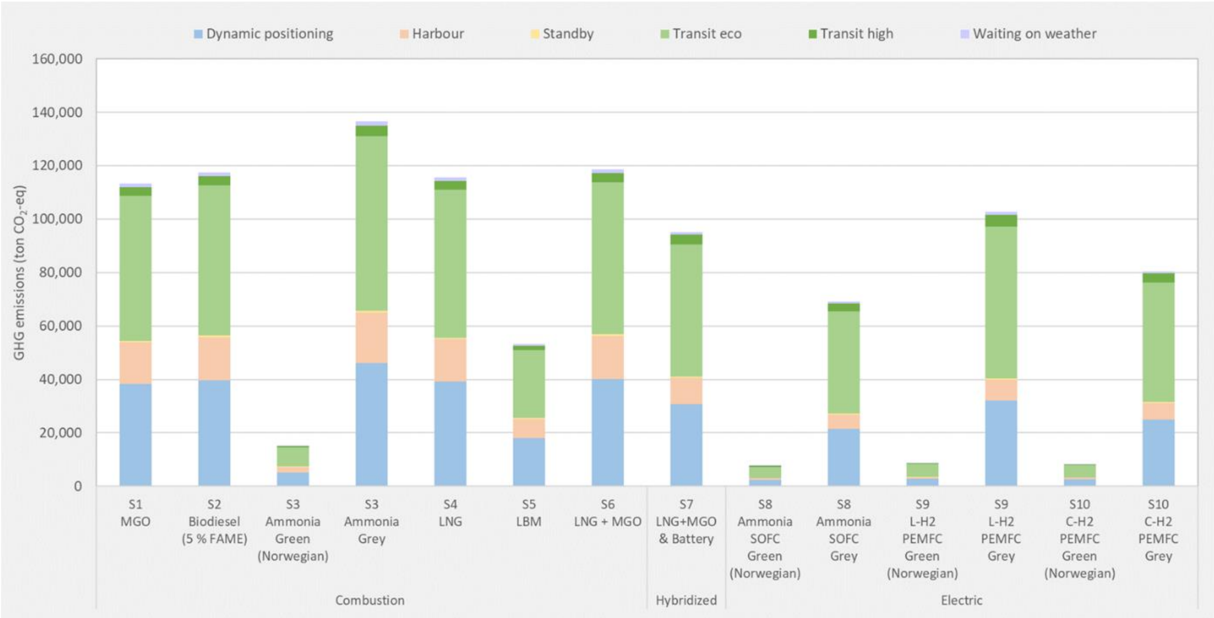


Figure 16 Use phase GHG emissions over a 10-year operating time period for the PSV scenarios

Across the different scenarios, dynamic positioning and transit in economical speed were by far the two most significant sources of GHG emissions. For the combustion-based scenarios, fuel use while in harbour was also a considerable source of emissions.

When Viking Energy was hybridized (Scenario 7), the fuel use was reduced markedly during the three most emission producing operational modes. Of the three modes, the relative emission reduction was most notable while operating in harbour with a reduction of nearly 40 %. The relative emission reductions while in dynamic positioning and in transit in economical speed were 24 % and 13 %, respectively.

When the ammonia SOFC is installed (Scenario 8) further emissions may be obtained, but the reduction potential strongly depends on the ammonia production pathway. The emission reduction will be particularly substantial if green (Norwegian) ammonia is used.

6.2. Case 2: Chemical tanker

The life cycle emissions of the chemical tanker were estimated based on a 25-year operating time period. Figure 17 presents the overall life cycle GHG emissions, while Figure 18 takes a closer look at use phase emissions broken down in terms of operational mode.

6.2.1. Total life cycle emissions

The total GHG emissions were estimated for each of the nine scenarios over a 25-year operation time period. Figure 17 reports the GHG emissions divided between production (charcoal), use phase (green), and disposal (yellow). Use phase emissions based on green (Norwegian) production pathways were denoted by a green colour in the stacked column, while the total life cycle emissions relying on the green (Nordic) production pathways were denoted by a green circle, blue production pathways with a blue circle, and grey production pathways by a grey circle.

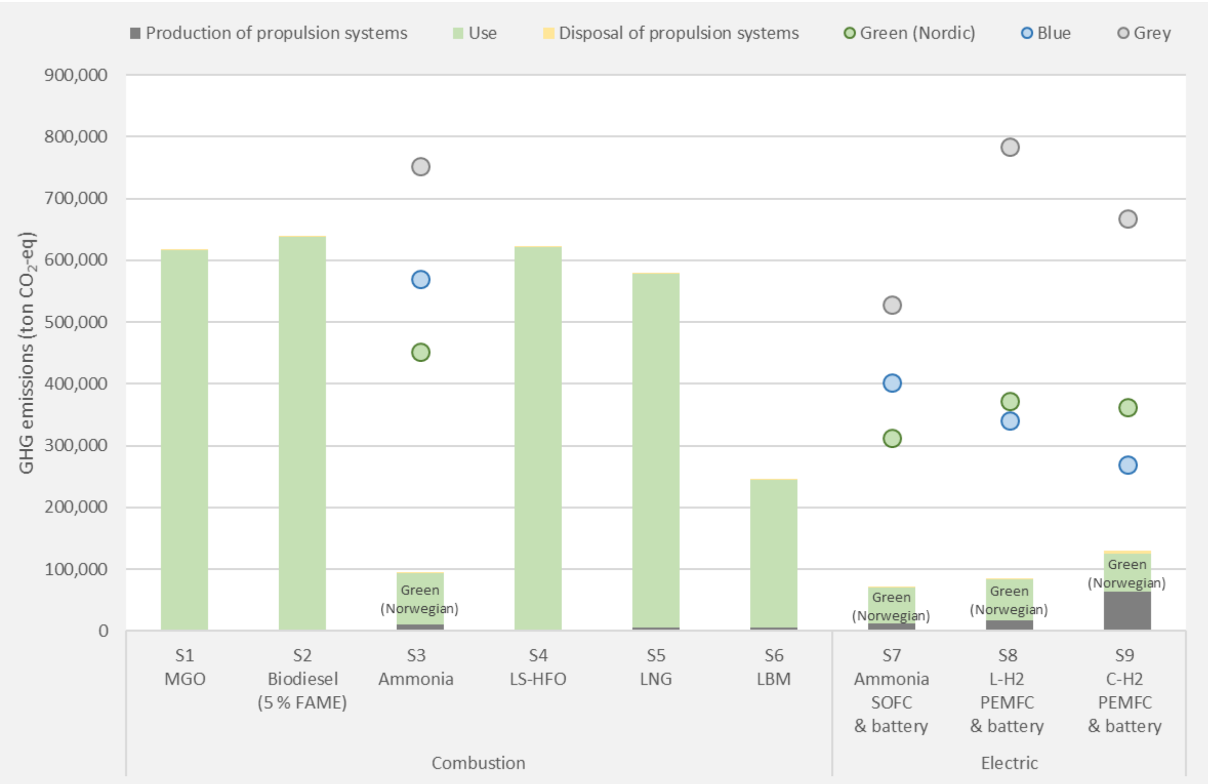


Figure 17: Total GHG emissions over a 25-year operating time period for the chemical tanker scenarios.

Results for the chemical tanker show many of the same general trends as for the express boat and the PSV, but there are some differences. Life cycle emissions for MGO, biodiesel, and LS-HFO are similar, while LNG has slightly lower life cycle emissions compared to these. This contrasts with the PSV results where the LNG fuel had higher emissions. For the tanker, LNG can offer emission reductions as the methane slips are particularly lower for the 2-stroke engine, which is responsible for 60 % of the tanker's fuel use. Of the combustion alternatives, green (Norwegian) ammonia offers the lowest life cycle emission. The LBM alternative also provides a significant emission reduction compared to the MGO scenario. For the chemical tanker, electric propulsion systems may offer emission reductions there are higher constraints on the production pathways of the energy carriers for the tanker compared to the PSV. The reason for this, is that the auxiliary battery significantly reduced fuel use (e.g., through peak shaving and avoiding engines running at low loads) when the PSV was hybridized, while for the tanker the auxiliary battery is only used to facilitate the use of fuel cells.

The life cycle emissions associated with combustion of liquid ammonia varies depending on the ammonia production pathway. When more carbon intensive production pathways are employed, the use of the so-called "zero-emission" ammonia fuel yields higher life cycle GHG emissions than conventional fossil fuels. Recall that the estimated emissions here do not include any potential nitrous oxide emissions associated with incomplete combustion of ammonia.

The higher propulsion system production emissions of the liquid ammonia, LNG, and LBM scenarios compared to the other combustion alternatives arise from the fuel tanks. While the fuel tanks for MGO, biodiesel, and LS-HFO are assumed to be an integral part of the vessel, the tanks for liquid ammonia, LNG, and LBM are not. The difference in fuel tank emissions between liquid ammonia and LNG and LBM stems from the estimated higher volume of ammonia compared to LNG and LBM, resulting in demand for more fuel tanks.

The difference in fuel tank emissions between the two PEMFC alternatives was observable for both the PSV and the chemical tanker. From a GHG emission perspective, these preliminary results suggest that when using green (Norwegian) hydrogen, there is an advantage using liquid hydrogen rather than compressed hydrogen. When blue or grey hydrogen are used, compressed offer lower life cycle emissions than liquid.

6.2.2. Use phase emissions per operational mode

For additional insights, Figure 18 presents the use phase emissions divided into the two operation modes for the ship: cruising and harbour. Note that Figure 18 only presents the results for the lowest (Norwegian green) and highest (grey) ammonia and hydrogen production pathways.

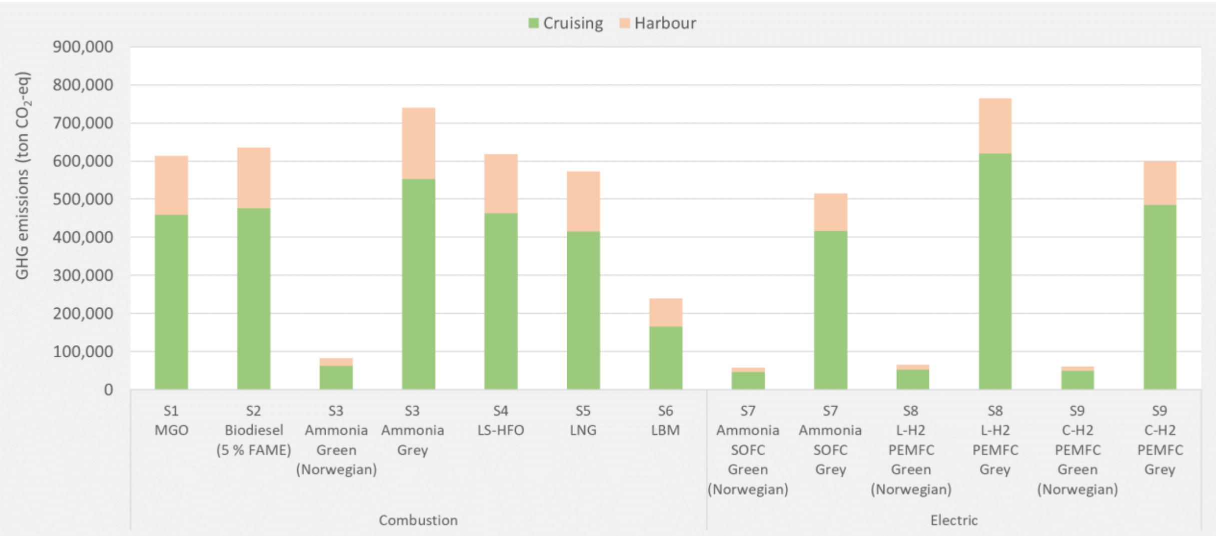


Figure 18: Use phase GHG emissions over a 25-year operating time period for the chemical tanker scenarios

Expectedly, the main operational mode, cruising, results in higher use phase emissions than when in harbour. What is perhaps more interesting, is how the share of emissions change among the different propulsion systems. The share of emissions stemming from cruising is generally somewhat lower for the combustion-based fuels (Scenarios 1 – 6) than for the electric alternatives relying on fossil fuels (Scenarios 7 – 9). The difference in use phase distribution among the two operational modes is further discussed below.

For Scenarios 1 – 4 cruising contributed to 75 % of the use phase emissions, while for Scenario 5 and 6 cruising contributed to 74 % and 72 %, respectively. The difference in emission contribution among Scenarios 1 – 4 and 5 – 6 stems from LNG and LBM having emissions due to methane slip. Because the estimated methane slip is much lower for the 2-stroke ME (used only during cruising) than for the 4-stroke AE (used during both cruising and harbour), the relative share of emissions stemming from harbour are higher for Scenarios 5 – 6 than for Scenarios 1 – 4.

For Scenarios 7 – 9 cruising contributed to 81 % of the use phase emissions. This distribution of use phase emissions reflects the energy requirements between the two operational modes as the fuel cells operate with one fixed energy efficiency.

6.3. Case 3: Express boat – summary and update

As Case 3 was considered in a preceding report (Asplan Viak, 2020), only a brief summary of the main findings are reported here. Note that the ammonia production pathways vary from the first study as data availability increased. In addition, grey production pathways were added for both ammonia and hydrogen.

Figure 19 presents the life cycle GHG emissions for the examined alternatives. In the figure, GHG life cycle emissions divided between production (charcoal), use phase (green), and disposal (yellow). Note that four production pathways were considered for ammonia and hydrogen and two electricity mixes were considered for battery charging. The result of all of these pathways have been indicated on the figure; use phase emissions based on green (Norwegian) production pathways were denoted by a green colour in the stacked column, while the total life cycle emissions relying on the green (Nordic) production pathways were denoted by a green circle, blue production pathways with a blue circle, and grey production pathways by a grey circle.

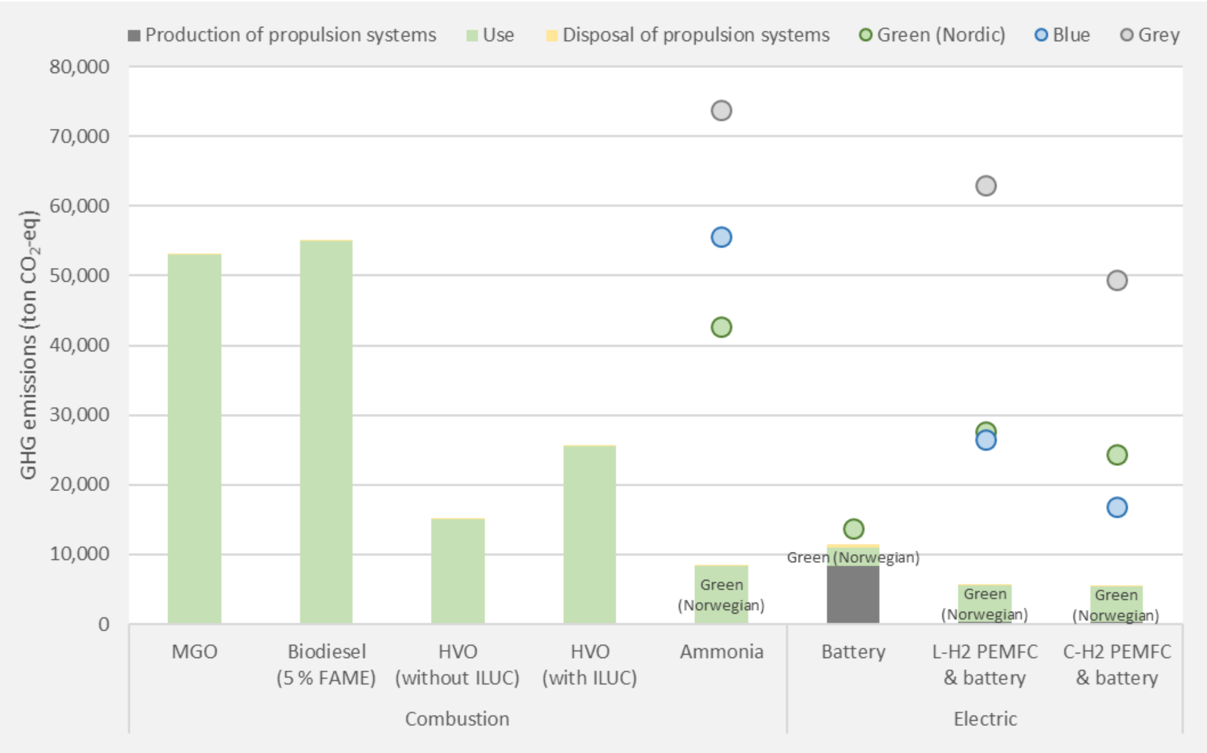


Figure 19 Total GHG emissions over a 10-year operating time period for the express boat scenarios.

While total life cycle GHG emissions vary significantly, some general trends are found. Generally, the electric propulsion systems have lower life cycle emissions compared to the combustion-based propulsion systems. Note that the production of all propulsion systems is considered, but aside from the battery propulsion system, these emissions are so low that they are not visible in the figure. The same holds for emissions associated with the disposal of the propulsion systems. As such, the use phase is the most significant source of emissions for all propulsion systems but the battery-based propulsion system where higher production emissions arise due to the battery. Note that the auxiliary battery required for the fuel cell alternatives is much smaller than the battery used in the fully battery powered propulsion system.

The alternatives considering combustion of ammonia in an internal combustion engine and hydrogen in PEMFCs depend very strongly on the production pathways. Use of green (Norwegian) hydrogen and ammonia results in very low GHG emissions. With 98 % of the generated electricity stemming from renewable sources (primarily hydropower), the Norwegian production mix is representative for renewable electricity. Using green (Nordic) or blue hydrogen in PEMFCs also yield emission reductions.

As such, the attractiveness of ammonia and hydrogen in terms of GHG emissions is very dependent on the production pathways.

7. DISCUSSION AND CONCLUSION

The goal of the study was to estimate and compare cradle-to-gate GHG emissions of various propulsion systems that may be used for different types of vessels. The reported results have provided useful insights to the GHG emissions of alternative propulsion systems for express boats, PSVs, and chemical tankers. This chapter discusses the main findings and concludes the report. Sub-chapter 7.1 considers the importance of the holistic systems perspective that the LCA approach provides. Sub-chapters 7.2 and 7.3 discuss some of the main uncertainties and limitations of the analysis, respectively. Finally, sub-chapter 0 concludes the study.

7.1. The life cycle perspective

The life cycle perspective taken in this report is crucial for obtaining a complete emissions picture of the various propulsion system alternatives. While much focus in the past has been on the combustion of fuels, the systems perspective offered by LCA is gaining traction.

Figure 20 illustrates the importance of the complete life cycle perspective for marine propulsion systems as we compare the total cradle-to-grave emissions (turquoise) with combustion emissions (green). Note that only the green (Norwegian) and grey production pathways for hydrogen and ammonia are shown for Scenarios 3 and 7 – 9.

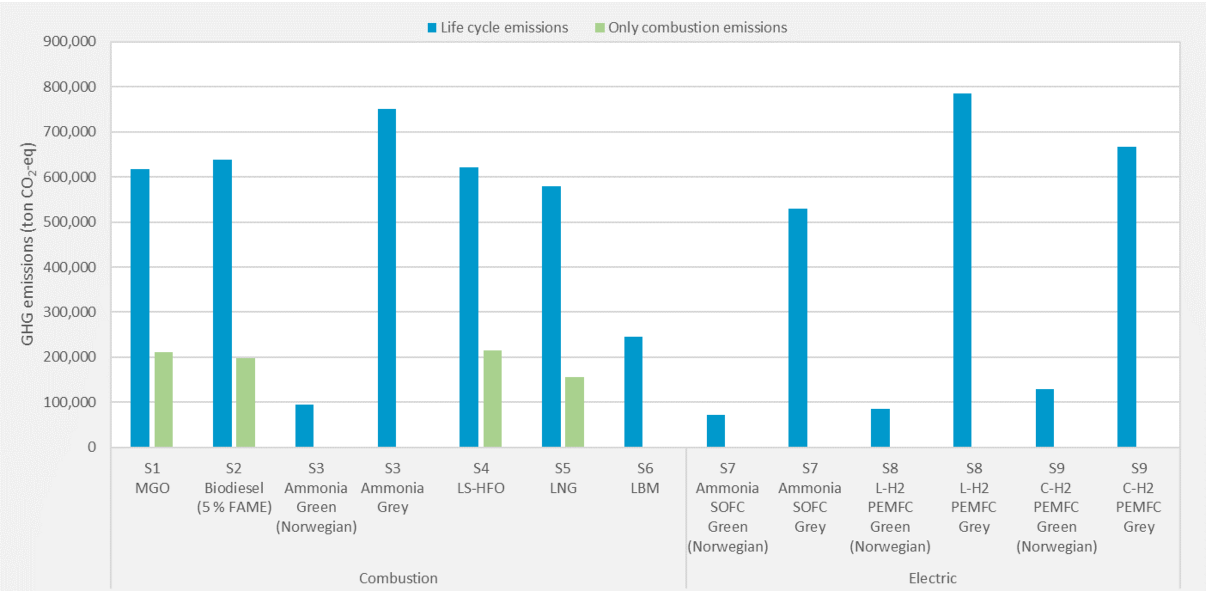


Figure 20 Comparison between emissions from a life cycle perspective and emissions solely from fuel combustion for the chemical tanker.

When only considering the combustion of fuels, some of the evaluated scenarios appear to be so-called "zero-emission" alternatives. However, for many of the new and emerging fuels and energy carriers considered in this report, a large share of the life cycle emissions does not occur in a combustion process. Thus, if our objective is truly to identify emission reduction potentials, we must consider the alternatives from a life cycle perspective.

7.2. Uncertainty

It is important to highlight that the evaluated alternatives are at different technology readiness levels, which affects the data availability and certainty of the results. As such, the results should be viewed as indications of expected life cycle GHG emissions of the various propulsion systems rather than a final answer. Data uncertainty is higher for emerging technologies. At the same time, one should also be aware that mature technologies are less likely to undergo any significant changes or improvements while emerging technologies still have the potential to develop and improve as the technology matures. As the emerging technologies progress, emission profiles will likely change, which may in turn necessitate an update of the analysis. An updated LCA can provide a more representative emission profile as the technology develops, but also evaluate whether the technological development is going in a desirable direction.

The express boat report provides a thorough evaluation of the uncertainties pertaining to Case 3 (Asplan Viak, 2020). Some of the uncertainties that were considered for Case 3 are transferrable to Cases 1 and 2. Generally, uncertainties associated with the use phase are more important than uncertainties associated with production and disposal because the emissions of the use phase are comparatively higher than those stemming from production and disposal. Even so, there are some exceptions to this general finding. For Case 3 (express boat), the fully battery powered alternative had high production emissions stemming from the battery. Similarly, for Case 1 (PSV) and Case 2 (chemical tanker), the production of the carbon fibre composite fuel tanks required for the compressed hydrogen caused high production emissions. The high production emissions associated with the battery are deemed reliable as the emission estimations were to a large extent based on primary data. In contrast, the reported emissions for the compressed hydrogen fuel tanks for Cases 1 and 2 are more uncertain as they are based on fuel volume estimates and the fuel tank size for Case 3 (express boat). Higher fuel tank capacities would yield lower emissions. As such, the estimated emissions associated with the carbon fibre fuel tank production for Cases 1 and 2 are highly uncertain. Even so, the high GHG emissions due to the production of the carbon fibre hydrogen tank highlight a potential issue for the compressed hydrogen scenarios from an emissions perspective. Note that there are also uncertainties associated with the other fuel tanks, but as these result in much lower emissions they are considered to be a lower source of uncertainty.

Uncertainties in production emission also arise due to the usable lifetime of the battery and fuel cells. According to battery manufacturers Corvus Energy and ZEM Energy, their models and experience call for no battery replacement during a 10-year period of operation. Whether the fuel cells will require replacement remains somewhat uncertain, but the SOFC developer indicated usable lifetimes in terms of hours of operation. To evaluate the uncertainty regarding usable lifetime, we plot the life cycle emissions as a function of SOFC stack replacements. Figure 21 depicts the effect of replacing SOFC stacks on total life cycle GHG emissions for the PSV. The circles represent the assumed number of SOFC stack replacements in the analysis.

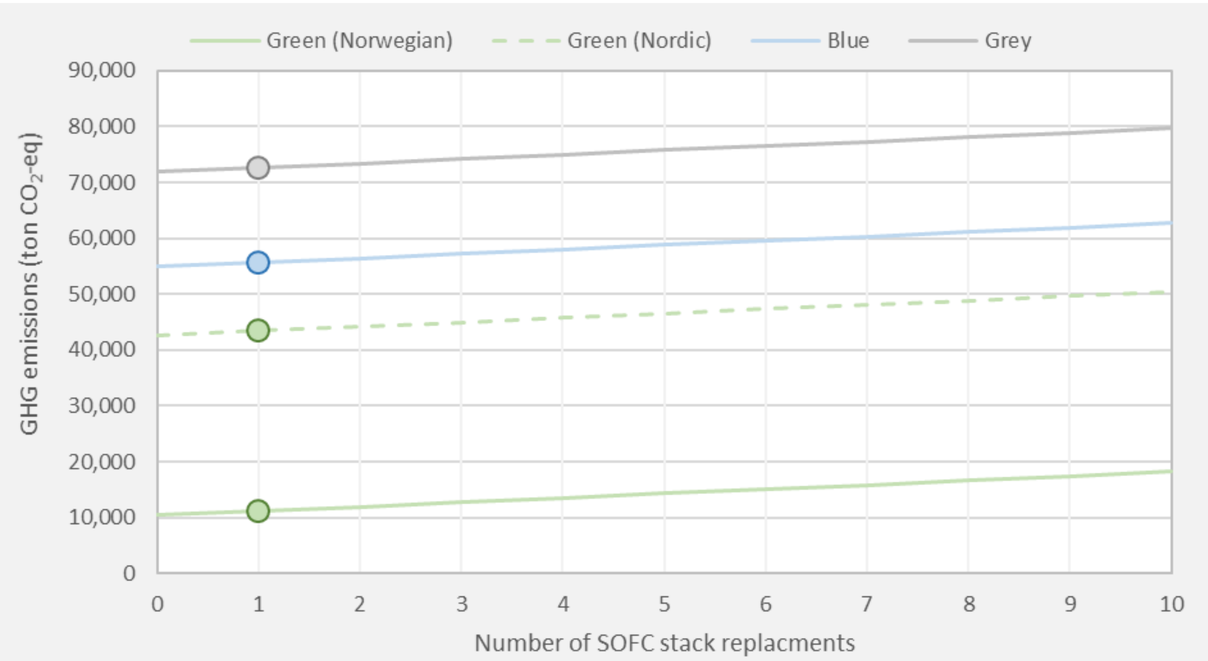


Figure 21 Life cycle GHG emission as a function of stack replacements for the ammonia SOFC PSV propulsion system.

As illustrated by the figure, the relative increase in emission is higher for the less emission emitting ammonia production pathways and lower for the more emission emitting ammonia production pathways. The analysis assumed a lifetime of 60 000 hours for the fuel cells, which the fuel cell developer considers representative for a mature SOFC. If the analysis had been based on a lifetime of 20 000 hours, which is more realistic in the short term, four replacements would have been required. While four replacements would increase the life cycle emissions, it does not affect the main findings sufficiently to change the conclusions of the study. While not considered separately, similar results can be found with respect to replacing the PEFMC stacks.

Regarding uncertainties associated with the use phase, the energy conversion efficiency is an important uncertainty aspect that was considered for the express boat (Case 3). Figure 22 presents the uncertainty analyses for in terms of GHG emissions as a function of energy conversion efficiency for the ammonia combustion engine and the PEMFC. The circles represent the assumed efficiency in the baseline for the express boat propulsion systems.

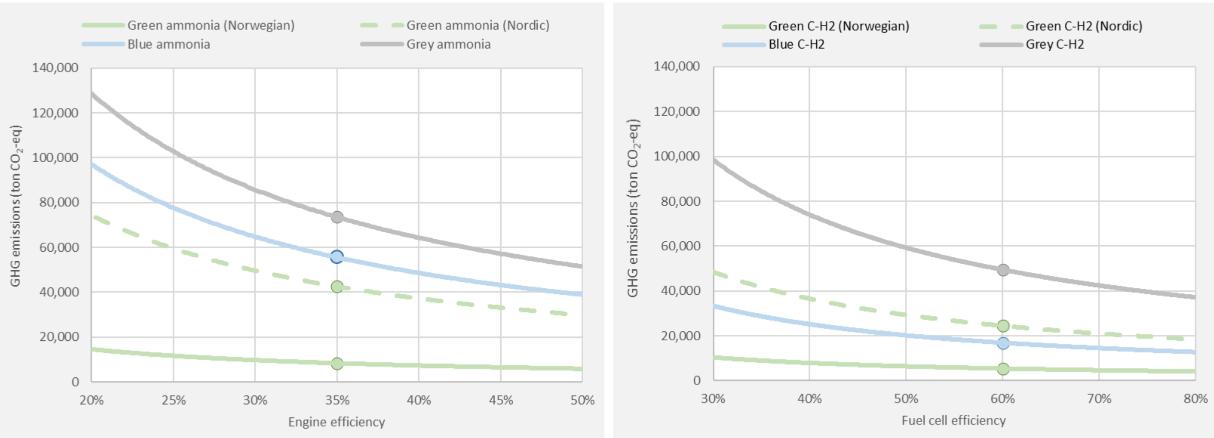


Figure 22 Uncertainty analysis considering emissions as a function of energy efficiency of an ammonia combustion engine (left) and PEMFC using compressed hydrogen(left).

The uncertainty analysis illustrated that both the efficiency and the fuel cycle emission factor strongly affect the life cycle emissions. As efficiency decreases, the slope of the curve increases, which results in higher emissions. Fuel and energy carriers with lower fuel cycle emission factor have a flatter curve compared to energy carriers with a higher fuel cycle emission factor. An interesting insight from this uncertainty analysis is that the uncertainty in terms of estimated emissions is lower with high energy conversion efficiencies and renewables, and higher with low energy efficiency and fossil energy sources.

Related to this finding is the results of the ammonia combustion engine and SOFC, as their energy efficiency are highly uncertain due to the low technology readiness level. In the study, a fuel cell efficiency of 70 % was assumed based on expected achievements for the ammonia SOFC as well as current SOFCs relying on other energy carriers. The ammonia combustion engine was assumed to have an energy efficiency of 35 % compared to 40 % for the conventional combustion engine for the express boat (Case 3) and equal efficiency as the combustion engines for the PSV (Case 1) and chemical tanker (Case 2). However, the ammonia combustion engine and SOFC may not achieve such high efficiencies. If green (Norwegian) ammonia is used, lower efficiencies will not affect the emission estimate as much as if green (Nordic), blue, or grey ammonia is used. Regardless, it is worth pointing out that the reported emissions for the ammonia scenarios are likely to be underestimated. As more reliable data regarding the energy conversion efficiency of these technologies become available, the analysis should be updated to provide a more representative emission profile of the ammonia propulsion systems.

Analysis update may also become advisable as the ammonia and LNG/LBM combustion process develops and data availability increase. While the complete combustion of ammonia causes no GHG emissions, incomplete combustion can result in the formation and emission of the potent climate gas nitrous oxide (Kobayashi *et al.*, 2019; Korean Register, 2020). As the ammonia combustion technology struggles with incomplete combustion, the GHG estimate almost certainly underestimates the life cycle emissions of the ammonia combustion scenarios. During the combustion of LNG and LBM, methane slip may occur. Methane slips stemming from operation in the 2-stroke and 4-stroke engines were estimated based secondary data and assumed to be static percentage shares irrespective of changes in SFOC and engine efficiencies. The static percentage share approach is likely more representative for the considered main engine in the chemical tanker propulsion system compared to the engine in the PSV propulsion system. It is worth noting that engine manufacturers are working on reducing methane slip and that future LNG engines may suffer less from methane slip.

While marine diesel oil (MDO) and regular heavy fuel oil (HFO) were not considered specifically in the study, these fuels have similar fuel cycle emission factors and consequently life cycle GHG emissions as MGO and LS-HFO. As such, the current study provides an indication of life cycle GHG emissions of propulsion systems relying on these fuels

There is also uncertainty associated with the emission factors of the biofuels, ammonia, and hydrogen. For all of these, various production pathways are available. The emission factor for ammonia and hydrogen is particularly sensitive to the technology readiness of the production pathways. For biofuels added uncertainty arise due to availability of various feedstocks and potential indirect land use change emissions. These aspects may result in uncertain and variable emission factors.

7.3. Limitations

It is important to point out that while several technical aspects were considered in the analysis, the LCA study does not consider the technical feasibility. Further, the study does not consider any applicable regulatory compliance requirements.

As the LCA study does not consider fuel availability, some comments are provided here. Fuel availability is generally not a concern for conventional fossil fuels. For biofuels, such as HVO and LBM, there may be issues in availability due to lower production levels. Availability of LNG may be limited as most harbours do not have LNG storage tanks currently. Availability of ammonia is generally not perceived as an issue as world production is high. While infrastructure is currently not available for ammonia, it is much less problematic to establish than it is for hydrogen. For propulsion systems relying on ammonia or hydrogen, supply should be based on green or blue pathways to obtain low GHG emissions; for combustion of ammonia it is crucial to secure low carbon production pathways, while for the use of liquid ammonia and hydrogen in fuel cells it not as necessary but preferable; the higher energy conversion efficiency of the fuel cells compared to the combustion engine places less constrain on the production pathway. While hydrogen is an attractive alternative in terms of GHG emissions, storage of hydrogen is an important challenge that must be overcome to make hydrogen a suitable alternative for the marine sector.

There are important differences in energy density among different propulsion systems. While these differences are generally well-documented, it can be challenging to incorporate and quantify these for a specific application. Even so, Case 3 concerning the fictitious express boat was able to incorporate the differences in gravimetric energy density (MJ/kg) quantitatively and volumetric energy density (MJ/l) qualitatively. For Cases 1 and 2, it was assumed in agreement with NCE Maritime CleanTech that fuel tanks for ammonia and hydrogen would be placed on deck without taking up any storage space. This is perhaps a simplifying assumption that may not reflect reality. Case 1 is based on an existing PSV, where some of the scenarios (6 and 7) relied on recorded data. But even so, scenarios considering a single fuel (Scenarios 1 – 5) or energy carriers (Scenarios 8 – 10) were entirely based on energy conversion calculations without considering how weight may affect energy demand during operation. Because of the lack of data, Case 2 does not incorporate how differences in weight may affect operational energy demand. To make a qualitative evaluation of how differences in gravimetric energy density affect the estimated GHG emissions, we consider the differences in fuel and hardware weight of the various scenarios. Figure 23 reports the differences in weight (left axis) as well as the percentage share of total estimated total DWT (right axis) for the chemical tankers. Blue denotes fuel weight and grey hardware weight. The grey-blue background denotes the combined share of fuel and hardware weight to the estimated total DWT.

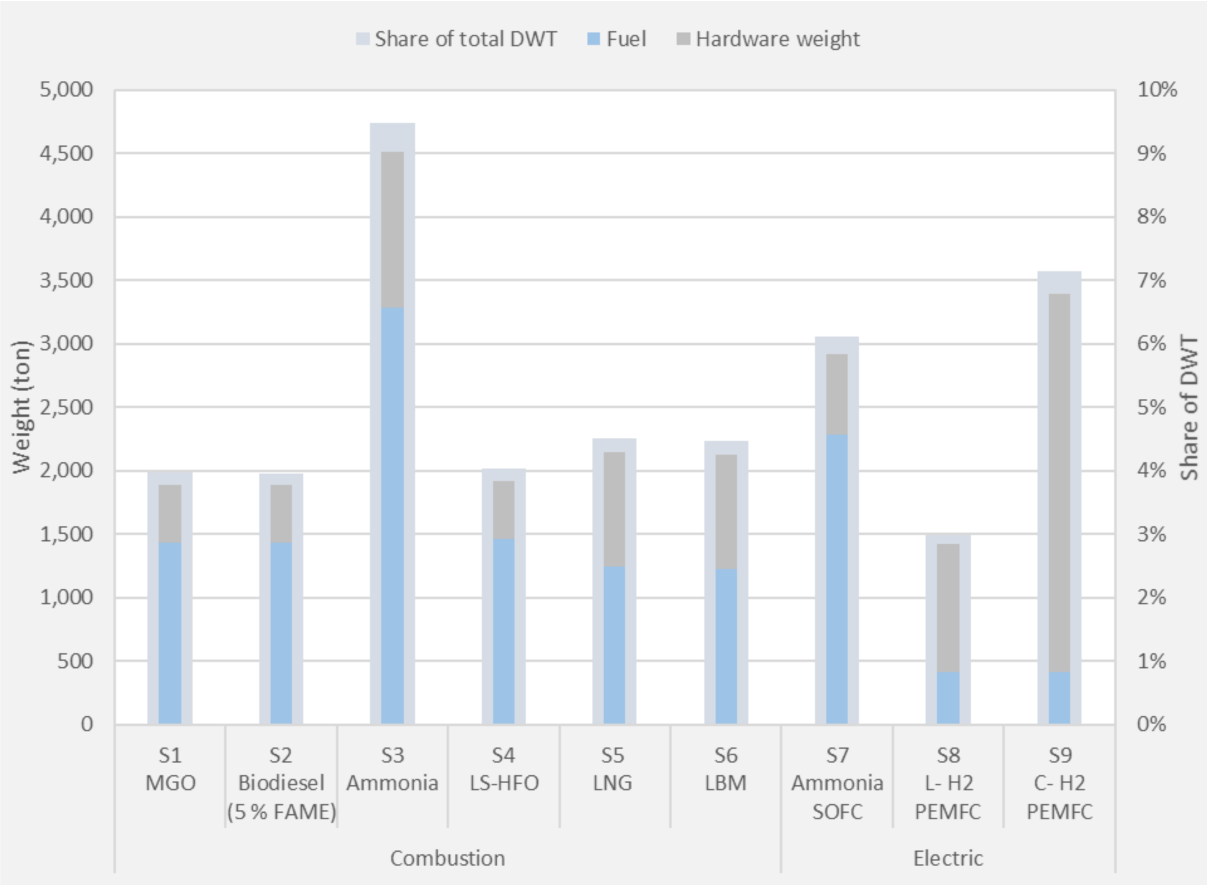


Figure 23 Differences in fuel and hardware weight (left axis), and percentage share of weight for the estimated total DWT of the chemical tanker (right axis).

Significant differences in weight can be observed among the different scenarios. Results deviating from Scenarios 1, 2, and 4 are likely to either underestimate or overestimate the emissions somewhat as the difference in gravimetric energy density is not considered in the analysis. While lower weights are likely to result in an overestimation of emissions, higher weights are likely to result in an underestimation. It is important to emphasize that the under- or overestimations of GHG emissions discussed here are only with respect to gravimetric energy and not in general.

Scenarios 1, 2, and 4 are very similar in terms of weight. These propulsion system alternatives are likely to be very similar in terms of weight compared to the conventional propulsion systems relying on LS-HFO and MGO. In contrast, the GHG emissions of the ammonia combustion propulsion system (Scenario 3) are likely underestimated as the fuels use as the wights of both the fuel and hardware are considerably higher compared to conventional propulsion systems.

The GHG emissions of Scenarios 5 and 6 also likely to be somewhat higher than the estimate due to the additional weight of these propulsion systems. What is interesting to observe here, is that the fuel is lighter than the conventional combustion fuels but that the hardware is heavier. This is due to the LNG/LBM fuel tank; recall that the fuel tanks for Scenarios 1, 2, and 4 are integrated into the vessel design and in this way, these tanks do not have any weight ascribed to them.

For the ammonia fuel cell propulsion system (Scenario 7), the energy demand and consequently GHG emissions are likely to be somewhat underestimated due to the higher weight, particularly associated with the fuel weight.

The hydrogen propulsion systems (Scenarios 8 and 9) differs significantly in terms of weight compared to all the other scenarios because hydrogen is very light, and that the hardware is rather heavy. The hardware is particularly heavy for the compressed hydrogen propulsion system (Scenario 9) due to the fuel tanks. Note that the weight estimate of the compressed hydrogen tanks is deemed highly uncertain as the estimated relies on fuel tanks intended for an express boat. While the liquid hydrogen scenario is likely to slightly overestimate the GHG emissions, the compressed hydrogen scenario is likely to underestimate the GHG emissions.

While the study attempted to consider and quantify all relevant aspects, certain aspects were not possible to cover due to data and time restrictions. Onshore infrastructure required for the various propulsion systems were not considered in the analysis. Infrastructure was omitted due to the lack of data availability and uncertainty as well as time constraints. Admittedly, differences arising from establishing fuel storage tanks, battery charger, or mooring systems were not captured in the analysis. Similarly, although the various propulsion systems that were considered in the analysis will have different maintenance requirements, maintenance of the propulsion systems was omitted in the analysis. Maintenance emissions are likely to be negligibly low and data collection may be impracticably demanding (Jeong *et al.*, 2018).

The findings reported in this study may not be used to draw conclusions regarding cases and alternatives not evaluated specifically in this report. Across the different case studies, we find that some alternatives may be suitable for one application but not so attractive for another. For instance, LNG may offer GHG emission reduction potential for application in the chemical tanker but not in the PSV. Thus, transferability of LCA results from one propulsion system application to another may be limited.

The attributional LCA carried out in this report focuses solely on GHG emission that may be ascribed to the propulsion systems and as such, the analysis does not capture all environmental aspects that may possibly result as a consequence of its application. This somewhat narrow focus has two main implications. First, as the focus is solely on GHG emissions the analysis only considers one of many environmental impacts. Thus, the analysis does not capture any environmental trade-offs that may exist among the different technologies. Note that environmental trade-offs are commonly observed when comparing various products or activities from a broader environmental perspective. Second, the attributional LCA carried out in this report does not capture any indirect effects that may arise when changing from a conventional to a new propulsion system. While consequential LCAs attempt to assess effects of such changes, the causal connections are extraordinarily complex and notably includes direct physical causation, market mediated effects, influence on capital investments and stock dynamics, and socially constructed causation and policy context (Majeau-Bettez *et al.*, 2017). Because no model can hope to fully account for all these causal connections and no standardized method for carrying out consequential LCA exist, indirect effects arising from a change in propulsion systems were not assessed in the study.

7.4. Conclusion

A range of different fuels and propulsion system configurations were evaluated and compared in the three case studies. Across the different case studies, we find that the life cycle perspective offered by the LCA method is crucial to provide a holistic emission profile of the various propulsion system alternatives. Considering solely the emissions associated with fuels excludes important parts of the propulsion system's emission profile, particularly for propulsion systems relying on new and emerging fuels, energy carriers, and technologies, such as ammonia, batteries, and fuel cells. As such, the life cycle perspective is required for making informed decisions.

Certain propulsion systems may offer GHG emission benefits for one application and operational profile, but disadvantages in another. An example of this is the use of LNG as a fuel; compared to MGO, LNG used in the chemical tanker offered somewhat reduced GHG emissions while in the PSV it yielded increased GHG emissions. The results from the three case studies suggest that liquid hydrogen offers GHG emission advantages for PSVs and chemical tankers, while compressed hydrogen is primarily advantageous for the express boat. Thus, when consolidating the findings from the three case studies we find that currently, there is not *one* ideal propulsion system alternative in terms of GHG emissions. Rather, to optimize the GHG emission reduction potential one must carefully consider the vessel type, application area, and operational profile of the vessel when deciding on propulsion system solutions.

A general finding from the three case studies is that electrification of marine propulsion systems offers promising GHG emission reduction potentials. Even though there is a shift in emissions from the use phase to the production phase for the partial or full electrification of propulsion systems, electrification of propulsion systems tends to reduce the total life cycle GHG emissions. However, it is important to emphasize that the emission reduction potential depends on the upstream emissions associated with the production of the various energy carriers. As such, the benefits of electrification may not be harvested under all conditions. Similarly, use of so-called "zero-emission" fuels such ammonia also requires careful consideration of whether low-emission options are available or not. If ammonia is to be considered as a low GHG emission transportation fuel, its production must stem from low-emission production pathways relying on a large share of renewables (green) or through production technologies employing CCS (blue). Thus, decision makers should carefully consider availability of low-emission fuels and energy carriers in the location of the intended vessel operation.

The LCA study has considered a range of propulsion system alternatives at different technology readiness levels. The certainty of reported emissions is likely higher for the propulsion systems – including energy conversion device and fuel or energy carrier – with a higher technology readiness level compared to those a with a lower. At the same time, the less mature alternatives are more likely to develop and improve. As key components of the propulsion systems develop, updated analyses are advisable. Updated analyses may increase the certainty of the results but may also ensure that the technology is developing in a desirable direction. As the data availability and technology improves, more detailed and comprehensive LCA studies can identify and aid effective emission reduction strategies for individual propulsion system components.

The aim of the study was to estimate and compare the life GHG emissions of various propulsion system alternatives for three different vessel types. While there are important uncertainties and limitations associated with the analysis, an overall picture of the GHG emissions is provided for the three case studies. Furthermore, the preliminary results provide useful insights and highlight important aspects pertaining to the GHG emissions of a range of propulsion system alternatives. The LCA study demonstrates that significant GHG emission reductions may be obtained for marine propulsion systems, and ultimately the transport sector, but its realization and optimization require informed and deliberate decision making.

BIBLIOGRAPHY

Advanced Motor Fuels (no date) *Compatibilty*. Available at: https://www.iea-amf.org/content/fuel_information/fatty_acid_esters/compatibility (Accessed: 3 April 2020).

Ahlgren, S. and Di Lucia, L. (2014) 'Indirect land use changes of biofuel production - A review of modelling efforts and policy developments in the European Union', *Biotechnology for Biofuels*. Biotechnology for Biofuels, 7(1), pp. 1–10. doi: 10.1186/1754-6834-7-35.

Al-Breiki, M. and Bicer, Y. (2021) 'Comparative life cycle assessment of sustainable energy carriers including production, storage, overseas transport and utilization', *Journal of Cleaner Production*. Elsevier Ltd, 279, p. 123481. doi: 10.1016/j.jclepro.2020.123481.

Asplan Viak (2020) *Life cycle assessment of express boat propulsion systems*.

Baumann, H. and Tillmann, A.-M. (2004) *The Hitch Hiker's Guide to LCA*. Lund, Sweden: Studentlitteratur.

Bengtsson, S., Andersson, K. and Fridell, E. (2011) 'A comparative life cycle assessment of marine fuels: Liquefied natural gas and three other fossil fuels', *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment*, 225(2), pp. 97–110. doi: 10.1177/1475090211402136.

Bureau of International Recycling (BIR) (2008) *Report on the Environmental Benefits of Recycling, October*. Available at: http://www.thenbs.com/topics/DesignSpecification/articles/benefitsMasterSpecifications.asp.

COWI (2019) *Utgreiing av hurtigbåtrute Bergen – Ålesund*.

Departementene (2019) *Handlingsplan - Regjeringens handlingsplan for grønn skipsfart*.

Det Kongelige Samferdselsdepartement (2018) *Nasjonal transportplan 2018 – 2029*. Norway.

Dimitrova, Z. and Maréchal, F. (2017) 'Environomic design for electric vehicles with an integrated solid oxide fuel cell (SOFC) unit as a range extender', *Renewable Energy*, pp. 124–142. doi: 10.1016/j.renene.2017.05.031.

DNV-GL (2019) *Sulphur limit in ECAs - increased risk of PSC deficiencies and detentions*. Available at: https://www.dnvgl.com/news/sulphur-limit-in-ecas-increased-risk-of-psc-deficiencies-and-detentions-142911.

DNV GL (2019) *Comparison of Alternative Marine Fuels*. Available at: https://sea-lng.org/wp-content/uploads/2019/09/19-09-16_Alternative-Marine-Fuels-Study_final_report.pdf.

Ecoinvent Centre (2019) *Ecoinvent 3.6*.

Edwards, R. *et al.* (2014) *WELL-TO-TANK (WTT) Appendix 2 - Version 4a*, *JRC Technical reports*. Ispra, Italy. Available at: https://ec.europa.eu/jrc/sites/jrcsh/files/wtt_appendix_2_v4a.pdf.

El-Houjeiri, H. *et al.* (2019) 'Life Cycle Assessment of Greenhouse Gas Emissions from Marine Fuels: A Case Study of Saudi Crude Oil versus Natural Gas in Different Global Regions', *Journal of Industrial Ecology*, 23(2), pp. 374–388. doi: 10.1111/jiec.12751.

Ellingsen, L. A.-W. *et al.* (2014) 'Life cycle assessment of a lithium-ion battery vehicle pack', *Journal of Industrial Ecology*, 18(1), pp. 113–124. doi: 10.1111/jiec.12072.

Ellingsen, L. A.-W., Singh, B. and Strømman, A. H. (2016) 'The size and range effect: lifecycle greenhouse gas emissions of electric vehicles', *Environmental Research Letters*, 11(5), pp. 1–8. doi: 10.1088/1748-9326/11/5/054010.

Ellingsen, L. A., Hung, C. R. and Strømman, A. H. (2017) 'Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions', *Transportation Research Part D: Transport and Environment*, 55, pp. 82–90. Available at: http://www.sciencedirect.com/science/article/pii/S1361920916309658.

Environment, M. of C. and (2020) 'Norway steps up 2030 climate goal to at least 50 % towards 55 %'. regjeringen.no.

ETIP Bioenergy (no date) *Biodiesel (FAME) production and use in Europe*. Available at: http://www.etipbioenergy.eu/value-chains/products-end-use/products/fame-biodiesel (Accessed: 3 April 2020).

European Commission (no date) *European Platform on Life Cycle Assessment (LCA)*. Available at: http://ec.europa.eu/environment/ipp/lca.htm (Accessed: 1 December 2016).

Finnveden, G. *et al.* (2009) 'Recent developments in Life Cycle Assessment', *Journal of Environmental Management*. Elsevier Ltd, 91(1), pp. 1–21. doi: 10.1016/j.jenvman.2009.06.018.

Gilbert, P. *et al.* (2020) 'Assessment of full life-cycle air emissions of alternative shipping fuels'. The Authors, 172(2018), pp. 855–866. doi: 10.1016/j.jclepro.2017.10.165.

Graedel, T. E., Allenby, B. R. and Comrie, P. R. (1995) 'Matrix Approaches to Abridged Life Cycle Assessment', *Environ. Sci. Technol.* American Chemical Society, 29(3), pp. 134A-139A. doi: 10.1021/es00003a751.

Guinée, J. *et al.* (2011) 'Life Cycle Assessment : Past, present, and future', *Environ. Sci. Technol. 2011,* 45(1), pp. 90–96.

Hellweg, S. and Milà i Canals, L. (2014) 'Emerging approaches, challenges and opportunities in life cycle assessment.', *Science (New York, N.Y.)*, 344(6188), pp. 1109–13. doi: 10.1126/science.1248361.

Hochschorner, E. and Finnveden, G. (2003) 'Evaluation of two simplified Life Cycle assessment methods', *The International Journal of Life Cycle Assessment*, 8(3), pp. 119–128. doi: 10.1007/BF02978456.

Hoen, A. *et al.* (2017) *Research for TRAN Committee - Decarbonisation of EU transport*. Brusesels: Policy Department for Structural and Cohesion Policies.

Hung, C. R., Ellingsen, L. A.-W. and Majeau-Bettez, G. (2018) 'LiSET: A Framework for Early-Stage Life Cycle Screening of Emerging Technologies', *Journal of Industrial Ecology*, pp. 1–12. doi: 10.1111/jiec.12807.

International Organization for Standardization (2006) *ISO 14040: Environmental management -- Life cycle assessment -- Principles and framework*. Geneva, Switzerland.

Jafarzadeha, S. *et al.* (2017) 'LNG-fuelled fishing vessels: a systems engineering approach Sepideh Jafarzadeh', *Transportation Research Part D: Transport and Environment*, 50, pp. 202–222.

Jalkanen, J. P., Johansson, L. and Kukkonen, J. (2016) 'A comprehensive inventory of ship traffic exhaust emissions in the European sea areas in 2011', *Atmospheric Chemistry and Physics*, 16(1), pp. 71–84. doi: 10.5194/acp-16-71-2016.

JEC - Joint Research Centre-EUCAR-CONCAWE collaboration (Forthcoming) *JEC Alternative Fuels Study*.

Jeong, B. *et al.* (2018) 'An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems', *Journal of Cleaner Production*. Elsevier Ltd, 187, pp. 111–130. doi: 10.1016/j.jclepro.2018.03.184.

Kobayashi, H. *et al.* (2019) 'Science and technology of ammonia combustion', *Proceedings of the Combustion Institute*. Elsevier Inc., 37(1), pp. 109–133. doi: 10.1016/j.proci.2018.09.029.

Korean Register (2020) *Forecasting the Alternative Marine Fuel - Ammonia*.

Koroneos, C. *et al.* (2004) 'Life cycle assessment of hydrogen fuel production processes', *International Journal of Hydrogen Energy*, 29(14), pp. 1443–1450. doi: 10.1016/j.ijhydene.2004.01.016.

Lasocki, J. (2018) 'Ammonia and conventional engine fuels: Comparative environmental impact assessment', *E3S Web of Conferences*, 44, pp. 1–8. doi: 10.1051/e3sconf/20184400091.

Lindstad, E. (2019) *Increased use of LNG might not reduce maritime GHG emissions at all – June 2019*.

Majeau-Bettez, G. *et al.* (2017) 'Choice of Allocations and Constructs for Attributional or Consequential Life Cycle Assessment and Input-Output Analysis', *Journal of Industrial Ecology*, pp. 1–15. doi: 10.1111/jiec.12604.

Makhlouf, A., Serradj, T. and Cheniti, H. (2015) 'Life cycle impact assessment of ammonia production in Algeria: A comparison with previous studies', *Environmental Impact Assessment Review*. Elsevier Inc., 50, pp. 35–41. doi: 10.1016/j.eiar.2014.08.003.

MAN AG (2016) *Diesel-electric Drives*. Available at: https://marine.mandieselturbo.com/docs/librariesprovider6/marine-broschures/diesel-electric-drives-guideline.pdf.

Maritime Battery Forum (2016) *Life cycle analysis of batteries in the maritime sector*.

Monterey Gardiner (2009) *DOE Hydrogen and Fuel Cells Program: Hydrogen Storage*, *U.S Department Of Energy*. Available at: http://www.hydrogen.energy.gov/storage.html.

Nasjonal varedeklarasjon 2018 - NVE (no date). Available at: https://www.nve.no/energiforsyning/varedeklarasjon/nasjonal-varedeklarasjon-2018/ (Accessed: 13 May 2020).

Platform supply vessel VIKING ENERGY (no date). Available at: https://www.wartsila.com/encyclopedia/term/platform-supply-vessel-viking-energy (Accessed: 3 July 2020).

Prussi, M. *et al.* (2020) *JEC Well-To-Wheels report v5*. doi: 10.2760/100379.

Rebitzer, G. *et al.* (2004) 'Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications', *Environment International*, 30(5), pp. 701–720. doi: 10.1016/j.envint.2003.11.005.

Rillo, E. *et al.* (2017) 'Life Cycle Assessment (LCA) of biogas-fed Solid Oxide Fuel Cell (SOFC) plant', *Energy*. Elsevier Ltd, 126(2017), pp. 585–602. doi: 10.1016/j.energy.2017.03.041.

Scarbrough, T. *et al.* (2017) *A review of the NAEI shipping emissions methodology*. Available at: https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1712140936_ED61406_NAEI_shipping_report_12Dec2017.pdf.

The International Council on Combustion Engines (2013) *Guideline for ship owners and operators on managing distillate fuels up to 7.0% v/v FAME (biodiesel)*. Available at: https://www.cimac.com/cms/upload/workinggroups/WG7/CIMAC_WG7_Guideline_for_Ship_Owners_and_Operators_on_Managing_Distillate_Fuels_May_2013.pdf.

'The ocean nation of Norway' (2018). regjeringen.no. Available at: https://www.regjeringen.no/en/topics/havet/the-ocean-nation-of-norway/id2609341/ (Accessed: 18 September 2020).

Thinkstep (2019) *Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel*.

TNO (2011) 'Environmental and Economic aspects of using LNG as a fuel for shipping in The Netherlands', pp. 1–48.

Transport & Environment (2016) *Globiom : the basis for biofuel policy post-2020*.

Trozzi, C. and Lauretis, R. De (2019) *International maritime navigation, international inland navigation, national navigation (shipping), national fishing, military (shipping), and recreational boats*, *Guidebook*.

Wärtsilä (2001) *Wärtsilä LNG-fuelled engines for offshore vessels*. Available at: https://www.wartsila.com/media/news/30-10-2001-wartsila-lng-fuelled-engines-for-offshore-vessels (Accessed: 3 July 2020).

Wärtsilä (no date a) *CHEMICAL TANKERS*, *Wärtsilä Encyclopedia of Marine Technology*. Available at: https://www.wartsila.com/encyclopedia/term/chemical-tankers (Accessed: 21 July 2020).

Wärtsilä (no date b) *OFFSHORE SUPPORT VESSELS (OSVs)*, *Wärtsilä Encyclopedia of Marine Technology*. Available at: https://www.wartsila.com/encyclopedia/term/offshore-support-vessels-(osvs) (Accessed: 6 July 2020).

Wood, S. and Cowie, A. (2004) *A Review of Greenhouse Gas Emission Factors for Fertiliser Production.*, *For IEA Bioenergy Task 38*.

Wulf, C. and Kaltschmitt, M. (2018) 'Hydrogen supply chains for mobility-Environmental and economic assessment', *Sustainability (Switzerland)*, 10(6), pp. 1–26. doi: 10.3390/su10061699.

APPENDIX A – LCA METHOD AND PROCEDURE

The text in this Appendix is taken directly from the report considering Case 3 (Asplan Viak, 2020).

The estimation of GHG emissions of the various propulsion systems was based on the LCA method. LCA offers a systematic framework and process for assessing environmental impacts that occur in complex supply chains – involving production, use and waste treatment – to the demand or delivery of goods and services (Hellweg and Milà i Canals, 2014). The European Commission describes LCA as *"the best framework for assessing the potential environmental impacts of products currently available"* (European Commission, no date) and governments all over the world encourage its use (Guinée *et al.*, 2011). A brief overview of the method and procedure is provided below.

Although LCA may be defined as the *"compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle"* (International Organization for Standardization, 2006), it can also be described as the whole procedure for how such studies are performed and interpreted (Baumann and Tillmann, 2004). The section below briefly explains the four main steps in LCA.

The LCA procedure is divided into four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation (see Figure A 1).

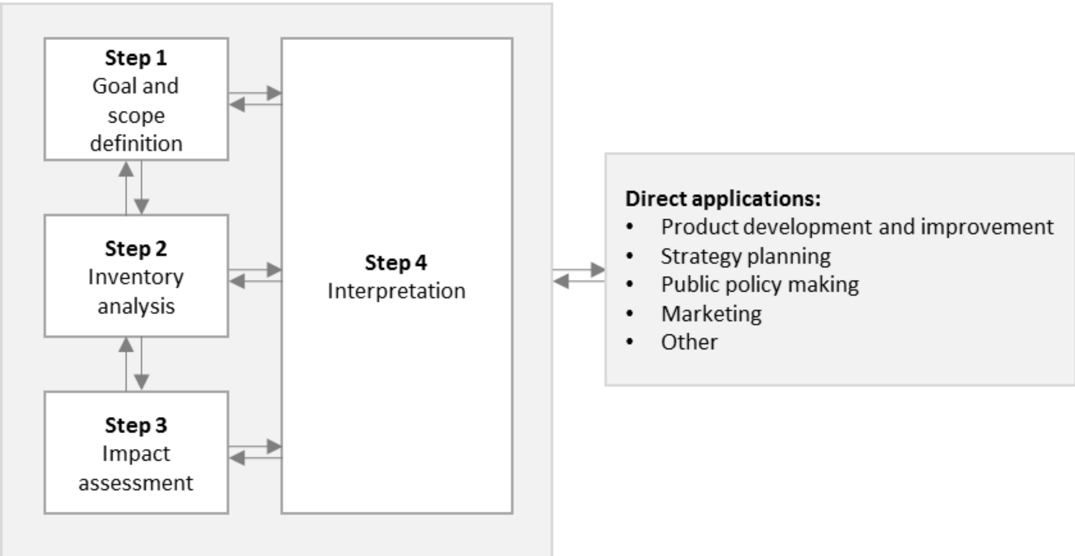


Figure A 1 Phases of a Life Cycle Assessment after ISO 14040 (International Organization for Standardization, 2006)

The first step, goal and scope definition, includes defining the objectives of the study and setting the system boundaries. In this step, the system boundary and functional unit are defined. The system boundary limits the unit processes and activities that will be included in the study. The definition of the functional unit is less critical in standalone studies, but for comparative studies, it forms the basis for comparison and is critical to perform a fair analysis between the alternatives. The functional unit must be representative of the function of the studied process or product (Baumann and Tillmann, 2004). For instance, in the LCA of express boats, the study objective could be to compare the GHG emissions of express boats with different propulsion systems. In this case, different functional units may be used. Examples include, but are not limited to, passenger kilometre (pkm) driven or lifetime of the boat.

In the second step, inventory analysis, an inventory is compiled. A flowchart describing the system to be modelled should be constructed. Data for inputs and outputs for each process in the life cycle are collected. Data collection is typically the most time consuming stage of an LCA (Rebitzer *et al.*, 2004).

This step also calculates the environmental loads of the system under study in relation to the functional unit (Baumann and Tillmann, 2004).

The third step, impact assessment, groups emissions and resource extractions according to the type of environmental loads they cause. This step uses characterization factors to convert emissions into common impact units for each impact category (Hellweg and Milà i Canals, 2014). In this study, we focus our attention on the global warming potential of GHG emissions, expressed in terms of kilogram carbon dioxide equivalents (kg CO_2-eq) and metric ton carbon dioxide equivalents (ton CO_2-eq).

The final stage of an LCA is the interpretation, which consists of two processes. The first process is analysis and presentation of the results. The second is to evaluate the results in order to establish confidence in the results. In LCA, the quality and uncertainty of data are continuously reviewed.

Although the four steps are presented in a sequential order, LCA is in practice an iterative process. As seen in Figure A 1, the four steps are interrelated. The iterative nature of the LCA procedure allows for adaption and adjustments of earlier steps due to findings in later phases of the study. For example, if one finds in the final step (interpretation) that the defined functional unit was unsatisfactory, one may go back to step one (goal and scope definition) and define a new functional unit. In this example, it follows that step two to four must also be repeated. Several iterations may be required in the course of an LCA study.

While LCA is a powerful tool, it is not without limitations (Hung, Ellingsen and Majeau-Bettez, 2018). In particular, the comprehensive nature of an LCA makes it costly and time intensive to perform (Graedel, Allenby and Comrie, 1995; Hochschorner and Finnveden, 2003; Finnveden *et al.*, 2009; Hellweg and Milà i Canals, 2014). When evaluating and comparing the GHG emission of several different technological solutions, collecting and analysing data for a full LCA can become an onerous task, possibly to the point of impractical. A common practice to deal with this issue, is to limit the scope of the LCA and to rely on data from previously published studies, databases or use proxies (Baumann and Tillmann, 2004).

APPENDIX B – EMISSION FACTORS FOR PROPULSION SYSTEMS

Primary data were collected to compile life cycle inventories for parts of the analysis where such data were available, but the study also relies on LCA data and results from previous studies and the *ecoinvent* database. To protect proprietary data and information, component data are withheld while energy estimates and emission factors assumed in the analysis are presented in the report. To be consistent with the attributional approach taken in the analysis, “cut-off by classification” processes were selected when using data from the *ecoinvent* (version 3.6) database.

The cradle-to-gate and disposal emission factors for engine, skid, boilers, auxiliary Li-ion battery, cryogenic fuel tanks for LNG, LBM, and ammonia, SOFC, and cables were established in the current study and are described below. The emission factors for the other components were established in the preceding LCA report (Asplan Viak, 2020) and can be found in that report.

Internal combustion engine and skid

A simplified cradle-to-gate study was performed for both the internal combustion engine and the skid. Both components were assumed to primarily consist of low-alloyed steel. In addition, engine production also required small shares of other metals and materials. The cradle-to-gate emission factor was estimated to be about 5.4 kg CO_2-eq/kg for the engine and 3.7 kg CO_2-eq/kg for the skid.

For both components, the disposal process was assumed to be a melting process. As ferrous metals make up the largest share of materials in both the engine and the skid, an emission factor for melting steel was assumed. The value of 0.7 kg CO_2-eq/kg reported by the Bureau of International Recycling was used in the analysis (Bureau of International Recycling, 2008).

The established emission factors for the engine and skid were in the analysis of both the PSV and the chemical tanker.

Boilers

The chemical tanker scenarios considering combustion of fuels, also require boilers. Because no emission factors were available for marine boilers, we assumed the emission factors of 7.1 kg CO_2-eq/kg for production and 0.7 kg CO_2-eq/kg for disposal. The production emission factor for production is based on the emission factor established for the electric motor (Asplan Viak, 2020), while the emission factor for disposal is emission factor for melting steel (Bureau of International Recycling, 2008). While there is some uncertainty associated with the use of proxies, the emission contribution of the boilers to the total life cycle emissions are really low. As such, the proxy use here not hold any significance on the overall results or conclusions.

Auxiliary Li-ion battery

The Li-ion battery onboard Viking Energy has a nominal capacity of 653 kWh. Although the battery was supplied by ZEM Energy, the material input is primarily based on data from Corvus Energy. While there may be differences in design and certain material choices, both the onboard battery (ZEM Energy) and the modelled battery (Corvus Energy) have similar characteristics as they are intended for the same marine purposes.

The battery inventory was compiled based on the nominal battery capacity (653 kWh), battery material composition data provided by Corvus Energy, and supplemented with inhouse battery inventory data that have been published in scientific peer-reviewed articles (Ellingsen *et al.*, 2014; Ellingsen, Singh and Strømman, 2016; Ellingsen, Hung and Strømman, 2017). The cradle-to-gate emission of the auxiliary battery equals an emission factor of 11.5 kg CO_2-eq/kg.

Note that the emission factor of the auxiliary Li-ion battery considered in this study differs from the Li-ion battery pack considered in the express boat study (Asplan Viak, 2020). The emission factors differ because the two batteries are intended and optimized for different purposes. As such, the battery design as well as material choices and amounts differ between the two battery types.

Viking Energy relies on a 653 kWh Li-ion battery pack. The battery pack was also considered for the fuel cell scenarios as fuel cell propulsion systems require an auxiliary Li-ion battery. While battery propulsion is not considered as a separate scenario for the chemical tanker, it was assumed that the SOFCs and PEMFCs would require a 2 612 kWh auxiliary battery as the fuel cells operate best under an even load.

Cryogenic fuel tank

For the PSV, LNG is stored in a large tank in the middle of the vessel. The tank is a horizontal cylinder with domed ends, fabricated from 304 grade stainless-steel (*Platform supply vessel VIKING ENERGY*). A simplified cradle-to-gate study was performed for the LNG tank, primarily based on the assumption of the tank being made from chromium steel 18/8.

The disposal process was assumed to be a melting process. The value of 0.7 kg CO_2-eq/kg for melting steel was used in the analysis (Bureau of International Recycling, 2008).

The established emission factors for the LNG tank were also assumed for LBM and ammonia and were used in the analysis of cryogenic fuel tanks for both the PSV and the chemical tanker.

Solid oxide fuel cell (SOFC)

As the fuel cell is currently under development, the SOFC that will be used in the PSV has not been assessed in an LCA study. Thus, the emission factor of the SOFC was based on the estimate provided by Rillo *et al.* (2017) who reports a cradle-to-gate emission factor of 552 kg CO_2-eq/kW. The value appears to be in good agreement to previous studies assessing SOFC, as shown in Table A 1.

Table A 1 Comparison of SOFC life cycle GHG emission between the case study reported by Rillo et al. (2017) and similar studies. Table is from Rillo et al. (2017).

Reference	Climate change kg CO_2 eq./kW	Notes
Case study	552	
Staffell et al. (2012) [42]	414–534	Merged inventory for 1 kW stack; BOP not included.
Karakoussis et al. (2001) [43]	383	Based on 1 kW Sulzer HEXIS planar SOFC.
Strazza et al. (2010) [13]	530	LCA of a 20 kW SOFC as auxiliary system.
Baratto et al. (2005) [44]	326	Life Cycle Assessment of a 5 kW planar SOFC as auxiliary power unit.
Primas et al. (2007) [41]	620	Simapro® report on CHP; LCA of a 125 kW tubular SOFC.

The cradle-to-gate emission factor of 552 kg CO_2-eq/kW was used in the analysis. The normalized emission factor of 67.3 kg CO_2-eq/kg listed in Table 7 assumes a specific mass of 8.2 kg/kW for the SOFC (Dimitrova and Maréchal, 2017). Note that this assumption has no bearing on the cradle-to-gate results, as the emission per kW was used in the analysis, while the emission per kg was only calculated to provide a normalized emission factor in terms of emission per weight.

As an emission factor for end-of-life treatment for SOFC were not obtained, the pyrometallurgical treatment for Li-ion batteries in the *ecoinvent* database was used as a proxy for disposal. Thus, an emission factor of 1.4 g CO_2-eq/kg was assumed as a proxy for the disposal of the PEMFC. The disposal emissions are, in contrast to cradle-to-gate emissions, affected by the assumed specific mass of 8.2 kg/kW.

The established emission factors for the SOFC were used in the analysis of both the PSV and the tanker.

Additional cables

Based on an LCA report considering a PSV, we assume a cradle-to-gate emission factor of 23.8 kg CO_2-eq/kg (Maritime Battery Forum, 2016). The relatively high emission factor stems primarily from use of aluminium.

The disposal process was assumed to be a melting process. The value of 0.5 kg CO_2-eq/kg aluminium reported by the Bureau of International Recycling was used in the analysis (Bureau of International Recycling, 2008).

For the tanker, it was assumed that cabling requirements would be about three times as much as what was required for Scenarios 8 – 10 for the PSV. This is a rough estimation based on the installed power of the fuel cells.

APPENDIX C – FUEL CYCLE EMISSION FACTORS

The fuel cycle emission factors for LS-HFO, LNG, LBM, and liquid ammonia were estimated in the current study and are described below. In addition, fuel cycle emission factors for grey hydrogen were also established for the current report. The fuel cycle emission factors for the other fuels were estimated in a preceding LCA report and are described in full there (Asplan Viak, 2020), while the information is briefly reproduced in the current report. For the sake of transparency, both the WTT and utilization as well as the total fuel cycle emission factors are reported.

MGO

MGO is similar to diesel fuel, but it has a higher density than diesel. The fuel cycle emission factor was estimated to be 86.4 g CO_2-eq/MJ in the express boat study, where WTT is 12 g CO_2-eq/MJ and combustion is 74.4 g CO_2-eq/MJ. The emission factor was based on the average value from three sources (Bengtsson, Andersson and Fridell, 2011; El-Houjeiri *et al.*, 2019; Thinkstep, 2019).

LS-HFO

The emission factor of LS-HFO (low sulphur with 1 % S) was based on Gilbert *et al.* (2020), who reports a WTT factor of 11.5 g CO_2-eq/MJ and utilization (combustion) factor of 75.7 g CO_2-eq/MJ. Thus, the fuel cycle emission factor used in the current study was 87.2 g CO_2-eq/MJ.

Biodiesel

Biodiesel is a blend of FAME and diesel. FAME blending cannot be in high concentrations without substantial risks for fuel quality, engine operation, exhaust emissions and infrastructure (ETIP Bioenergy). In Europe, maximum 7 % v/v FAME is allowed in diesel fuel and 5 % v/v in the U.S (Advanced Motor Fuels). Due to limited experience with biodiesel blends in the marine sector, in 2010 the ISO marine fuel specification was modified to require marine fuels to contain no more than de minimis (i.e. less than approximately 0.1 % v/v) levels of biodiesel (The International Council on Combustion Engines, 2013). While biodiesel is not extensively used in the marine sector today, in this analysis it was assumed that biodiesel with a blend of 5 % v/v FAME could be used in a diesel-cycle combustion engine.

A forthcoming JEC report estimates a WTT factor of FAME to be 38.6 g CO_2-eq/MJ in 2020 (JEC - Joint Research Centre-EUCAR-CONCAWE collaboration, forthcoming). The WTT factor for diesel was assumed to be 18.9 g CO_2-eq/MJ. Assuming 5 % v/v FAME yields a WTT factor of 19.8 g CO_2-eq/MJ. The combustion factor for diesel was assumed to be 73.2 g CO_2-eq/MJ. Note that the emissions factor assumes that emissions associated with the combustion of biofuels are offset by the renewable credit given to biofuels due to the capture of CO_2 during the growth stage of the plants. This provides a total combustion factor of 69.8 g CO_2-eq/MJ.

Note that any potential emissions associated with indirect land use change (ILUC) were not considered in the current study. The primary reason for not considering potential ILUC emission is that the amount of FAME in biodiesel is only 5 % v/v and would have limited impact on the estimated results. Furthermore, there is great uncertainty regarding whether biofuel use will result in any land use change and what the effect would be as the quantification of ILUC is challenging (Transport & Environment, 2016).

HVO

HVO is a drop-in fuel that can be used in diesel engines either without or minor modifications. HVO is commonly referred to as renewable diesel and is produced via hydroprocessing of oils and fats. Same as for FAME, the emissions factor assumes that emissions associated with the combustion of biofuels are offset by the renewable credit given to biofuels due to the capture of CO_2 during the growth stage of the plants.

The JEC report estimated the WTT emission factor for HVO to be 24.4 g CO_2-eq/MJ for 2020(JEC - Joint Research Centre-EUCAR-CONCAWE collaboration, no date). According to the report, advanced feedstocks (animal fat, used cooking oil, and lignocellulosic feedstock) are used to produce about 57% of the HVO available on the European market in 2020.

There is uncertainty associated with the fuel cycle emission factors for biofuels, particularly with respect to emissions stemming from land use change. The production of biofuel feedstock may in some cases lead to direct land use changes (DLUC) and indirect land use changes (ILUC). While DLUC takes place when cultivation of biofuel feedstock modifies the land use on the land where it is grown, ILUC is the unintended land use changes around the world induced by the expansion of croplands for biofuel feedstock in response to the increased global demand for biofuels. For example, when biofuel feedstocks are produced on existing agricultural land, the demand for food and feeds crop remain and may lead to conversion of e.g. forest to agricultural land. The GHG emissions associated with this indirect land use change may lead to substantial GHG emissions.

Quantification of GHG emissions due to ILUC is very different from quantification of DLUC, as the theory in ILUC modelling is based on economic market reactions to increase demand for biofuels, whereas quantifying DLUC relies more on natural science. Emissions due to DLUC is usually zero or very low because biofuel feedstock is normally produced on previous crop or pastureland. It is common to use economic equilibrium models to estimate ILUC, and researchers have developed and used several different economic models.

Among the most commonly used models are the Modeling International Relationships in Applied General Equilibrium (Mirage) model developed by the European Commission French National Institute for Agricultural Research, the UN and the World Trade Organization and the Global Biosphere Management Model (GLOBIUM) by the International Institute for Applied Systems Analysis, Ecofys, and E4Tech(Ahlgren and Di Lucia, 2014; Hoen *et al.*, 2017).

Both the Globium and the Mirage model report significant emissions due to ILUC, but Globium reports higher emissions than Mirage, as illustrated in Figure A 2. This is particularly the case for feedstocks that are primarily grown outside of Europe (palm and soybean). The large discrepancy in results for ILUC models illustrates the uncertainty and lack of scientific agreement associated with ILUC models in general.

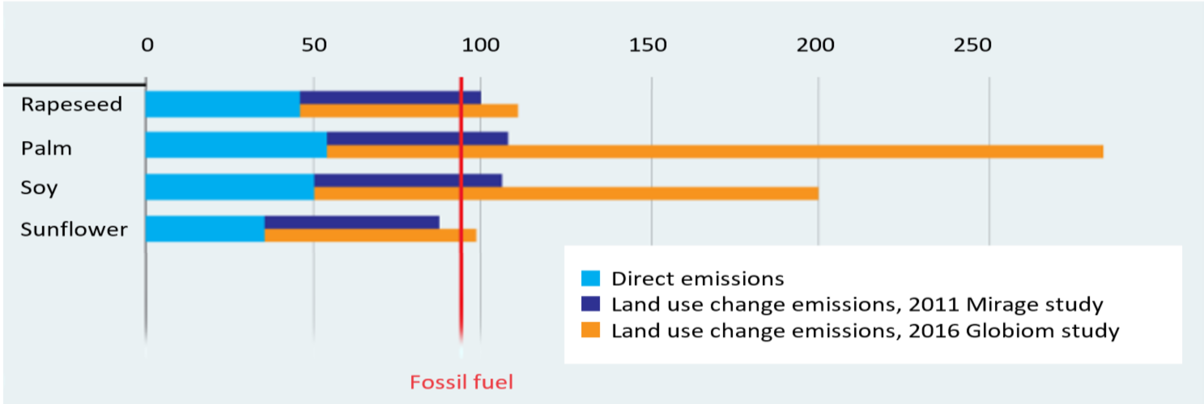


Figure A 2 GHG emissions from FAME made from different feedstocks. The figure is taken from Transport & Environment (2016).

In this study, both FAME and HVO are considered. Because FAME only makes up 5 % of the biodiesel, the inclusion of ILUC emissions may not affect the results significantly even though an increase may be expected. HVO on the other hand, is not blended with diesel but used as a drop-in fuel. In the analysis, a rough approach to consider ILUC emissions for HVO production was taken. The HVO fuel cycle emission factor assumes that 57% of the feedstocks used for production stem from advanced feedstocks (e.g., waste animal fats and agricultural waste) not subject to ILUC emissions, while the remaining 43 % of feedstocks used for HVO production stems from first generation feedstocks that may be associated with ILUC emissions. When assuming that ILUC emission doubles the fuel cycle emission factor of first-generation feedstocks, the HVO fuel cycle emission factor increases from 24.4 g CO_2-eq/MJ to 41.6 g CO_2-eq/MJ. Both emission factors were used in the analysis.

Liquid ammonia (L-NH_3)

While fuel cycle emission factors for liquid ammonia were established in the preceding LCA report (Asplan Viak, 2020), updated fuel cycle emission factors were used in the current report due to improved data availability. Note that the updated emission factors were used for all three cases in the current report.

For ammonia, the WTT factor equals the total fuel cycle emission factor. As complete combustion of ammonia does not result in GHG emissions, there are no combustion emissions associated with fuel utilization. Note that incomplete combustion of ammonia potentially resulting in emission of nitrous oxide (N_2O) was not considered in the study, primarily due to lack of data. Use of ammonia in fuel cells does not result in any GHG emissions.

Liquid ammonia may be used as a fuel in an internal combustion engine or as an energy carrier in a SOFC. Hydrogen may be produced through different production pathways, such as electrolysis or by reforming natural gas. Today, nearly all hydrogen is produced from natural gas (DNV GL, 2019). In the analysis, we consider both green, blue, and grey ammonia.

Two green ammonia WTT emission factors were established, one assuming Norwegian electricity and one assuming Nordic electricity. The green ammonia WTT emission factors were based on energy estimates by Yara and transport emissions based on Al-Breiki and Bicer (2021). The total energy demand was estimated to be about 10 kWh/kg ammonia for a future state-of-art plant. It was assumed that green ammonia was transported 400 km by ship, which is the same transport distance used for green hydrogen. The estimated WTT factor for the green (Norwegian) and green (Nordic) were estimated to be 11.6 g CO_2-eq/MJ and 60.2 g CO_2-eq/MJ, respectively.

The WTT emission factor for blue ammonia was estimated to be 78.7 g CO_2-eq/MJ. The cradle-to-gate (production) was based on (Makhlouf, Serradj and Cheniti, 2015) and emissions associated with distribution was based on Al-Breiki and Bicer (2021). The WTT emission factor for grey ammonia was estimated based on the average production emission from three sources (Wood and Cowie, 2004; Lasocki, 2018; Ecoinvent Centre, 2019) and transport emissions based on Al-Breiki and Bicer (2021). Note that for both blue and grey ammonia a transport distance of 4 000 km by ship was assumed, and is the same distance used for grey and blue hydrogen.

LNG and LBM

The WTT factor for LNG and LBM were respectively based on the Edwards *et al.* (2014) and a forthcoming report from the JEC (Joint Research Centre-EUCAR-CONCAWE) consortium on alternative transportation fuels, respectively. The WTT factors were estimated to be 19.4 g CO_2-eq/MJ for LNG and 27.4 g CO_2-eq/MJ for LBM.

The combustion factors for LNG and LBM were both based on Edwards *et al.* (2014). Thus, the combustion factor was set to 55.1 g CO_2-eq/MJ for LNG. Note that the combustion factor for LBM is zero as it assumes that carbon released during combustion equals the amount of carbon captured during the growth phase of the biomass. This is a common simplifying assumption made for biofuels.

In addition, GHG emissions from methane slip were estimated. According to Jafarzadeha *et al.* (2017), most LNG-fuelled engines operate on the Otto cycle, which results in a methane slip of 2 – 3 %. TNO received methane data from an engine supplier who states methane slip of 2.0 % at high loads and 2.5 – 8.5 % at very low loads for both SI and DF engines (TNO, 2011). Thinkstep (2019) performed a study for SEA/LNG and SGMF evaluating the GHG emissions of LNG as a marine fuel. Lindstad (2019) critiqued the Thinkstep report for advantageous thermal efficiency assumptions for LNG combustion compared to other fuels and low methane slip estimates, resulting in favourable results for LNG. Lindstad (2019) points out that at high power, LNG might give a marginally better thermal efficiency, but at power lower than 50 % the diesel-based option gives much better fuel utilization and because most ships use around 50 % of installed power to operate at speed 2 – 4 knots or more below the designed speed, there are no good reasons for using a higher thermal efficiency for LNG compared to diesel. Regarding methane slips, Lindstad (2019) highlight that it is only the high pressure (diesel cycle) 2-stroke engine that has low methane slip, but for all other LNG engine options methane slip is significant. A summary of the reported results from the Thinkstep (2019) and Lindstad (2019) reports are presented in Table A 2.

Table A 2 Comparison of methane slip

Engine type		Lindstad (2019)	Thinkstep (2019)
		Percentage	Percentage
2-stroke	Diesel-DF	0.2 %	0.1 %
	Otto-DF	2.6 %	1.5 %
4-stroke	Otto-SI	2.7 %	1.3 %
	Otto-DF	3.3 %	2.5 %

For both LNG and LBM, the current study assumed methane percentage slips as reported by Lindstad (2019).

For the PSV, the 4-stroke Otto-SI engine was assumed in the scenario of a pure LNG (Scenario 4) and LBM (Scenario 5) vessel and the 4-stroke Otto-DF was assumed for the scenarios using a dual fuel engine (Scenarios 6-10). While the SFOC varies during operation, a simplifying measure was taken by assuming a constant SFOC of 163 g/kwh (η=45 %) to estimate the methane slip, based on the estimate numbers by Lindstad (2019).

For the chemical tanker, the 2-stroke Otto-DF engine was assumed for the main engine and the 4-stroke Otto-SI engine was assumed for the auxiliary engine. The methane slip for the main engine was estimated based on a constant SFOC of 155 g/kWh (η=56 %). The methane slip for the auxiliary engine was estimated based on a constant SFOCs of 163 g/kWh (η=45 %), based on the estimate numbers by Lindstad (2019).

Table A 3 reports the estimated fuel cycle emission factors measured in g CO_2-eq/MJ for LNG and LBM. To be consistent with the WTT and combustion factors, a characterization factor of 25 was used to estimate the global warming potential of methane in terms of CO_2-equivalents. Recall that the combustion factor for LBM is zero as it assumes that carbon released during combustion equals the amount of carbon captured during the growth phase of the biomass.

Table A 3 Contribution to total fuel cycle emission factor for LNG and LBM different engines. Note that SFOC is incorporated in the emission factors.

Vessel	**Engine type**	**Fuel**	WTT	Combustion	Methane slip	**Total fuel cycle emission factor**
			g CO_2-eq/MJ			
PSV	DF Otto cycle 4-stroke (3.3 % methane slip)	LNG	19.4	55.1	16.6	91.1
		LBM	27.4	0	16.6	44.0
PSV & Chemical tanker (AE)	SI Otto cycle 4-stroke (2.7 % methane slip)	LNG	19.4	55.1	13.8	88.3
		LBM	27.4	0	13.8	41.2
Chemical tanker (ME)	DF Diesel cycle 2-stroke (0.2 % methane slip)	LNG	19.4	55.1	1.2	75.7
		LBM	27.4	0	1.2	28.6

Electricity

In this study, two electricity mixes were considered: the Nordic electricity mix and the Norwegian electricity mix. The Nordic consumption mix estimated by Asplan Viak is 112 g CO_2-eq/kWh (equivalent to 31.1 g CO_2-eq/MJ). The value represents the electricity at low voltage, thus including transmission and distribution losses. The Norwegian production mix consists primarily of electricity generated from hydropower. Based on the emission factor of the Norwegian production mix provided by NVE (*Nasjonal varedeklarasjon 2018 - NVE*, no date) and emissions associated with transmission and distribution from the *ecoinvent* 3.6 database, the Norwegian consumption mix at low voltage was estimated to be 21.4 g CO_2-eq/kWh (equivalent to 5.9 g CO_2-eq/MJ).

Hydrogen

The WTT factor of hydrogen depends on the production route and whether the hydrogen is compressed or liquified. Because hydrogen is not combusted, there is no combustion factor for hydrogen. While the WTT factors for compressed grey hydrogen, liquid grey hydrogen, and compressed blue hydrogen are taken entirely from the JEC well-to-tank Appendix 2 technical report (Edwards *et al.*, 2014), the emission factors for green liquid and compressed hydrogen and blue liquid hydrogen were estimated based on data from the JEC well-to-tank Appendix 2 technical report (Edwards *et al.*, 2014) and Wulf and Kaltschmitt (2018). Emissions associated with liquification was estimated based on the energy requirement (11.6 kWh/kg hydrogen) for the liquification process (Koroneos *et al.*, 2004; Monterey Gardiner, 2009). Emissions associated with compression was based on the energy requirement (3.5 kWh/kg hydrogen) for the compression process (Monterey Gardiner, 2009). Note that compressed hydrogen requires more transport because it takes up more volume than the liquid hydrogen and this results in higher transport emissions.

The WTT factors for the various hydrogen production pathways are given in Figure A 4.

Table A 4 WTT factor for various hydrogen production pathways.

WTT factor (g CO_2-eq/MJ)	Green		Blue	Grey
	Nordic electricity	Norwegian electricity		
Compressed hydrogen (C-H_2)	51.0	10.6	35.0	103.9
Liquid hydrogen (L-H_2)	57.8	11.3	55.7	132.7

Note that because CCS only removes about 85 % of the carbon and that it only applies to the SMR processes (compression and liquification), the liquid blue hydrogen has a significantly higher emission factor than that of compressed blue hydrogen because liquification is much more energy demanding than compression. Some of the difference is also due to longer transportation distances for hydrogen produced from SMR compared to hydrogen produced from electrolysis.

APPENDIX D – SPECIFIC FUEL OIL CONSUMPTION

Platform supply vessel

SFOC data for the engine were based on test data of the engine type used in Viking Energy (Wärtsilä 6R32DF) from the FellowSHIP project.

Figure A 3 presents the SFOC numbers form the FellowSHIP project (green) and the estimated engine efficiency (blue) based on fuel use as a function of engine load.

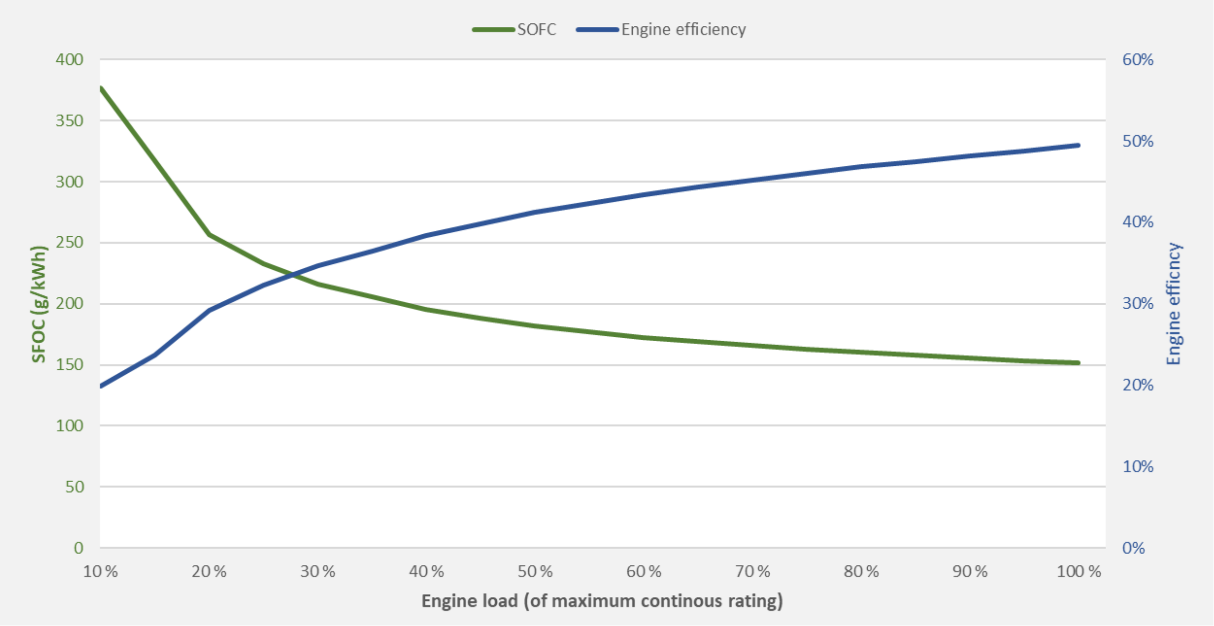


Figure A 3 Specific fuel oil consumption and engine efficiency as a function of engine load based on fuel use of the Wärtsilä 6R32DF

Chemical tanker

Data from the sea trials show engine performance at various conditions. At the design parameters (indicated transit speed at app. 14 knots) the engine SFOC is 155 g/kWh at 65 % load. This corresponds with the engines lowest SFOC and highest efficiency factor at approximately 55.6 %.

The SFOC and performance data are based on the sea-trials performed by the shipbuilder Hudong-Shonghua Shipbuilding Group CO., LTD and engine manufacturing affiliates at MAN Energy Solutions Norway.

Figure A 4 presents the SFOC numbers assumed for the main engine of the chemical tanker.

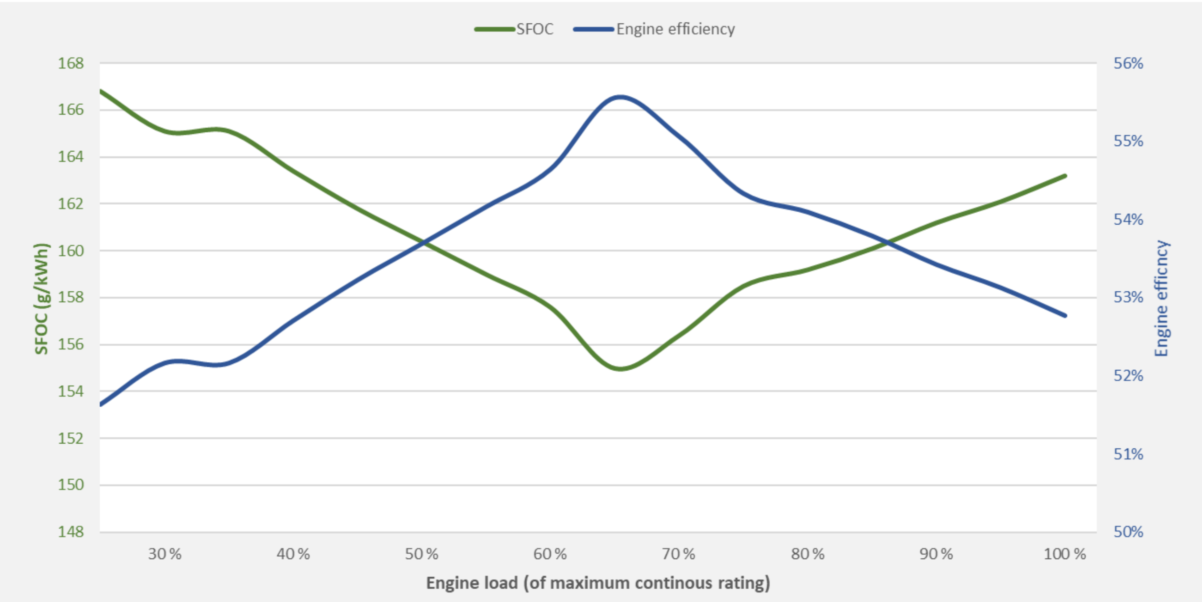


Figure A 4 Specific fuel oil consumption and engine efficiency as a function of engine load based on fuel use of the Man B&W 6G50ME-C9.5