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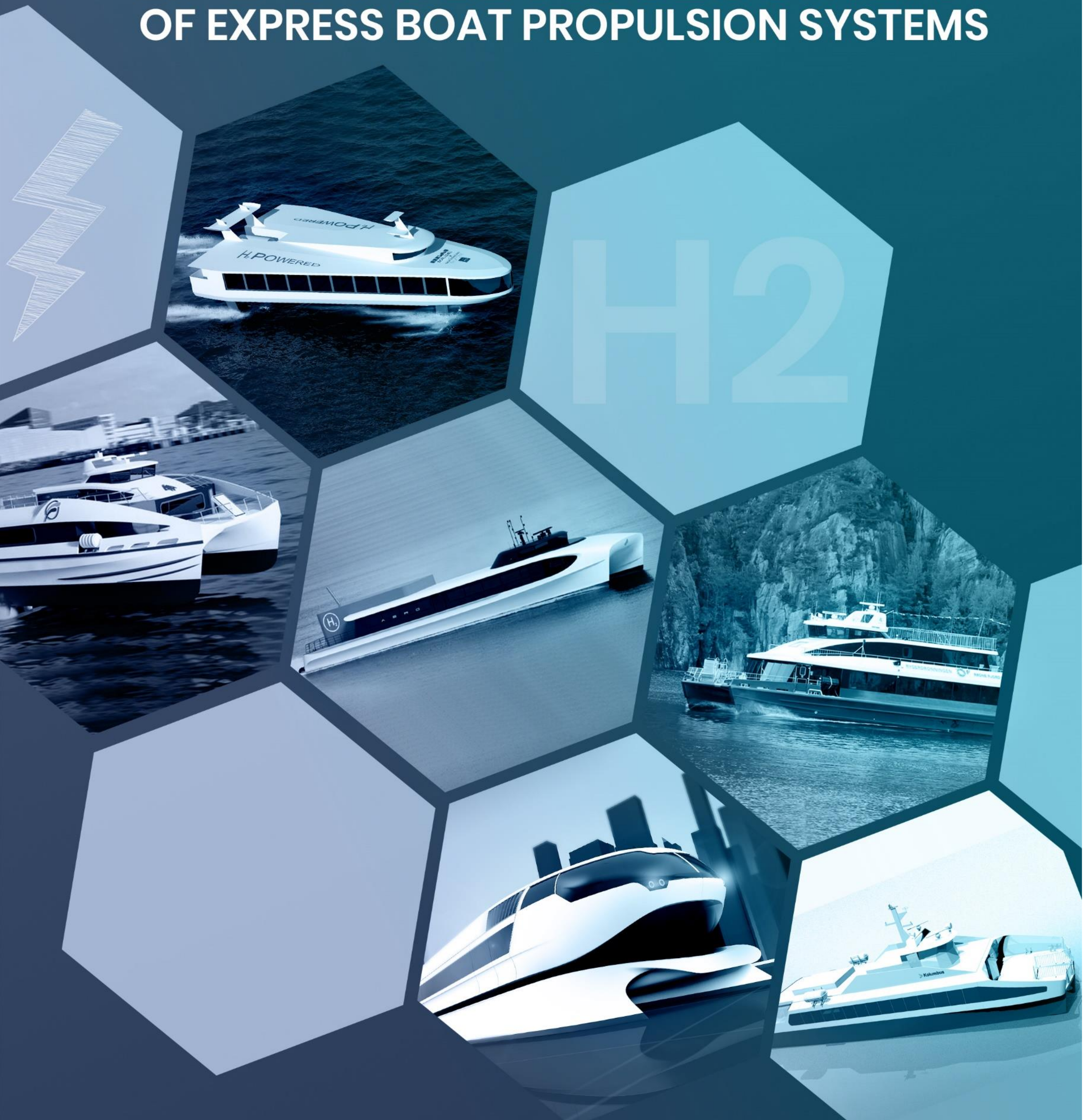
LIFE CYCLE ASSESSMENT
OF EXPRESS BOAT PROPULSION SYSTEMS



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Summary

The adoption of alternative propulsion systems in express boats may offer greenhouse gas (GHG) emission reductions, but a life cycle perspective is required to obtain the complete emissions picture as emissions arise both upstream and downstream of the use phase. Addressing this topic, NCE Maritime CleanTech has requested Asplan Viak AS to do a comparative life cycle assessment (LCA) study of alternative express boat propulsion systems. The goal of the study was to estimate and compare the life cycle GHG emissions of various propulsion systems that may be used to motor an express boat. LCA was used to estimate cradle-to-grave emissions of 15 alternative propulsion systems for a fictitious express boat. Two wide categories of propulsion technologies were considered for the boat: internal combustion engine and electric motor. The cradle-to-grave GHG emissions were calculated for a 10-year period of operation and considered the most relevant components as well as fuels and energy carriers. Thus, the functional unit of the studied propulsion systems was set to the service life of ten years. Because the various technology options are at different technology readiness levels, the preliminary results are associated with some uncertainty; data uncertainty is higher for novel and emerging technologies. For these technologies, the most important uncertainty aspects were evaluated in a robustness analysis. The uncertainty is particularly significant with respect to the estimated energy use and battery size for the battery electric propulsion system. Decision makers should be particularly cautious regarding the uncertainty of the preliminary results for the battery electric propulsion system. While the electric propulsion systems show great potential as a measure to reduce GHG emissions from express boats, both the battery electric and hydrogen electric propulsion systems have low gravimetric and volumetric energy densities, which may limit their applicability in express boats. Both ammonia and hydrotreated vegetable oil (HVO) are alternative fuels for combustion engines that may offer lower lifecycle GHG emissions compared to MGO, but their emissions profile strongly depends on their production pathways. For HVO, the limited supply may also be an issue. The preliminary results should be viewed as an indication of expected life cycle GHG emissions of the various propulsion systems rather than a final answer as there is significant uncertainties associated with the results. Even so, the results provide useful insights and highlighted important aspects pertaining to the life cycle GHG emissions of alternative propulsion systems for express boats.

PREFACE

This report is produced by Asplan Viak AS commissioned by NCE Maritime CleanTech. The report considers greenhouse gas emissions of various express boat propulsion systems for a given case study. The analysis will provide early insights of propulsion systems at different stages of technology readiness levels.

The analysis and report were prepared by Linda Ager-Wick Ellingsen. Internal quality assurance was performed by John Ingar Jenssen and Erik Skontorp Hognes.

The project was done in cooperation with NCE Maritime CleanTech represented by Hege Økland and Norled represented by Ivan Østvik. In addition to Hege Økland and Ivan Østvik, Tore Boge in NCE Maritime CleanTech and Bjørn Sundland in BKK provided inputs to the report. Brødrene Aa, Corvus Energy, and ZEM are relevant industry actors that provided information for the parts of the analysis.

Trondheim, 08.07.2020

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ABBREVIATIONS

AC	Alternating current
CCS	Carbon capture and storage
C-H_2 (Nordic)	Compressed hydrogen gas produced through electrolysis using the Nordic electricity mix
C-H_2 (Norwegian)	Compressed hydrogen gas produced through electrolysis using the Norwegian electricity mix
C-H_2 (SMR + CCS)	Compressed hydrogen gas produced through steam methane reformation with carbon capture and storage
CO_2-eq	Carbon dioxide equivalent
DC	Direct current
FAME	Fatty acid methyl esters
GHG	Greenhouse gas
HVO	Hydrotreated vegetable oil
IMO	The International Maritime Organization
kWh	kilowatt hour
LCA	Life cycle assessment
L-H_2 (Nordic)	Liquid hydrogen produced through electrolysis using the Nordic electricity mix
L-H_2 (Norwegian)	Liquid hydrogen produced through electrolysis using the Norwegian electricity mix
L-H_2 (SMR + CCS)	Liquid hydrogen produced through steam methane reformation with carbon capture and storage
Li-ion	Lithium-ion
MGO	Marine gasoil
NH_3 (Nordic)	Ammonia based on hydrogen produced through electrolysis using the Nordic electricity mix
NH_3 (Norwegian)	Ammonia based on hydrogen produced through electrolysis using the Norwegian electricity mix
NH_3 (SMR + CCS)	Ammonia based on hydrogen produced through steam methane reformation with carbon capture and storage
NTP	National Transport Plan
PEMFC	Proton exchange membrane fuel cells
SMR	Steam methane reformation

1. INTRODUCTION

After more than a century and a half of industrialization, deforestation, and large scale agriculture, quantities of greenhouse gases (GHG) in the atmosphere have risen to record levels not seen in three million years[1]. By quickly releasing massive amounts of carbon that would otherwise release slowly into the atmosphere over millions of years, humans have induced a major perturbation in the carbon cycle. The increase of carbon in the troposphere causes anthropogenic climate change, which is expected to have severe consequences on human health and ecosystems[2,3].

The Paris Agreement brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects[4]. 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 emissions by at least 40 % by 2030 compared to 1990 levels[5]. According to the Paris Agreement, each country must submit new or updated Nationally determined contributions every five years. Norway was one of 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.

The transport sector is the largest source of direct GHG emissions in Norway, with nearly one third of total national emissions[6]. The National Transport Plan (NTP) aims to facilitate significant GHG emission reductions for the transport sector. According to the current NTP, the Government aims for use of biofuels or so-called "low- or zero emission vessels" in 40% of all short sea shipping[7]. 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[7]. In the Green Shipping Action Plan, the Norwegian government has stated that emission for inland shipping shall be reduced by 50% within 2030[8].

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 the same year (2050).

The adoption of alternative propulsion systems may offer GHG emission reduction, but as emissions arise in both upstream and downstream processes a life cycle perspective is required to obtain a complete picture of the GHG emissions. Addressing this issue, NCE Maritime CleanTech has requested Asplan Viak AS to do a comparative life cycle assessment (LCA) study of alternative express boat propulsion systems.

The goal of the study was to estimate and compare the life cycle GHG emissions of various propulsion systems that may be used to motor an express boat. LCA was used to estimate the cradle-to-grave emissions of 15 alternative propulsion systems, as requested by NCE Maritime CleanTech.

This report is organized into five main chapters. This introductory chapter establishes the background and motivation for the report and formulates the overarching aim. Chapter 2 describes the conceptual basis and method. Chapter 3 provides information about the case study and presents the inventory data used in the analysis. Chapter 4 presents the results of the main analysis as well as a robustness analysis. Finally, Chapter 5 discusses the results and concludes the study.

2. LIFE CYCLE ASSESSMENT - METHOD AND PROCEDURE

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[9]. The European Commission describes LCA as *"the best framework for assessing the potential environmental impacts of products currently available"*[10] and governments all over the world encourage its use[11]. 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"*[12], it can also be described as the whole procedure for how such studies are performed and interpreted[13]. 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 1).

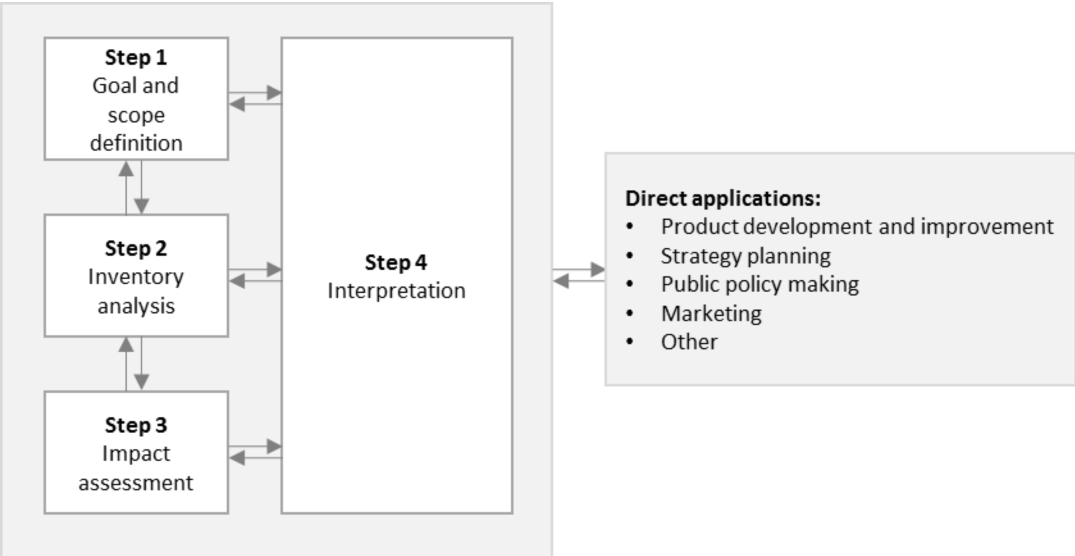

Figure 1 Phases of a Life Cycle Assessment after ISO 14040[12]

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[13]. 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[14]. This step also calculates the environmental loads of the system under study in relation to the functional unit[13].

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[9]. 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 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[15]. In particular, the comprehensive nature of an LCA makes it costly and time intensive to perform[9,16–18]. 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[13].

3. SYSTEM DESCRIPTION AND INVENTORY ANALYSIS

The goal of the study was to estimate and compare the life cycle GHG emissions of various propulsion systems that may be used to motor an express boat. The analysis considers various options for the propulsion system of a fictitious express boat. 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. Even so, the preliminary results will provide insightful information and highlight important aspect pertaining to the life cycle GHG emissions of various express boat propulsion technologies.

The cradle-to-grave GHG emissions were calculated for a 10-year period of operation and considered the most relevant 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.

Sub-chapter 3.1 provides information about the case study, 3.2 describes the different propulsion technologies and the scenarios considered in the analysis, while sub-chapter 3.3 provides an overview of the emission factors used for the different components and fuels or energy carriers. Finally, sub-section 3.4 describes the robustness analysis.

3.1. Case study – operational profile

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 fictional 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 2.

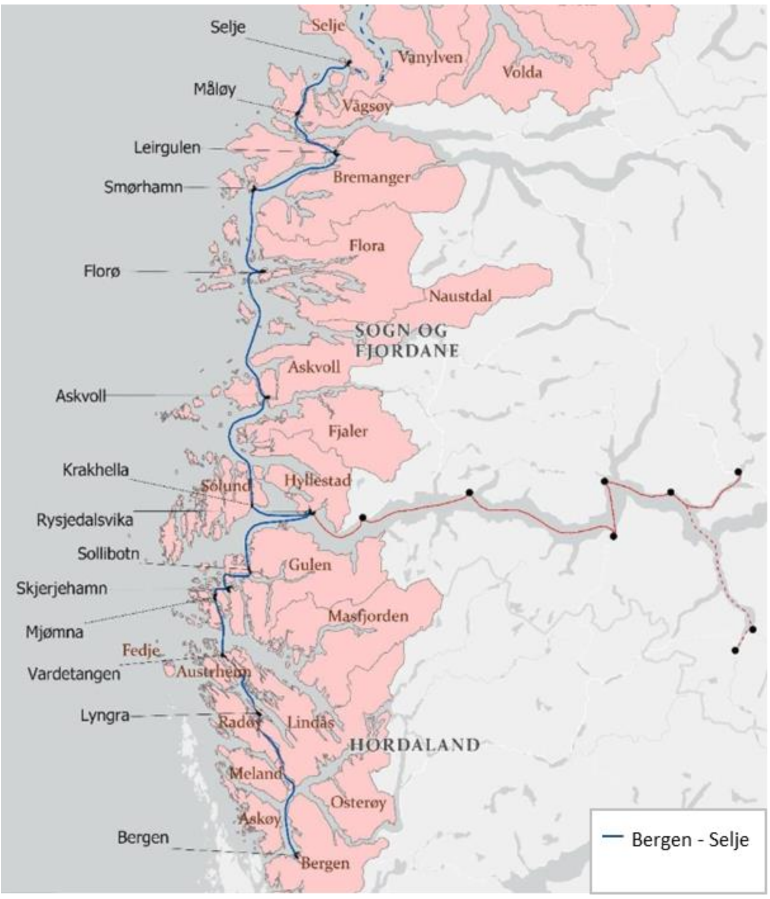

Figure 2 The route between Bergen and Selje. Figure is taken from*[19]*.

3.2. System description

Two wide categories of propulsion technologies were considered for the boat: internal combustion engine and electric motor. In total, 15 different express boat propulsion system scenarios were considered. The scenarios are summarized in Table 1.

Table 1 Overview of considered propulsion system alternatives

Scenario acronym	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
NH_3 (Nordic)	Liquid ammonia based on hydrogen produced through electrolysis using the Nordic electricity mix	Combustion
NH_3 (Norwegian)	Liquid ammonia based on hydrogen produced through electrolysis using the Norwegian electricity mix	Combustion
NH_3 (SMR + CCS)	Liquid ammonia based on hydrogen produced through steam methane reformation with carbon capture and storage	Combustion
Battery (Nordic)	Nordic electricity mix for charging Li-ion battery	Electric
Battery (Norwegian)	Norwegian electricity mix for charging Li-ion battery	Electric
L-H_2 (Nordic)	Liquid hydrogen produced through electrolysis using the Nordic electricity mix for use in PEMFC	Electric
L-H_2 (Norwegian)	Liquid hydrogen produced through electrolysis using the Norwegian electricity mix for use in PEMFC	Electric
L-H_2 (SMR + CCS)	Liquid hydrogen from steam methane reformation with carbon capture and storage for use in PEMFC	Electric
C-H_2 (Nordic)	Compressed hydrogen produced through electrolysis using the Nordic electricity mix for use in PEMFC	Electric
C-H_2 (Norwegian)	Compressed hydrogen produced through electrolysis using the Norwegian electricity mix for use in PEMFC	Electric
C-H_2 (SMR + CCS)	Compressed hydrogen from steam methane reformation with carbon capture and storage for use in PEMFC	Electric

The analysis considered the production and use of the fuels and energy carriers, onboard fuel tanks, combustion engines, batteries, fuel cells, inverters, and electric motors. In addition, disposal of the fuel tanks, engines, batteries, fuel cells, power converters, and motors were also considered. Thus, the analysis was performed as a cradle-to-grave analysis.

The two main types of propulsion technologies considered in this study are described in the next two sections.

3.2.1. The combustion-based propulsion systems

In the combustion-based propulsion systems, a fuel is combusted in an internal combustion engine that generates mechanical work for propulsion. Figure 3 provides an overview of the combustion-based propulsion system, while the text below considers the system in more detail.

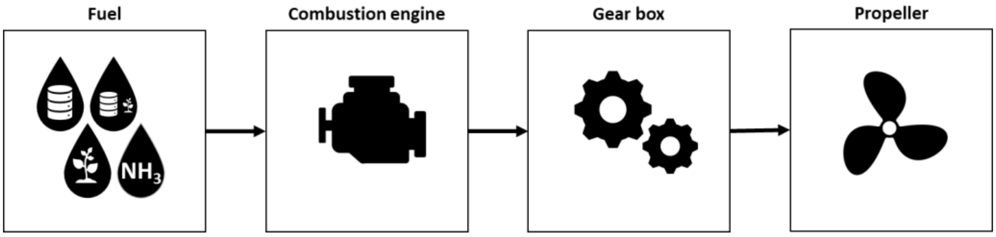

Figure 3 The combustion-based propulsion system

In the combustion-based propulsion system, energy is provided through the combustion of a fuel. Both marine gasoil (MGO), biodiesel – a fuel where fossil diesel is blended with fatty acid methyl esters (FAME), hydrotreated vegetable oils (HVO), and liquid ammonia were considered in this study. The fuel is stored in a fuel tank and supplied to the internal combustion engine during use. For the MGO and the biofuels the fuel tank is likely to be designed as an integral part of the boat's hull, while cryogenic tanks were assumed for the liquid ammonia.

For the analysed fuels, different ignition techniques may be employed in the engine. Both MGO, biodiesel, and HVO are typically injected directly to a combustion chamber where the fuel is ignited through compression. Using ammonia in conventional internal combustion engines is challenging due to its poor fuel properties and specially designed engines are required[20]. 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 without the addition of a pilot fuel in a compression engine because the pilot fuel use will be marginal compared to the ammonia use and likely to have minute effect on the total life cycle emissions.

Once the fuel is ignited, the combustion engine produces mechanical energy. The rotational speed of the mechanical work is reduced through a gear box before it supplies mechanical work at a lower rpm to a controllable pitch propeller.

3.2.2. The electric propulsion systems

In the electric propulsion system, electricity is provided from an electrochemical device to an electric motor that generates mechanical work for propulsion. Figure 4 provides an overview of the electric propulsion system, while the text below considers the system in more detail.

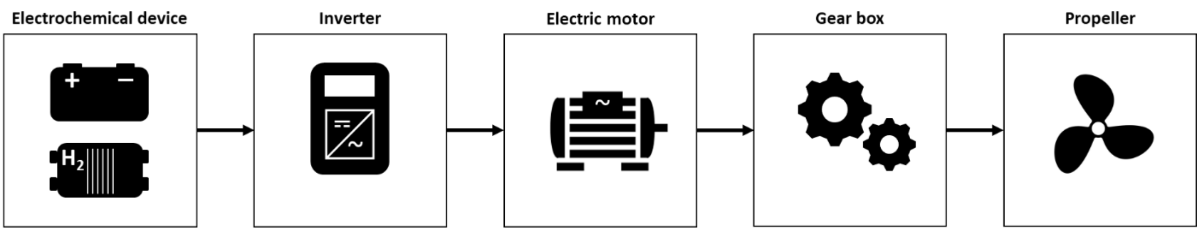

Figure 4 The electric propulsion system

In the electric propulsion system, energy is supplied from an electrochemical device. Both a lithium-ion (Li-ion) battery and a hydrogen proton exchange membrane fuel cell (PEMFC) were considered in this study.

The boat using a PEMFC for energy supply requires hydrogen storage tanks. Liquid hydrogen is stored in cryogenic tanks at -253°C at ambient pressure[21]. The advantage for the cryogenic liquefied hydrogen is that it has a considerably higher energy content per unit of volume than compressed hydrogen gas, and consequently it requires less storage space[21]. Both compressed hydrogen gas and liquid hydrogen were considered in the analysis. Because PEMFCs operate best under an even load, the PEMFC propulsion system also requires an auxiliary Li-ion battery.

The battery powered boat does not require a tank, but it was assumed that an onshore battery and power converter for charging in Selje was required as the layover is only two hours. It was assumed that the onshore battery pack was 26% smaller than the onboard battery pack. Note that potential reuse of the battery packs for second life applications after ten years of operation was not considered in the analysis.

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). Note that the PEMFC delivers low voltage current and therefore the power converter must also increase the voltage coming from the PEMFC. The inverter controls the voltage fed to the electric motor through switching devices.

The permanent magnet AC electric motor converts the electrical energy to mechanical energy. As in the combustion-based propulsion system, the rotational speed of the mechanical work is reduced through a gear box before it supplies mechanical work at a lower rpm to a controllable pitch propeller.

3.2.3. Processes considered to be outside of the system boundary

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.

Any auxiliary motors and generators required to produce electricity for non-propulsive energy were not considered for any of the propulsion systems as this study was solely concerned with the propulsion. Similarly, the batteries are dimensioned solely with respect to propulsion and not to deliver electricity for non-propulsive applications.

Onshore infrastructure required for the various propulsion systems were not considered in the analysis. Thus, potential establishment of onshore fuel storage tanks, battery charger, 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. Similarly, the battery charger was only considered with respect to its efficiency.

Although the various propulsion systems that were considered in the analysis will have different maintenance requirements, maintenance of the propulsion systems were omitted in the analysis. Studies assessing fossil and electric passenger vehicles report that maintenance do not cause any significant emissions[22–24]. A similar situation is likely to be the case for the express boats. Thus, maintenance was omitted as emissions are likely to be negligibly low and data collection may be impractically demanding[25].

3.3. Inventory data

Primary data were collected to compile life cycle inventories for parts of the analysis where such data were obtainable, but the study also relies on LCA data and results from previous studies and the *ecoinvent* database. To protect proprietary data, only the emission factors and the total energy use assumed in the analysis will be presented here. However, Appendices A-C provide further information about components (Appendix A), fuels and energy carriers (Appendix B), and energy use and efficiency (Appendix C). Appendix A and B also describe how the emissions factors of the components and the fuels and energy carriers were determined, respectively. In addition, Appendix

D considers uncertain data that were examined in the robustness analysis. To be consistent with the attributional approach taken in the analysis, "cut-off by classification" processes were selected when using data from the *ecoinvent* database.

The next sections present a summary of the emission factors used in the analysis. An emission factor is a coefficient quantifying the emissions for a given product or activity. For example, an emissions factor for a component could be expressed in terms of kg CO_2-eq/kg and for a fuel it could be expressed in terms of kg CO_2-eq/MJ. Multiplying the emission factor by the amount (e.g., kg or MJ) of a given product or activity calculates the GHG emissions associated with the product of activity.

3.3.1. Production of propulsion system components

Table 2 presents the cradle-to-gate emission factors associated with component production. More information about the components and the emission factors can be found in Appendix A.

Table 2 Summary of cradle-to-gate emission factors for components

Component	**Production emission factor (kg CO_2-eq/kg)**	**References**
Combustion engine	3.3	Average of Hawkins et al.[22] and Ellingsen[26]
Battery	15.7	Current study (data from Brødrene Aa, Corvus Energy and Ellingsen et al.[27–29])
Inverter	4.4	*ecoinvent* 3.5 database[30]
PEMFC	10.8	Estimated based on Usai et al.[31]
Electric motor	7.1	Average of Nordelöf et al.[32] and Hawkins et al.[33]
Composite fuel tanks	21.0	Usai et al.[31]
Cryogenic fuel tanks	17.1	Current study (data from Usai et al.[31] and *ecoinvent* 3.5 database[30])
Converter	4.4	ABB[34]

The composite fuel tanks are used for MGO, biodiesel, HVO, and compressed hydrogen, while the cryogenic tanks are used for liquid ammonia and liquid hydrogen. 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 emissions than the composite fuel tanks. While three cryogenic tanks are required for the liquid hydrogen propulsion system, nine composite fuel tanks are required for the compressed hydrogen propulsion system. For the ammonia propulsion system, it was assumed that two smaller cryogenic tanks that provide the same total storage volume as 1.5 cryogenic tank for liquid hydrogen was used for liquid ammonia storage.

3.3.2. Use phase

The use phase emissions are a product of the energy use and the emission factors of the energy. This section first considers the round-trip energy demand, and then the emission factors of the fuels and energy carriers.

To estimate the round-trip energy demand, the effective energy use served as a starting point. The effective energy use is the effective power (vessel resistance multiplied by operating speed) times the trip duration. The effective energy demand for the battery electric propulsion case and the hydrogen electric propulsion case (with compressed hydrogen) were provided by Brødrene Aa. Note that these energy estimates include complete vessel and propulsion system weights. Thus, the battery electric propulsion case had higher effective energy demand than the hydrogen electric propulsion case due to the higher weight.

The effective energy use estimated by Brødrene Aa may be considered as an optimistic (low) energy use as Norled provided a significantly higher estimate for the same route. To ensure consistency with the effective energy use for the hydrogen propulsion system (and the combustion-based propulsion systems), the lower energy estimate provided by Brødrene Aa was applied in the main analysis. The higher energy use provided by Norled was applied in the robustness analysis (described in Appendix D, section D.2 on page 46) and the results are shown in sub-section 4.2.2.

It was assumed that the propulsion system with liquid hydrogen tanks had the same effective energy use as the propulsion system with compressed hydrogen because these two propulsion systems weigh about the same. The effective energy demand for the combustion-based propulsion cases were estimated based on findings from the CatRES method[35]. Based on these findings, it was estimated that compared to the hydrogen propulsion system the MGO, biodiesel, and HVO propulsion systems had 5.7% lower energy demand and that the ammonia propulsion system had 4.1% lower effective energy demand due to their lower weights.

The total operational energy demand was calculated by dividing the estimated effective energy use by the energy conversion efficiency. Note that for the battery propulsion system, onshore efficiency losses were also considered. Detailed information regarding the estimations and assumptions regarding energy use and efficiencies can be found in Appendix C, while Table 3 summarizes the total energy demand in terms of kilowatt hour (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 3 Round-trip energy demand

		Combustion		Electric	
		Fossil/biofuel	NH_3	Battery	PEMFC
Round-trip energy use	kWh	46 669	53 883	33 758	35 954

The electric propulsion systems have lower round-trip energy use compared to the combustion-based propulsion systems. Note that any the waste heat deriving from energy conversion in the combustion engine, PEMFC, or battery that may potentially be used for onboard heating was not considered in the analysis as it is outside the system boundary (i.e., boat propulsion). Use of this heat may reduce the energy requirement for heating onboard the boats, particularly for the combustion-based boat. The higher energy use of the ammonia fuelled propulsion system compared to the fossil and biofuel propulsion systems stems from the assumed lower conversion efficiency of the ammonia combustion engine as well as slightly higher effective energy use due to its comparatively higher weight stemming from the cryogenic fuel tanks.

To estimate the GHG emissions connected with the operation, emission factors for the various fuels and energy carriers were established. A literature review was performed to establish representative fuel cycle emission factors for the various fuels and energy carriers. The fuel cycle considers the entire value chain of the fuels and energy carriers at each stage from energy resource extraction, production, distribution, and conversion (for conventional fuels, this is commonly referred to as well-to-wake emission factors). This ensures consistent system boundaries whether it is fossil fuels, biofuels, electricity, or hydrogen.

Table 4 provides a summary of the fuel cycle (well-to-wake) emission factors used in the analysis. More information about the fuels and energy carriers and their emissions factors can be found in Appendix B. Some of the emission factors are taken directly from the cited study while others are estimated in the current study based on data from previous studies.

Table 4 Summary of fuel cycle emission factor for fuels and energy carriers.

Fuel/energy carrier	Fuel cycle emission factor ($g\ CO_2$-eq/MJ)	Reference
MGO	86.4	Average value (based on El-Houjeiri et al.[36], Thinkstep[37], and Bengtsson et al.[38])
Biodiesel	89.6	Current study (data from JEC Alternative fuels[39])
HVO (without indirect land use change emissions)	24.4	JEC Alternative fuels[39]
HVO (with indirect land use change emissions)	41.6	Current study (data from JEC Alternative fuels[39] and Globiom[40])
Liquid ammonia (Nordic)	89.9	Current study (data from Wulf et al[41], Bicer et al.[42], Gardiner[43], Asplan Viak, and JEC WTT report[44])
Liquid ammonia (Norwegian)	43.7	Current study (data from Wulf et al[41], Bicer et al.[42], Gardiner[43], NVE[45], *ecoinvent* 3.5 database[30], and JEC WTT report[44])
Liquid ammonia (SMR with CCS)	71.6	Current study (data from Bicer et al.[42], Asplan Viak, and JEC WTT report[44])
Electricity (Nordic)	31.1	Asplan Viak
Electricity (Norwegian)	5.9	Current study (data from NVE[45] and *ecoinvent* 3.5 database[30])
Liquid H_2 (Nordic)	57.8	Current study (data from Wulf et al[41], Bicer et al.[42], Asplan Viak, JEC WTT report[44], and Koroneos et al.[46])
Liquid H_2 (Norwegian)	11.3	Current study (data from Wulf et al[41], Bicer et al.[42], Asplan Viak, JEC WTT report[44], and Koroneos et al.[46])
Liquid H_2 (SMR with CCS)	55.7	Current study (data from Bicer et al.[42], Asplan Viak, and JEC WTT report[44])
Compressed H_2 (Nordic)	51.0	Current study (data from Wulf et al[41], Bicer et al.[42], Gardiner[43], Asplan Viak, and JEC WTT report[44])
Compressed H_2 (Norwegian)	10.6	Current study (data from Wulf et al[41], Bicer et al.[42], Gardiner[43], NVE[45], *ecoinvent* 3.5 database[30], and JEC WTT report[44])
Compressed H_2 (SMR with CCS)	35.0	Current study (data from on JEC WTT report[44])

Biodiesel has a higher emission factor than MGO because diesel, which is the main fuel in biodiesel, has a higher emission factor than MGO as diesel is further refined than MGO, resulting in higher well-to-tank emissions. For HVO, the analysis considers both the exclusion and inclusion of potential emissions due to indirect land use change (ILUC). When the production of biofuel feedstocks take place on agricultural land, the demand for food and feeds crop remain and may lead to conversion of pristine land areas, consequently resulting in ILUC in another location. Only first-generation feedstocks (e.g., rapeseed, palm, and soy) are affected by ILUC, while advanced feedstocks (e.g., waste animal fats and agricultural waste) are not subject to ILUC emissions. Note that ILUC emissions are very uncertain, both with respect to whether they arise and by how much. In the analysis, it was assumed that the inclusion of ILUC emissions would double the emission factor for first generation feedstocks (more information can be found in Appendix B, section B.3.).

3.3.3. End-of-life treatment of propulsion system components

End-of-life treatment was considered as decommissioning through disposal. Thus, the estimated emissions are limited to the process of disposing of the component, while subsequent recycling processes to recover the materials were excluded. In line with this system boundary and the attributional LCA approach[47], the components were not ascribed any credits for potentially supplying recycled materials to the market (which may substitute virgin materials that have higher emission factors than recycled materials).

Table 5 presents the emission factors associated with component disposal. A detailed overview of the emission factors can be found in Appendix A.

Table 5 Summary of end-of-life emission factors for components

Component	Disposal emission factor (kg CO_2-eq/kg)	Data references
Combustion engine	0.7	The Bureau of International Recycling[48]
Battery	0.9	*ecoinvent* 3.5 database[30]
Inverter	0.3	*ecoinvent* 3.5 database[30]
PEMFC	0.5	*ecoinvent* 3.5 database[30]
Electric motor	0.7	The Bureau of International Recycling[48]
Composite fuel tanks	1.7	Meng et al.[49]
Cryogenic fuel tanks	1.7	Meng et al.[49]
Converter	0.3	*ecoinvent* 3.5 database[30]

As for production of fuel tanks, per tank the cryogenic tank has higher disposal emissions than the composite fuel tanks as the cryogenic tank is heavier than the composite fuel tanks.

3.4. Robustness analysis

Some of the data used in the analysis entail uncertainty, particularly for novel and emerging technologies. Some of the most important parameters for the various propulsion systems were considered in a robustness analysis. Table 6 provides a brief description of the evaluated aspects, while Appendix D provides further details.

Table 6 Particularly uncertain aspects evaluated in the robustness analysis

Propulsion system	Evaluated aspects
NH_3	• Efficiency of internal combustion engine
Battery	• Energy use and source in battery cell manufacture • No need for onshore battery pack at dock in Selje • One replacement of onboard battery • Higher effective energy use and larger battery pack (data provided by Norled)
Hydrogen	• Efficiency of fuel cell

4. RESULTS

The results of the main analysis as well as the robustness analysis are presented in this chapter. The life cycle GHG emissions associated with the main analysis is presented in Section 4.1 and the robustness analysis in Section 4.2.

4.1. Main analysis

The life cycle (cradle-to-grave) GHG emissions are presented in terms of emissions associated with propulsion system production, use, and disposal. Figure 5 presents the life cycle GHG emissions for the examined alternatives. In the figure, emissions stemming from the production of the propulsion systems are grey, use phase emissions are blue, and emissions from disposal of the propulsion systems are green. Recall that for all propulsion systems, the use phase considers energy resource extraction, production, distribution, and conversion (well-to-wake emissions).

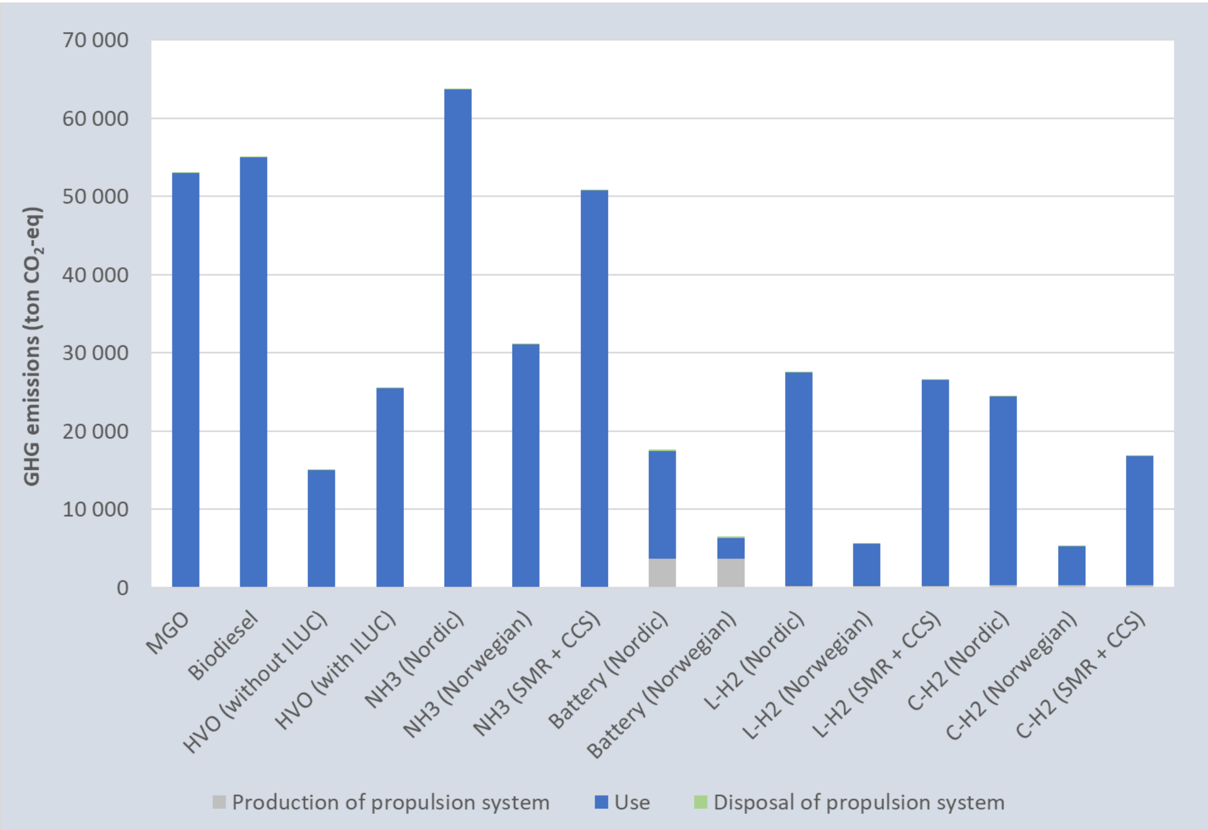

Figure 5 Life cycle GHG emissions distributed over production of propulsion system, use phase, and disposal of propulsion system.

Abbreviations: MGO – marine gasoil, HVO (without ILUC) – hydrotreated vegetable oil without estimations of indirect land use change emissions, HVO (with ILUC) – hydrotreated vegetable oil with estimations of indirect land use change emissions, NH3 (Nordic) – liquid ammonia based on hydrogen produced through electrolysis using the Nordic electricity mix, NH3 (Norwegian) – liquid ammonia based on hydrogen produced through electrolysis using the Norwegian electricity mix, NH3 (SMR + CCS) – liquid ammonia based on hydrogen produced through steam methane reformation with carbon capture and storage, L-H2 (Nordic) - liquid hydrogen produced through electrolysis using the Nordic electricity mix, L-H2 (Norwegian) - liquid hydrogen produced through electrolysis using the Norwegian electricity mix, L-H2 (SMR + CCS) – liquid hydrogen produced through steam methane reformation with carbon capture and storage, C-H2 (Nordic) – compressed gaseous hydrogen produced through electrolysis using the Nordic electricity mix, C-H2 (Norwegian) – compressed gaseous hydrogen produced through electrolysis using the Norwegian electricity mix, C-H2 (SMR + CCS) – compressed gaseous hydrogen produced through steam methane reformation with carbon capture and storage.

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.

For the combustion-based propulsion systems, most of the life cycle emissions are associated with the use phase, which contributes to 99.7-99.9% of the total emissions. Biodiesel primarily consists of diesel with a 5% v/v FAME, and because diesel has a higher emission factor than MGO, biodiesel ends up having a higher emission factor than MGO. Note that the combustion emissions associated with FAME (in biodiesel) and HVO are offset by the renewable credit given to biofuels due to the capture of carbon dioxide during the growth stage of the plants (as described in Appendix B.2. and B.3., respectively).

The use phase emissions of HVO solely reflects upstream emissions associated with fuel production. The total life cycle emissions of the HVO propulsion system were calculated both with and without ILUC emissions. The inclusion of potential ILUC emissions raised the life cycle emissions by 70% compared to the exclusion of ILUC emissions.

Use phase emissions associated ammonia stems solely from the production of the fuel as the combustion of ammonia does not result in GHG emissions. The three ammonia pathways considered in this analysis yield strikingly different results. Ammonia based on hydrogen from electrolysis using the Norwegian electricity mix (primarily based on hydropower) yields the lowest ammonia emissions of the three pathways. In contrast, using the Nordic electricity mix in the electrolysis process to produce hydrogen yields the highest ammonia emissions. The electrolysis process used to produce hydrogen is extremely energy demanding, which places restrictions on the energy sources from a GHG emissions perspective. Although the Nordic electricity mix is produced from a reasonably high share of renewables, its use in the electrolysis process results in a fairly high emission factor for the hydrogen. In comparison, ammonia produced with hydrogen from steam methane reformation (SMR) employing carbon capture and storage (CCS) is actually preferable from a climate mitigation perspective. Using ammonia based on SMR with CCS provides a similar result as the MGO-fuelled propulsion system.

For the battery electric propulsion system, the production phase contributes significantly to the total life cycle emissions. The higher production emission is primarily attributed to the battery. This is similar to what is seen in electric vehicles studies[22,28,50]. Also here, the Norwegian electricity mix shows great benefit compared to the Nordic electricity mix. Both battery propulsion systems break even with conventional MGO-fuelled propulsion system within the first year and from then on provides a comparative GHG emission benefit. As noted, there is uncertainty associated with the effective energy use (and consequently the battery size) assumed in the main analysis. Thus, the life cycle emission of the battery electric propulsion system may be higher than that presented in Figure 5. This aspect is evaluated in the robustness analysis in sub-section 4.2.2.

The results for the hydrogen propulsion system reflects the difference in hydrogen sources as noted in connection with ammonia. In terms of emissions, the transportation advantage of requiring less volume for liquid hydrogen compared to compressed gaseous hydrogen was not able to compensate for the higher energy demand from the liquification process. Consequently, liquid hydrogen had higher fuel cycle emissions than compressed hydrogen.

4.2. Robustness analysis

The robustness analysis considered a range of particularly uncertain and sensitive parameters and aspects in the analysis, as summarized in Table 6 and detailed in Appendix D.

4.2.1. Ammonia

The energy efficiency of the ammonia internal combustion engine was assumed to be 35%, which is 5% lower than internal combustion engines fuelled with MGO, biodiesel, and HVO. The lower efficiency was assumed due to the difficulties in completely combusting ammonia inside the combustion chamber[20]. The uncertainty analysis evaluates the impact that the engine efficiency has for the life cycle GHG emissions for the ammonia-based propulsion system, as shown in Figure 6 where the emissions are plotted as a function of engine efficiency. The ammonia baseline scenarios are indicated with a circle on the graph line.

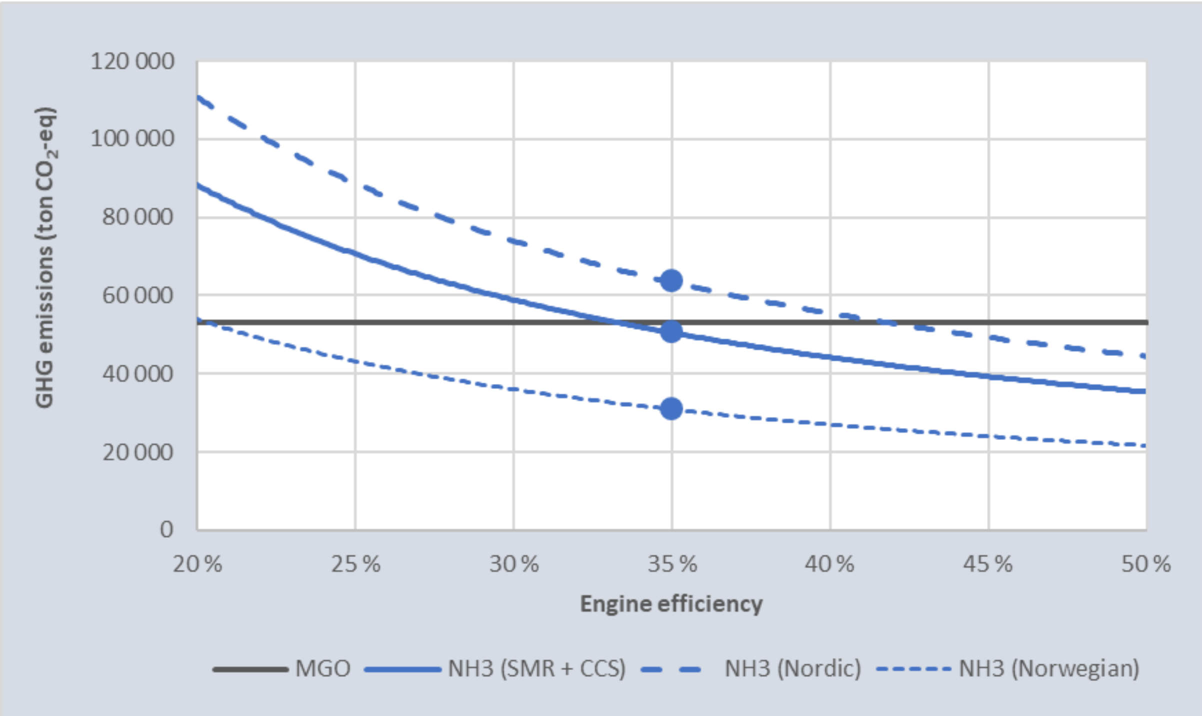

Figure 6 Uncertainty analysis of the ammonia propulsion system - emissions as a function of engine efficiency

The engine efficiency is clearly an important parameter with high sensitivity for the results. When ammonia is produced using hydrogen from electrolysis, the engine must achieve efficiencies similar to that of an engine using MGO to deliver similar results. In contrast, when ammonia is produced using hydrogen from SMR with CCS, the ammonia propulsion system may have significantly lower engine efficiency compared to the MGO propulsion system.

While Figure 6 only considers the life cycle emissions of the ammonia-based propulsion system, similar trendlines can be found for the other combustion-based propulsion systems. The trendline will flatten out and decrease with lower fuel cycle emission factors, and vice versa.

4.2.2. Battery

For the battery propulsion system, four uncertain aspects were considered: energy use and source in cell manufacture, no need for onshore battery in Selje, replacement of onboard battery, and higher effective energy use. The result of the battery uncertainty analysis is shown in Figure 7.

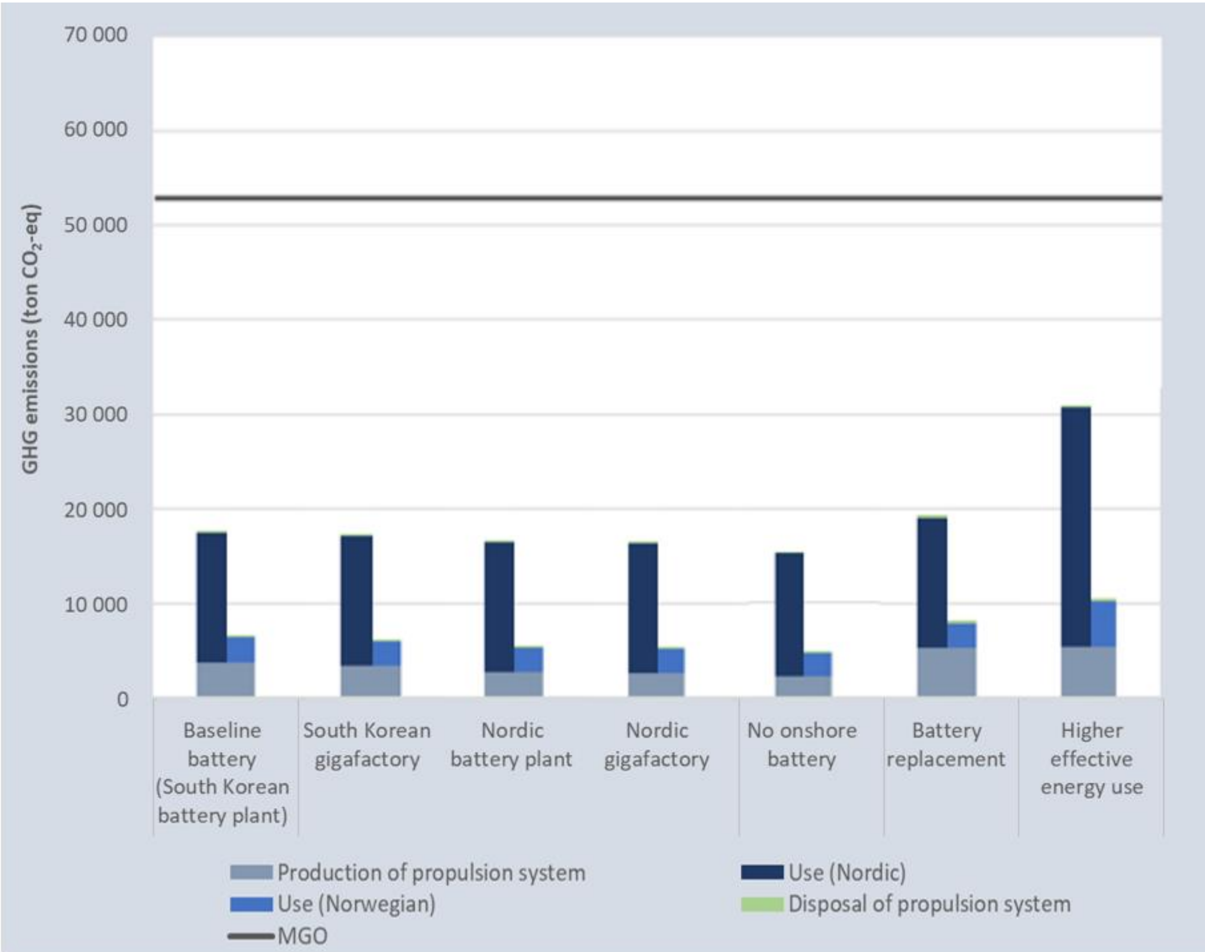

Figure 7 Uncertainty analysis of the battery propulsion system – emissions considering uncertainty aspects

The uncertainty analysis illustrates how sensitive the life cycle GHG emissions of the battery propulsion system are to various parameters. Particularly the higher effective energy use is an important aspect as it near doubles the life cycle GHG emissions.

The lower energy demand assumed for the gigafactories has particularly large effects when the more GHG emission intensive South Korean electricity mix is used compared to the lower GHG emissions intensive Nordic electricity mix is used. This implies that from a GHG emissions perspective, it is more important to establish battery cell manufacturing plants in areas with less carbon intensive electricity mixes than to replace regular sized battery plants with gigafactories to obtain energy savings (and consequently emissions savings) due to economies of scale.

If an onshore battery is not required at the dock in Selje, the total life cycle emissions of the battery propulsion system decrease by 13% when charged with the Nordic electricity mix and 26% with Norwegian electricity mix. In fact, the uncertainty analysis indicates removing the need for an onshore battery pack is more advantageous from a lifecycle GHG emissions perspective than both reducing the energy demand and lowering the carbon intensity of the electricity in battery cell manufacture.

If replacement of the onboard battery is necessary within the ten years of operation, the life cycle GHG emissions of the battery propulsion system increase by 25% and 9% with the Nordic and Norwegian electricity mixes, respectively.

The higher effective energy estimate that was provided by Norled for the study yields the highest life cycle GHG emissions of the scenarios considered in the battery uncertainty analysis. The total energy use per round-trip increased from around 34 000 kWh to 62 000 kWh. The higher energy use resulted in 46% higher production emissions and 83% higher use phase emissions. The higher production emissions were primarily due to the larger battery packs. The uncertainty analysis shows that the effective energy demand is a particularly important factor in terms of GHG emissions for the battery propulsion system as it not only affects the use phase emissions but also the cradle-to-gate emissions and to a smaller extent, also the disposal emissions.

4.2.3. PEMFC

The conversion efficiency of the fuel cell was assumed to be 60% in the hydrogen baseline scenarios. The uncertainty analysis evaluates the impact fuel cell efficiency has for the life cycle GHG emissions for the hydrogen-based propulsion systems. Figure 8 shows the total life cycle GHG emissions as a function of fuel cell efficiency for the four different hydrogen pathways considered in the analysis. The liquid hydrogen baseline scenarios are indicated with a circle on the graph line, while the compressed hydrogen baseline scenarios are indicted with a triangle.

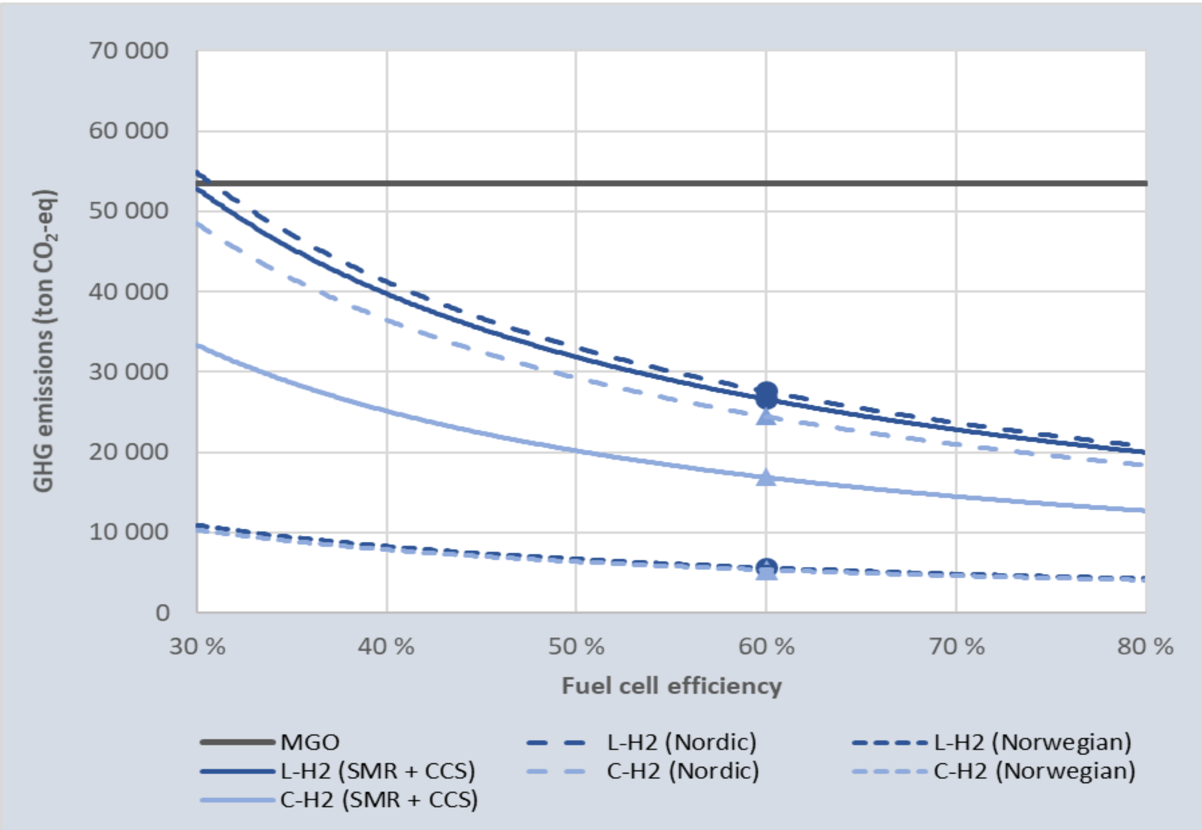

Figure 8 Uncertainty analysis of the hydrogen propulsion systems – emissions as a function of fuel cell efficiency

Under most operating conditions, the hydrogen propulsion systems offer lower life cycle GHG emissions compared to the MGO fuelled propulsion system. As the efficiency of the fuel cell increases, the emission differences among the hydrogen propulsion system becomes lower, and vice versa.

5. DISCUSSION AND CONCLUSION

The goal of the study was to estimate and compare the cradle-to-grave GHG emissions of various propulsion systems that may be used to motor an express boat. While the previous chapter presented results for the propulsion system of a fictious express boat, this chapter discusses the findings, consider the limitations, and concludes the study.

5.1. Discussion of results

The reported results have provided useful insights to the GHG emissions of alternative propulsion systems for express boats. The results should be viewed as an indication of expected life cycle GHG emissions of the various propulsion systems rather than a final answer. The robustness analysis addressed several aspects and assumptions in the main analysis that were identified as particularly important. Here, the results and the evaluated uncertainties as well as other aspects are discussed.

It is important to emphasise that the evaluated alternatives are at different technology readiness levels, which affects the data availability and certainty of the results. As such, data uncertainty in the analysis is higher for the 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.

For all propulsion systems, the efficiencies of the various propulsion system components were assumed to stay constant independent of operating conditions. In reality, the efficiencies will vary under different operating conditions, and the assumptions are therefore a source of uncertainty. The device efficiency, whether it is a combustion engine or fuel cell, has the potential to affect the life cycle emissions considerably; the effect is more prominent for fuels and energy carriers that are based on fossil sources than those based on renewable sources as the emission factor is higher for fossil sources.

For the propulsion systems fuelled by MGO, biodiesel and HVO no uncertainty analysis was done. That is not to say that there is no uncertainty associated with the results. The life cycle emissions of these propulsion system were almost entirely due to the fuel emissions, being a product of fuel use and emission factors.

For fuel use, uncertainties stem from the assumed effective energy use and engine efficiency. Compared to the compressed hydrogen propulsion case, the effective energy was estimated to be 5.7% lower for MGO, biodiesel, and HVO and 4.1% lower for the ammonia. This fuel estimate should be considered as a preliminary approximation.

Engine efficiency depends on operating conditions and engine design. The estimated engine efficiency was set based on the specific fuel consumption of the engine used in the express boat currently servicing the route. The specific fuel consumption displayed low sensitivity to load over the published operating conditions, indicating that the engine efficiency only changes moderately under different operating conditions.

Uncertainty may also arise from the fuel cycle (well-to-wake) emission factors. The emission factor of 86.4 g CO_2-eq/MJ for MGO was calculated as the average value from three studies[36–38]. The different values from the various studies may stem from uncertainties in the original studies, but it may also reflect the variability in upstream emissions associated with crude oil extraction[51]. For the biofuels there are uncertainties associated with ILUC emissions. The inclusion of ILUC emissions has a limited effect on the biodiesel emission factor as only 5% v/v of the fuel is based on FAME, but for HVO there is significant uncertainty associated with the potential emissions stemming from ILUC associated with first-generation feedstocks. The uncertainty and lack of scientific agreement associated with ILUC models makes it challenging to estimate potential ILUC emissions[40]. Here, the ILUC emissions were considered in rudimentary manner by doubling the emission factor of first-generation feedstocks, raising the life cycle GHG emissions of the HVO-based propulsion system from approximately 15 000 ton CO_2-eq to 26 000 ton CO_2-eq. Note that less conservative assumptions regarding ILUC emissions can lead to even higher life cycle emissions for the HVO-fuelled propulsion system.

It should also be highlighted that HVO supply cannot be guaranteed. A forthcoming report has estimated the HVO availability in Europe currently and towards 2030 and find that its supply is limited[39]. By choosing the HVO-fuelled propulsion system, one might run the risk of having to replace HVO with fossil fuels, which would significantly reduce the climate mitigation potential. Due to the high uncertainty associated with the results and the limited supply, the use of HVO may not be as attractive as the results portrayed in Figure 5 indicate.

For the ammonia-based propulsion system, incomplete combustion of ammonia is a challenge that entails further uncertainty. While the complete combustion causes no GHG emissions, incomplete combustion can result in the formation and emission of the potent climate gas nitrous oxide (N_2O)[20,52]. While the potential formation and emission of nitrous oxide constitutes a significant uncertainty, a quantitative uncertainty analysis of this issue was outside the scope of this study. The production pathway is also an important factor pertaining to the ammonia-based propulsion system. If ammonia is to be considered as a potential transportation fuel from a climate mitigation perspective, one must ensure that hydrogen pathways with sufficiently low carbon emissions are used (e.g. electrolysis using electricity from renewables or production technologies with CCS)[53]. As the electrolysis process is very energy demanding, one must use electricity from low carbon sources such as renewables to obtain a GHG emission benefit compared to the production route using SMR with CCS.

The emission profile of the battery electric propulsion system differs from the other alternatives. For most of the considered propulsion system, the use phase emissions were the dominant source of life cycle emissions. For the battery propulsion system, however, the battery production emissions contributed with as much 20% and 55% of the total life cycle emissions when charged with the Nordic and Norwegian electricity mixes, respectively. As such, the uncertainties associated with the battery are of great importance. The most important aspects were considered in the battery uncertainty analysis, which showed that the results were highly sensitive to the evaluated aspects. While there is also uncertainty associated with the battery energy efficiency, which was set to 90%, it was not evaluated in an uncertainty analysis as the emission factors of the electricity mixes were relatively low. However, one should be aware that a lower energy efficiency will increase life cycle emissions of the battery-based propulsion system and that a higher efficiency will decrease the emissions.

For the battery propulsion case, two strikingly different effective energy demand numbers were supplied by Brødrene Aa and Norled. In the main analysis, the lower effective energy use was assumed as this ensured congruency with the effective energy use for the hydrogen propulsion case (as well as the effective energy use for the combustion-based propulsion systems cases). In the uncertainty analysis, the higher energy use was considered, which provided a near doubling of the life cycle GHG emissions. This clearly emphasises the uncertainty associated with the preliminary results for the battery electric propulsion system. As the effective energy use and battery size in both cases were estimated based on a fictitious boat, it is impossible within the scope of the LCA study to determine what estimate is more representative for an actual express boat intended for this specific route. The non-linear correlation between weight and effective energy use may result in ever increasing battery size to fulfil the energy use, thereby preventing the realization of the battery electric propulsion system. This is an important issue that is challenging to properly address in simplified vessel resistance models commonly used to predict effective energy use.

For the hydrogen propulsion system, one of the most important sources of uncertainty stems from the fuel cell energy conversion efficiency. The conversion efficiency was found to be more important when hydrogen had a higher fuel cycle emission factor. As for the battery, there is also uncertainty associated with the durability and lifetime of the fuel cell, predominantly due to catalyst poisoning from impurities in the hydrogen as well as dissolution and agglomeration[54]. Because the production emissions of the PEMFC only contributed to 0.3-1.6% of total life cycle emission, potential replacement requirements will not significantly distort the emission profile of the hydrogen propulsion systems. Challenges associated with transport and storage of hydrogen were not considered in the LCA study. Storage of hydrogen for marine use will require specially designed storage tanks, and there is currently limited experience with marine storage and use of hydrogen[55]. Hydrogen storage is an important challenge that must be overcome to make hydrogen a suitable alternative for express boat applications.

5.2. Limitations

The LCA study considered and compared various propulsion system alternatives. 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.

The differences in energy densities among the different propulsion systems were considered as far as possible given. The relationship between gravimetric and volumetric energy density of various fuels and energy carriers are shown in Figure 9.). Note that compared to liquid fuels both the battery and hydrogen propulsion systems have relatively low gravimetric and volumetric energy densities when the storage systems are considered, as indicated by the arrows[56].

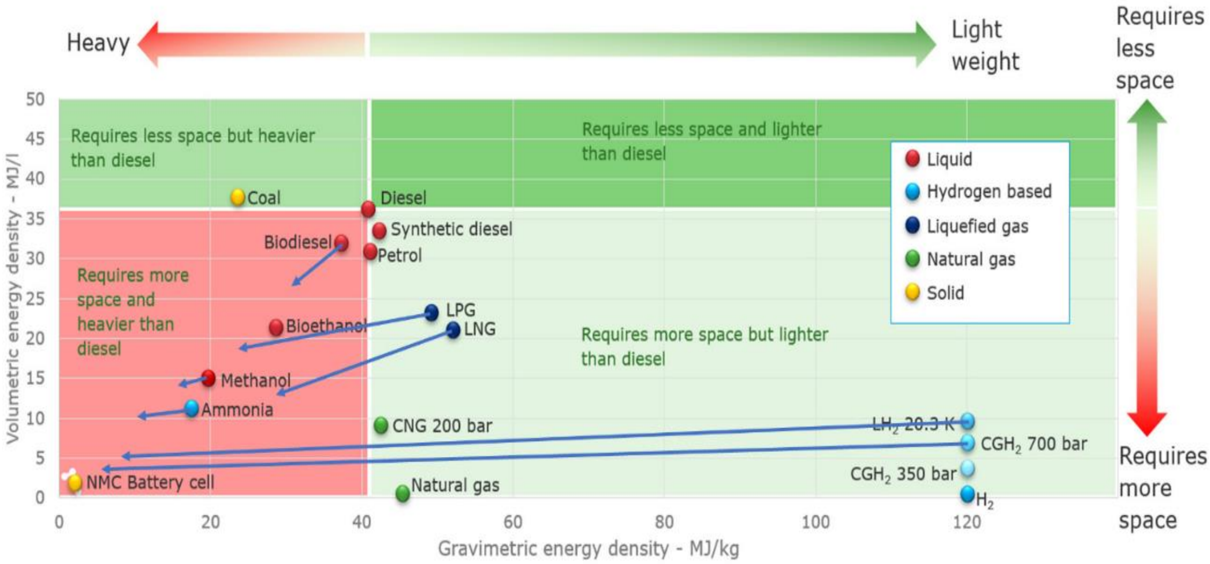

Figure 9 Energy densities for different fuels and energy carriers. The arrows represent the impact on density when considering the storage systems for the different types of fuel (indicative values only). Figure is from [55].

The gravimetric energy density (MJ/kg) was captured quantitively in the LCA analysis through the effective energy use, which was considerably higher for the battery electric propulsion case compared to the lighter alternatives. The volumetric energy density (MJ/l) was not considered to the same extent. The increased space requirement due to lower volumetric energy density was considered by Brødrene Aa and reportedly, the battery will fit barely just.

The chosen functional unit set to the service life of ten years does not capture any potential effect of reduced passenger capacity. To capture such differences, one can alternatively use a functional unit of passenger kilometre (pkm), which is commonly used in LCA studies of various transport modes. However, no quantitative data was available to allow for detailed investigation of how any potential space restrictions may affect the emission results per passenger for the fictitious propulsion systems.

While it was reported that the batteries would fit barely just for the fictitious express boat, space restrictions onboard may in reality limit the suitability of the electric propulsion systems, particularly the battery electric propulsion system. Such technical feasibility considerations, as well as regulatory compliance requirements, are outside the scope of the LCA study.

Onshore infrastructure required for the various propulsion systems were not considered in the analysis. Admittedly, differences arising from establishing fuel storage tanks, battery charger, or mooring systems were not captured in the analysis. Onboard fuel storage tanks for hydrogen contributed marginally to the total life cycle emissions of the hydrogen propulsion systems, while onshore energy for hydrogen compression and liquification was considered in the fuel cycle (well-to-wake) emission factors. Thus, emissions associated with establishing onshore hydrogen storage tanks are unlikely to add any significant emissions or change the emissions profile of the hydrogen propulsion systems. Similarly, while establishing a battery charger will cause GHG emissions, these are likely to be miniscule compared to the total life cycle emissions of the battery electric propulsion system. This expectation is supported by findings in LCA studies on electric vehicles where the charger is found to cause miniscule emissions[23,33]. Any differences in energy or material use associated with mooring systems are also likely to cause marginal life cycle emission differences. Thus, while omitting onshore infrastructure constitutes a limitation from a systems perspective, it is unlikely to cause any substantial difference to the overall emissions findings or conclusion of the study.

While this report focuses solely on GHG emission, it is worth mentioning that climate change is but one of many environmental impacts. LCA studies comparing passenger vehicles with fossil fuels, batteries, and hydrogen fuel cells generally report environmental trade-offs for the various propulsion technologies[22,57]. The findings from the passenger vehicle studies are relevant because they are principally transferrable to the propulsion systems of express boats. Generally, the higher environmental impact and resource use associated with the production phase of the electric propulsion systems places constraints on the environmental intensity of the energy carrier used during the use phase; in many cases, a significant share of renewables are required in the production of the energy carrier used during boat operation in order to compensate for the higher environmental loads associated with the production of the electric propulsion system. However, such compensations are not always achievable; use of energy carriers produced from renewable energy may not compensate for higher environmental impacts that are largely caused by metal use, such as toxicity and eutrophication[22,57]. Note that such environmental trade-offs are commonly observed when comparing various products or activities from a broader environmental perspective.

5.3. Conclusion

The LCA study considered and compared the life cycle GHG emissions of alternative propulsion systems that may be used to motor a fictitious express boat. The preliminary results should be viewed as an indication of expected life cycle GHG emissions of the various propulsion systems rather than a final answer as there is significant uncertainties associated with the results. Furthermore, novel and emerging technologies are more likely to develop and improve than technologies with a higher technology readiness level.

Generally, the electric propulsion systems had lower life cycle emissions than the combustion-based propulsion systems. Although electric propulsion systems have potential GHG benefits, these benefits cannot be harnessed everywhere and under all conditions; a significant share of renewables are required in the production of the energy carriers used during boat operation. This was particularly evident for the hydrogen electric propulsion system where different electricity mixes were considered for hydrogen production through electrolysis. The electric propulsion systems represent new promising technologies as they generally have higher onboard energy efficiency and enable the use of renewable sources. However, the electric propulsion systems are not without challenges, the low gravimetric and volumetric energy densities are particularly important and may limit their applicability in express boats.

None of the considered propulsion system alternatives stand out as an ideal candidate to replace MGO in express boats. While the electric propulsion systems show great potential as a measure to reduce GHG emissions from express boats, the challenges associated their lower volumetric energy density were not fully captured in the current LCA study. When considering how the lower volumetric energy affects passenger capacity, the electric propulsion systems may not offer the same GHG emission advantage. This aspect should be considered in future analyses as data availability increase. At the current state of the technology, both ammonia, battery, and hydrogen propulsion systems are facing technological challenges that cannot be sufficiently examined in an LCA study but rather require technological assessments. For the battery electric propulsion system, there is considerable uncertainty associated with the life cycle emissions. In the analysis, two widely different effective energy use numbers (and consequently battery pack sizes) were applied. The lower estimate applied in the main analysis provided a much more favourable results compared to the higher estimate applied in the uncertainty analysis. As effective energy use is a challenging issue to properly address in simplified vessel resistance models, it is in the current study impossible to say which one of the two estimates is more representative for an actual express boat servicing the studied route. As such, decision makers should be particularly cautious regarding the uncertainty of the preliminary results for the battery electric propulsion system. The emission estimate of the HVO-fuelled propulsion system is associated with large uncertainty due to potential ILUC emissions. Furthermore, its supply cannot be guaranteed and if fossil diesel or MGO is used to replace HVO, the GHG emissions reduction potential is not fully realized.

The aim of this report was to consider and compare the life GHG emissions of various alternatives. While there are important uncertainties and limitations associated with the analysis, an overall picture of the GHG emissions is provided. Furthermore, the preliminary results provide useful insights and highlighted important aspects pertaining to the GHG emissions of alternative propulsion systems for express boats.

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APPENDIX A - COMPONENTS

A.1. Combustion engines

Most ships use the marine diesel engine, an internal combustion engine working in a diesel cycle, powered by marine diesel or heavy fuel oil.

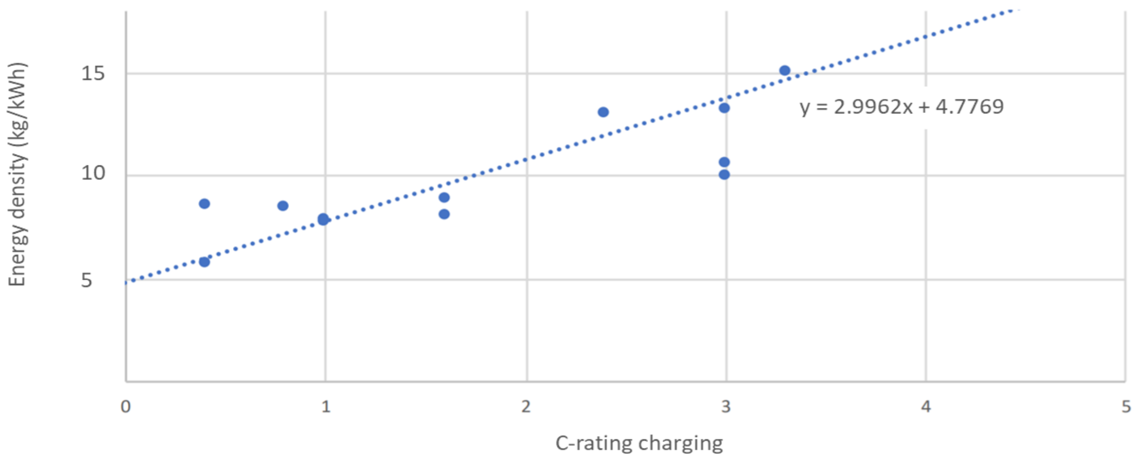
Emission factors from the literature were used to estimate the emissions stemming from production of the combustion engines. While no information was found regarding marine combustion engines in specific, LCA results were found for combustion engines used in passenger cars. An average of 3.3 kg CO_2-eq/kg was calculated based on two data sources[22,26]. While using proxy data is common practice when specific data is unavailable for an LCA study, it does require careful consideration. Here, it was deemed that the emission factors for the passenger vehicle engines are representative also for marine combustion engines used in express boats because the most important structural materials in 4-stroke engines are the same: cast iron, alloy and structural steels, and aluminum alloys (where the three main elements used in the metal alloys are iron, aluminum and carbon)[58]. Furthermore, the production emission of an engine derives primarily from the metals, and per kg of engine, the composition of metals is unlikely to differ much between combustion engines in passenger vehicles and express boats. Thus, it was assumed that the emission of 3.3 kg CO_2-eq/kg of engine would be about the same regardless of application. Note that the life cycle emissions of the combustion-based propulsion systems are almost entirely due to the combustion of fuels, while the production of propulsion system components have marginal contributions to the total life cycle emissions. As such, any errors in the emission factor assumption has little to no significant effect on the overall results.

An engine is mainly made up of various metal alloys, so the material used in the engine and its components can be recycled. The disposal process was assumed to be a melting process. As ferrous metals make up the largest share of materials in the engine, 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[48].

A.2. Li-ion battery

The Li-ion batteries offers an unmatched combination of high energy and power densities compared to competing battery technologies. Consequently, they are the preferred choice for electromobility[59]. Li-ion batteries have been used in electric vehicles for decade and more recently, also been applied for maritime applications.

Maritime batteries tend to have lower energy density than batteries found in electric vehicles, mainly due to considerations regarding charging power and lifetime[60]. The correlation between charging time and weight can be found by plotting the energy density of the battery as a function of the C-rate during charging. Increased power increases the weight, as shown in Appendix figure 1.



Appendix figure 1 C-rate versus energy density for maritime batteries. The figure is reproduced from [60].

Battery lifetime is another important aspect to consider. Battery degradation is not linear, and it occurs due to two main processes: calendaring and cycling. Calendaring refers to the decomposition of the electrolyte over time (regardless of use). Cycling refers to various use related factors (e.g., depth of discharge, C-rate, and number of cycles) that generally results in two main issues: capacity fade through the solid electrolyte interface layer and power fade through increase in internal impedance.

Selecting suitable batteries for express boats requires a balance of energy density, power density, and lifetime. Selecting a battery with high C-rate and over-dimensioning the size (to avoid high depth-of-discharge and reduce cycle numbers) can prolong battery lifetime, but it comes at the cost of lower energy density. Over-dimensioning leads to larger, heavier, and more expensive battery packs, and the additional weight require more effective energy.

For the main analysis, it was assumed that the battery pack would last the ten years of operation. This assumption is based on both model results and experience from Corvus Energy and ZME. The estimated DoD for the studied battery in the current study was 67%. After ten years of operation, the battery is disposed of.

To allow for sufficient charging during the two hour lay-over in Selje, the battery-powered boat will most likely require an onshore battery and power converter. While the onshore battery is not directly a part of the propulsion system, it was considered in the analysis because it is an essential part of the battery-powered propulsion system. Thus, the battery-powered propulsion system requires at least two battery packs, one onshore in Selje and one onboard the vessel. Information about the onboard battery capacity and weight was provided by Brødrene Aa. It was assumed that the onshore battery pack was 26% smaller in terms of capacity compared to the onboard battery pack. The assumption was based on discussions with Corvus Energy and ZEM.

The battery inventory was compiled based on the battery specifications provided by Brødrene Aa, battery material composition data provided by Corvus Energy, and supplemented with inhouse battery inventory data that have been published in scientific peer-reviewed articles[27–29]. The cradle-to-gate emissions equals an emission factor of 15.7 kg CO_2-eq/kg.

There are several competing industrial recycling processes for Li-ion batteries, and the processes are typically a combination of mechanical separation, pyrometallurgical treatment, and hydrometallurgical treatment[54]. In this analysis, it was assumed that the battery was disposed through a combined pyro- and hydrometallurgical treatment process. The emission factor 0.9 kg CO_2-eq/kg from the *ecoinvent* 3.5 database was assumed[30].

A.3. Hydrogen PEMFC

The hydrogen PEMFC is the most commonly considered fuel cell technology for electromobility applications[54]. Although PEMFCs have been considered for electromobility applications for decades[63], the technology has not been widely adopted. With the increased focus on reducing GHG emission, PEMFCs have received renewed attention.

In the PEMFC, hydrogen is used as an energy carrier. During use, the cell transforms the chemical energy released during the electrochemical reaction of hydrogen and oxygen to electrical energy. Auxiliary components are required to generate electrical power with a fuel cell stack. These components are usually referred to as the balance of plant (BoP), and make up a large part of the overall system[63].

While a number of published peer-reviewed studies analyse the cradle-to-gate emissions of PEMFC for electric passenger vehicle[57,64–66], no studies providing sufficiently detailed and transparent data inventories for PEMFCs for express boats were found. The results from a forthcoming study (also assessing PEMFCs for passenger vehicles) by Usai et al. addresses many of the shortcomings in the preceding PEMFC studies[31]. The reported emission factor of 35.0 kg CO_2-eq/kW for the PEMFC including BOP was assumed for the current study. The assumed emission factor is in good agreement with the average of previous studies[57,64–66]. The emission factor of 35.0 kg CO2-eq/kW was used to calculate the production emission of the PEMFC. Note that for the given PEMFC this equals 10.8 kg CO_2-eq/kg (as provided in Table 2).

At end-of-life, the recyclers will aim to recovery platinum from the PEMFC. The most common platinum recovery approaches include selective chlorination or gas phase volatilization, hydrometallurgical and pyrometallurgical processes[67]. Because EOL treatment data were unavailable for PEMFCs, the hydrometallurgical treatment of Li-ion batteries in the *ecoinvent* database was used as a proxy. While the *ecoinvent* database also includes pyrometallurgical treatment of Li-ion battery batteries, this process was found less suitable because pyrometallurgical treatment of the fluorinated Nafion membrane would result in the emission of highly toxic hydrogen fluoride[68,69]. Thus, the emission factor of 0.5 kg CO_2-eq/kg was assumed as a proxy for the disposal of the PEMFC.

A.4. Inverter

An inverter is used to convert the DC supplied by the battery and the fuel cell to AC suitable for the electric motor. The *ecoinvent* database provides an emission factor of about 4.4 kg CO_2-eq/kg for a 500 kW inverter.

Emission factors specifically for disposal of inverters were not obtained. As a proxy, the ecoinvent process for mechanical dismantling of industrial devices was assumed. The process has an emission factor of 0.3 kg CO_2-eq/kg. The process includes manual depollution and the mechanical treatment (shredder) of the remaining parts. As a four-step procedure with shredder-separation-shredder-separation is often used in Europe for waste electronics, the mechanical shredding procedure was assumed to be a suitable proxy for disposal of the inverter.

A.5. Electric motor

The motor used in the express boat is a permanent magnet AC electric motor. Nordelöf et al. (2018) report the production emission of three different types of permanent magnet motors based on motor production in both Sweden and the US. The emission factors for the motors produced in Sweden were in the range of 6.5-6.7 kg CO_2-eq/kg, while the motors produced in the US ranged slightly higher at 7.4-7.8 kg CO_2-eq/kg. The higher production emission from the US produced motors stem from the more carbon intensive electricity. Hawkins et al. 2013 report a production impact of 6.9 kg CO_2-eq/kg. While the abovementioned values were derived for permanent magnet DC electric motors for electric passenger vehicles, the derived values are likely to be similar for the AC permanent magnet motor because of the similarity in materials. The values are also likely to scale well with size. Thus, the average of the seven reported values, 7.0 kg CO_2-eq/kg, was assumed for the AC permanent magnet motor for the electric boats. Similar to the internal combustion engine, the electric motor also has insignificant contribution to the total life cycle emissions of the electric propulsion systems.

For disposal of the electric motor, the same approach was taken as for the internal combustion engine. Thus, the emission factor of 0.7 kg CO_2-eq/kg reported by the Bureau of International Recycling was assumed for disposal of the electric motor[48].

A.6. Onboard fuel tanks

Fuel tanks are required for MGO, biodiesel, HVO, ammonia, compressed and liquid hydrogen.

Fuel tanks for MGO, biodiesel and HVO are likely to be an integral part of the boat hull. The tanks will be made of composite carbon-fibre because the hull is made of the same material. Ammonia is generally stored either under pressure at atmospheric temperature or fully refrigerated at -33°C and atmospheric pressure[70]. While the normal material of construction for ammonia storage vessels and tanks is carbon steel[70], it was assumed the onboard tanks were similar to the cryogenic tanks used for liquid hydrogen.

Brødrene Aa provided information regarding the number and weight of the tanks required for the compressed hydrogen propulsion system. The fuel tanks were assumed to be a similar as those applied in hydrogen tanks in PEMFC passenger vehicles. Hydrogen fuel tank for passenger vehicle applications are required to have an aluminum-alloy tank lined internally with plastic lining and wrapped externally in a protective layer of composite carbon-fibre, with one more shock-absorbing protective layer of fibre-glass material added outside that protective layer[21].

The emission factor for composite carbon-fibre fuel tanks was 21 kg CO_2-eq/kg. The emission factor is based on a recent study that considered a hydrogen carbon-fibre tank for an electric vehicle[31]. As the majority of the emissions stems from production of the carbon-fibre, it was assumed to be a representative value also for composite carbon-fibre tanks on boats.

Liquid hydrogen is stored at extremely low temperatures in cryogenic tanks. Liquid hydrogen is usually adopted only when high storage density is required[21]. It was assumed that the cryogenic tanks were made in a similar manner as the hydrogen tanks for compressed hydrogen, but that they also contained a steel liner. The cryogenic tanks were also assumed for the liquid ammonia, but less storage capacity was assumed due to the higher volumetric energy density compared to liquid hydrogen.

The emission factor for the cryogenic fuel tanks was 17.1 kg CO_2-eq/kg. The emission factor was partly based on hydrogen carbon-fibre tank for an electric vehicle[31] and steel from the *ecoinvent* 3.5 database.

Disposal of fuel tanks was based on end-of-life treatment of carbon-fibre. Carbon-fibre may be achieved through various routes. A study assessing disposal through landfilling, incineration, mechanical, pyrolysis, fluidized bed, and chemical treatment report emissions in the range of 0.035-3.1 kg CO_2-eq/kg. While landfilling is an unlikely faith due to strict landfilling regulations, it is uncertain which one of the other disposal methods will be used. Thus, the average value of the latter five abovementioned options resulting in 1.7 kg CO_2-eq/kg was assumed. The factor was assumed for both the composite and cryogenic fuel tanks.

A.7. Onshore power converter

An onshore transformer and power converter are required to allow the onshore battery to charge the onboard battery. The emission factor of 4.4 kg CO_2-eq/kg for a 660 kW frequency converter reported in an environmental product declaration by ABB was assumed for the onshore converter[34]. This emission factor is similar to the assumed emission factor of the inverter. It was assumed that the emission factor is representative for a combined transformer and converter and that the weight of the onshore converter was the same as the onboard inverter used in the battery powered boat.

APPENDIX B - FUELS AND ENERGY CARRIERS

B.1. MGO

MGO is similar to diesel fuel, but it has a higher density than diesel. MGO is typically found on fishing boats, small ferries or tugs. For MGO, four fuel cycle emission factors were obtained from the literature. The reported values were in the range of 72.4-95.1 g CO_2-eq/MJ[36–38]. In this study, the average value of 86.4 g CO_2-eq/MJ was assumed.

B.2. 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[71]. In Europe, maximum 7% v/v FAME is allowed in diesel fuel and 5% v/v in the U.S[72]. 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[73].

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 combustion engine used in an express boat. A forthcoming JEC report estimates a WTT emission factor of FAME to be 38.6 g CO_2-eq/MJ in 2020[39]. Note that the emissions factor assumes that emissions associated with the combustion of biofuels is offset by the renewable credit given to biofuels due to the capture of CO_2 during the growth stage of the plants. The fuel cycle emission factor for diesel was assumed to be 92.1 g CO_2-eq/MJ. The fuel cycle emission factor for the biodiesel (5% v/v FAME) was calculated to be 89.6 g CO_2-eq/MJ.

B.3. 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 is offset by the renewable credit given to biofuels due to the capture of CO_2 during the growth stage of the plants.

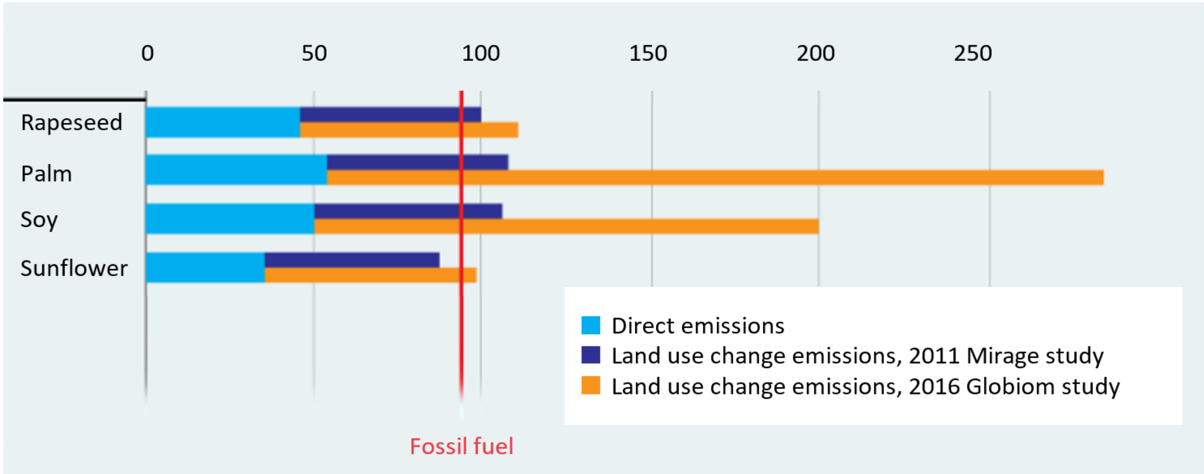
The JEC report estimated the WTT emission factor for HVO to be 24.4 g CO_2-eq/MJ for 2020[39]. According to the report, advanced feedstocks (animal fat, used cooking oil, and lignocellulosic feedstock) are used to produce about 57% of the HVO available on the European market in 2020.

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[74,75].

Both the Globium and the Mirage model report significant emissions due to ILUC, but Globium reports higher emissions than Mirage, as illustrated in Appendix figure 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.



Appendix figure 2 GHG emissions from FAME made from different feedstocks. The figure is taken from [40].

In this study, both FAME and HVO are considered. Because FAME only makes up 7% 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 to 41.6 g CO_2-eq/MJ. Both emission factors were used in the analysis.

Note that the HVO availability is expected to be very limited in the considered timeline towards 2030.

B.4. Ammonia

Ammonia has been produced and utilized as a fertilizer, chemical raw material, and refrigerant for the past 100 years[52]. Recently it has also received attention as a low-emission fuel as its combustion does not result in GHG emissions. The ammonia emission factor was estimated based on the estimated fuel cycle emission factor for compressed hydrogen (as described in section B.6.) as well as ammonia production data provided by Bicer et al.[42] and nitrogen production emission estimate from the *ecoinvent* 3.5 database[30].

The estimated ammonia emission factors were 89.9 g CO_2-eq/MJ and 43.1 g CO_2-eq/MJ with hydrogen based on electrolysis from the Nordic and Norwegian electricity mix, respectively. The estimated ammonia emission factor was 71.6 g CO_2-eq/MJ with hydrogen from SMR with CCS.

B.5. Electricity

As the Li-ion battery converts energy from electrical to chemical and back to electrical energy again, its operation is emission free. However, generation and distribution of the electricity used for charging the battery results in upstream emissions that are ascribed to the battery use. The upstream emissions associated with the charging electricity depends on the energy conversion technology used for generating the electricity.

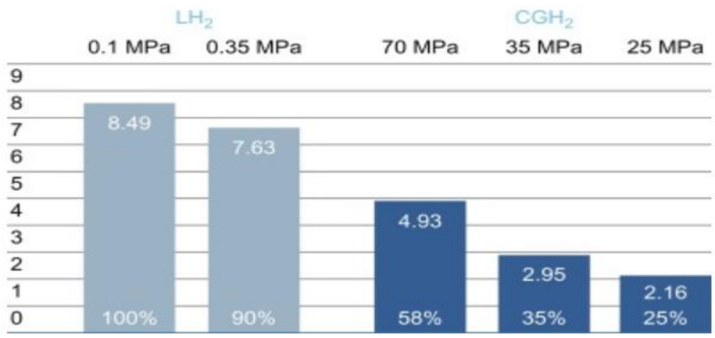
In this study, two electricity mixes were considered: the Nordic electricity mix and the Norwegian electricity mix. The Nordic consumption mix estimated by Asplan Viak is 112 g CO_2-eq/kWh (equivalent to 31.1 g CO_2-eq/MJ). The value represents the electricity at low voltage, thus including transmission 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[45] and emissions associated with transmission and distribution from the *ecoinvent* 3.5 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).

B.6. Hydrogen

PEMFCs use hydrogen without causing any direct emissions, but there are upstream emissions associated with the hydrogen value chain. The upstream emissions depend on the production route and whether the hydrogen is compressed or liquified. Hydrogen can be produced by employing various energy sources, such as electrolysis or by reforming natural gas. Today, nearly all hydrogen is produced from natural gas[55]. In this study, it was assumed that hydrogen was produced either through steam methane reformation (SMR) at a facility with carbon capture and storage (CCS) or through electrolysis. For the electrolysis process, both the Nordic and Norwegian electricity mix were considered.

Emission factors for hydrogen produced from electrolysis using the Nordic and Norwegian electricity mixes were estimated based on data from the JEC well-to-tank Appendix 2 technical report[44] and Wulf et al.[41]. Emissions associated with liquification was estimated based on the energy requirement (11.6 kWh/kg hydrogen) for the liquification process[43,46]. Emissions associated with compression was based on the energy requirement (3.5 kWh/kg hydrogen) for the compression process[43].

Compressed hydrogen requires more transport because it takes up more volume than the liquid hydrogen and this results in higher transport emissions. As shown Appendix figure 3, liquid hydrogen has considerably higher energy content per unit of volume than compressed hydrogen gas. Thus, it was assumed that compressed hydrogen required about three times as much transport by truck as liquid hydrogen.



Appendix figure 3 Energy content of the states of aggregation (MJ/l) for hydrogen. The figure is taken from [21].

The estimated emission factors were 57.8 g CO_2-eq/MJ for liquid hydrogen when produced with the Nordic electricity mix and 11.3 g CO_2-eq/MJ when produced with Norwegian electricity mix, and 51.0 g CO_2-eq/MJ for compressed hydrogen produced with the Nordic electricity mix and 10.6 g CO_2-eq/MJ when produced with the Norwegian electricity mix.

Emission factors for hydrogen produced from SMR with CCS were estimated based on data from the JEC well-to-tank Appendix 2 technical report[44] and Bicer et al.[42]. This resulted in 55.7 g CO_2-eq/MJ for liquid hydrogen and 35.0 g CO_2-eq/MJ for compressed hydrogen[44].

APPENDIX C – ENERGY USE AND EFFICIENCY

The total operational energy demand was calculated by dividing the estimated effective energy use by the energy conversion efficiency, as shown in the equation below.

$$E_{operation} = \frac{E_{eff}}{\eta_{EC}}$$

Where $E_{operation}$ is the total operational energy demand, E_{eff} is the effective energy use, and η_{EC} is the total energy conversion efficiency of energy conversion technologies.

Effective energy use - E_{eff}

The effective energy use is the effective power (vessel resistance multiplied by operating speed) times the trip duration. The effective energy demand for the battery electric propulsion case and the hydrogen electric propulsion case (with compressed hydrogen) were provided by Brødrene Aa. Note that these effective energy demand estimates include complete vessel and propulsion system weights. Thus, the battery electric propulsion case had higher effective energy demand than the hydrogen electric propulsion case due to the higher weight.

The effective energy use for the compressed hydrogen propulsion case served as a starting point to estimate the energy use for the remaining propulsion cases as specific propulsion energy demand was unavailable for these. It was assumed that the propulsion system with liquid hydrogen tanks had the same effective energy use as the propulsion system with compressed hydrogen because these two propulsion systems weigh nearly the same. As the effective energy use was not made available for the combustion-based propulsion cases, their effective energy use were estimated based on findings from the empirical CatRES model developed by Rambech[35], using estimated differences in displacement and assuming constant vessel length. In addition to uncertainties in the estimated weights, this empirical method has known limitations. Thus, the associated energy requirements for the combustion-based propulsion systems should be reviewed as a very preliminary approximation. Compared to the effective energy demand of the propulsion system using compressed hydrogen, the effective energy requirements were estimated to be 5.7% lower for the MGO, biodiesel, and HVO fuels and 4.1% lower for the ammonia fuel than for the compressed hydrogen electric propulsion system.

Energy conversion efficiency - η_{EC}

For the combustion-based technologies, η_{EC} is the engine efficiency. For the electric technologies, the total energy conversion efficiency is the product of the efficiencies of the motor, electrochemical device, and the power inverter, as shown in the equation below.

$$\eta_{EC} = \eta_{E} * \eta_{ED} * \eta_{PC}$$

Where η_{E} is the engine efficiency, η_{ED} is the electrochemical device efficiency, and η_{PC} is the inverter (PC - power converter) efficiency. While the efficiency of the devices varies under different operating conditions, a fixed efficiency was assumed in this analysis. The efficiencies were based on relevant litterature[55,76–79]. For the internal combustion engine, the efficiency was estimated based on the specific fuel consumption of the engine used in the express boat currently servicing the route. The specific fuel consumption had a relatively low sensitivity to load over the published operating conditions compared to other engines, indicating the engine efficiency only changes moderately under different operating conditions. Note that no reliable data sources were found for the energy efficiency of ammonia combustion in an internal combustion engine. The efficiency was assumed to be 5% lower than engines fuelled by MGO, biodiesel, and HVO due to the difficulties in completely combusting ammonia in the combustion chambers[20].

The assumed efficiencies used to calculate the total energy conversion efficiency are shown in Appendix table 1.

Appendix table 1 Assumed efficiencies used for estimating the total energy conversion efficiency

		Combustion		Electric	
		Fossil/biofuel	NH3	Battery	PEMFC
Total energy conversion efficiency	η_{EC}	**40 %**	**35 %**	**82 %**	**55 %**
Engine efficiency	η_E	*40 %*	*35 %*	*95 %*	*95 %*
Electrochemical device efficiency	η_{ED}			*90 %*	*60 %*
Power converter	η_{PC}			*96 %*	*96 %*

Propulsive efficiency - η_{prop}

The estimated effective energy, E_{eff}, inherently includes propulsive efficiency, n_{prop}. The total propulsive efficiency is the product of hull efficiency, propeller efficiency in open water, relative rotative propeller efficiency, and shaft (including reduction gear) efficiency, as shown in the equation below.

$$\eta_{prop} = \eta_H * \eta_O * \eta_R * \eta_S$$

Where η_H is the hull efficiency, η_O is the open water propeller efficiency, η_R is the relative rotative propeller efficiency, and η_S is the shaft efficiency. Note that the propulsive efficiency could not be calculated as the study considers a the fictitious boat and was rather estimated based on efficiency values given in the literature[80]. The total propulsive efficiency was assumed to be the same for all propulsion systems. In reality, differences in the propulsive efficiency occur. However, the simplified approach of using the same efficiency for all boat designs was taken as the propulsive efficiency is extremely intricate and challenging to estimate.

The assumed efficiencies used to calculate the total propulsive efficiency are shown in Appendix table 2.

Appendix table 2 Assumed efficiencies used for estimating the total propulsive efficiency

		Combustion		Electric	
		Fossil/biofuel	NH3	Battery	PEMFC
Total propulsive efficiency	η_{prop}	**74 %**	**74 %**	**74 %**	**74 %**
Hull efficiency	η_H	*110 %*	*110 %*	*110 %*	*110 %*
Propeller efficiency open water	η_O	*70 %*	*70 %*	*70 %*	*70 %*
Relative rotative efficiency	η_R	*100 %*	*100 %*	*100 %*	*100 %*
Shaft efficiency (incl. reduction gear)	η_S	*96 %*	*96 %*	*96 %*	*96 %*

Operational energy efficiency - $\eta_{operation}$

Based on the estimated total propulsive efficiency and the energy conversion efficiency, the total operational energy efficiency, $\eta_{operation}$, was estimated based on the equation below.

$$\eta_{opeartion} = \eta_{prop} * \eta_{EC}$$

The calculated operational energy efficiency is shown in Appendix table 3.

Appendix table 3 Estimated total operational energy efficiency

		Combustion		Electric	
		Fossil/biofuel	NH3	Battery	PEMFC
Total operational efficiency	$\eta_{operation}$	**29 %**	**26 %**	**61 %**	**40 %**
Total propulsive efficiency	η_{prop}	*74 %*	*74 %*	*74 %*	*74 %*
Total energy conversion efficiency	η_{EC}	*40 %*	*35 %*	*82 %*	*55 %*

Total energy efficiency – η_{total}

For all propulsion systems but the battery electric one, the total operational energy efficiency equals the total energy efficiency. In contrast, the battery propulsion system must also consider the charger and if relevant, an onshore battery and power converter. The onshore efficiency is the product of the charger, onshore battery and converter efficiencies, as shown in the equation below.

$$\eta_{onshore} = \eta_C * \eta_{ED} * \eta_{PC}$$

Where $\eta_{onshore}$ is the efficiency of onshore components. If there is no onshore battery and power converter, the onboard efficiency equals the onshore efficiency. Note that the onshore and onboard efficiencies for electrochemical devices (battery) and power converter were the identical.

In the main analysis, it was assumed that the dock in Selje has a battery and power converter, while the dock in Bergen does not. Thus, the energy efficiency was not the same both ways in the main analysis. In one of the battery uncertainty analyses, the efficiency was assumed to be the same for both directions as an onshore battery was assumed also for the dock in Bergen as well (see section D.3. in Appendix D).

The assumed efficiencies for calculating the onshore efficiency for the battery propulsion system is shown in Appendix table 4.

Appendix table 4 Assumed efficiencies used for estimating the onshore efficiency for the battery electric propulsion system

		Electric	
		Battery (Selje)	Battery (Bergen)
Onshore efficiency		**83 %**	**96 %**
Charger efficiency	η_C	*96 %*	*96 %*
Electrochemical device efficiency	η_{ED}	*90 %*	
Power converter	η_{PC}	*96 %*	

The total efficiency for the battery propulsion system, η_{total},was calculated as shown in the equation below.

$$\eta_{total} = \eta_{operation} * \eta_{onshore}$$

Because the requirements for onshore battery and power converter are not assumed to be the same for the two one-way end destinations, the total energy efficiency differs.

Appendix table 5 presents the estimated total energy efficiency for the battery electric propulsion system, with one estimate for the dock in Selje and one for the dock in Bergen. Recall that the dock in Selje includes a battery charger, battery, and a power converter while the dock in Berger includes on a battery charger.

Appendix table 5 Estimated total energy efficiency of battery electric propulsion system

		Electric	
		Battery (Selje)	Battery (Bergen)
Total energy efficiency	η_{total}	**50 %**	**58 %**
Onshore efficiency	$\eta_{onshore}$	*83 %*	*96 %*
Operational efficiency	$\eta_{operation}$	*61 %*	*61 %*

Appendix table 6 provides a summary of the total energy efficiency for all of the considered propulsion systems. Both energy efficiencies are provided for the battery propulsion system.

Appendix table 6 Estimated total energy efficiency of all propulsion system

		Combustion		Electric	
		Fossil/biofuel	NH_3	Battery	PEMFC
Total energy efficiency	η_{total}	**29 %**	**26 %**	**58 % and 50%**	**40 %**
Onshore efficiency	$\eta_{onshore}$	*N/A*	*N/A*	*83% and 96 %*	*N/A*
Operational efficiency	$\eta_{operation}$	*29 %*	*26 %*	*61 %*	*40 %*

Total energy use - E_{total}

The total energy demand, E_{total}, is calculated as shown in the equation below.

$$E_{total} = \frac{E\ operation}{\eta_{total}}$$

Appendix table 7 presents the estimated total one-way energy use for all propulsion systems. As the battery propulsion system has different total energy efficiencies depending on onshore efficiencies, the total one-way energy use differs. The higher value represents the total energy efficiency including an onshore battery and power converter.

Appendix table 7 Estimated one-way energy use for all propulsion systems

		Combustion		Electric	
		Fossil/biofuel	NH3	Battery	PEMFC
One-way energy use	kWh	23 335	26 941	17 767 and 15 990	17 977

The estimated round-trip energy use is presented in Table 3 on page 17 in the main text.

APPENDIX D – ROBUSTNESS ANALYSIS

Uncertainty is particularly prevalent for novel and emerging technologies, primarily because data is less available, but challenges may also arise due to variability in reported data. The robustness analysis considers what was perceived as the most critical uncertainties. Robustness analysis was performed for the novel propulsion systems using ammonia, battery, and PEMFC.

D.1. Ammonia – engine efficiency

The use of ammonia in internal combustion engines has a low technology readiness level[55]. As such, it is challenging to find reliable information about the energy conversion efficiency of ammonia through combustion in the engine. In the main analysis, the engine energy efficiency was set to 35%, which may be optimistic given the technology readiness level. In the robustness analysis, the life cycle emissions were calculated as a function of engine efficiency to find how this parameter affects the results. The results are shown in Figure 6.

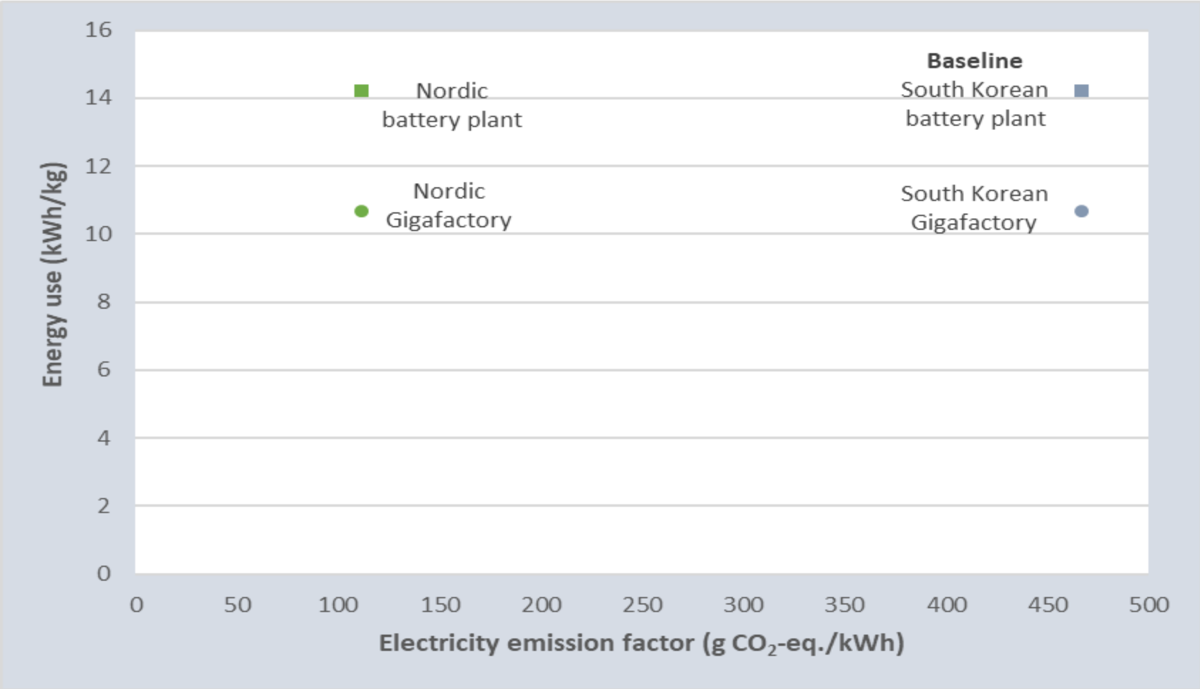
D.2. Battery – cell manufacture, onshore battery, lifetime, and effective energy use

The uncertainty analysis regarding battery propulsion systems considers four aspects: cell manufacture, onshore battery, lifetime, and effective energy use. The results of the analysis are shown in Figure 7, while the text below describes the four aspects.

Cell manufacture
Energy demand and production location were considered in the uncertainty analysis of battery cell manufacture. One of the perhaps most significant uncertainties regarding the battery production emissions is associated with energy use in cell manufacture[29,81–83]. Up until recently, Li-ion cells were primarily produced in South Korea, China, and Japan[84–86], countries that all use high shares of fossil fuels to generate electricity. Production location can affect the battery production emissions as the electricity emission factor depends on the energy sources used to generate the electricity. In the uncertainty analysis, both the electricity demand and location for battery cell manufacture were considered.

In the main analysis (baseline), the assumed cell manufacturing energy demand of 14.2 kWh/kg cell was met by the South Korean electricity mix, which was considered representative for current large scale production factories[28,83]. The uncertainty analysis considered a lower energy demand of 10.8 kWh/kg cell, assumed to be more representative for the energy demand at a larger scale gigafactory[81,82,87]. To consider forthcoming battery cell manufacture, the Nordic electricity mix was assumed in line with forthcoming production plants by Northvolt in Sweden and Freyr in Norway.

The electricity demand and emissions factors used in the various scenarios are shown in Appendix figure 4. The Nordic electricity mix is denoted by green, while the South Korean electricity mix is denoted by blue. Energy demand assumed in current large-scale battery factories are denoted by a square marker, while expected energy demand assumed for recent and forthcoming gigafactories are denoted by a circle.



Appendix figure 4 Data used in the uncertainty analysis of battery cell manufacture

Onshore battery in Selje

An uncertainty analysis was performed to consider the emission effect of not requiring an onshore battery pack at the dock in Selje. By removing the onshore battery, the onshore efficiency increases slightly, resulting in slightly lower overall energy use per round-trip.

Lifetime of battery pack

To evaluate the possibility that the onboard battery pack may need replacement, the uncertainty analysis considered a battery lifetime of only five years for the onboard battery pack.

Effective energy use

In addition to the effective energy use estimate supplied by Brødrene Aa, Norled supplied an additional estimate that had been prepared for them for the considered route. The estimate supplied by Norled was significantly higher than the estimate provided by Brødrene Aa, indicating that there is significant uncertainty associated with estimating the effective energy use for a battery electric express boat servicing the studied route. The higher effective energy demand resulted in a round-trip total energy demand increase from 33 758 kWh to 61 929 kWh. The higher effective energy use increases the need for components both onboard and onshore. The uncertainty analysis considers the higher energy demand provided by Norled and includes the increased demand for propulsion system components. As in the main analysis, it was assumed that there was one onshore and onboard battery pack and that the battery would last five years.

D.3. PEMFC – fuel cell efficiency

Even though the PEMFC technology has been around for decades already, the use of hydrogen in PEMFC has a relatively low technology readiness level[55]. As such, it is challenging to find reliable and representative information about the energy conversion efficiency of the cells. In the main analysis, the engine energy efficiency was set to 60%[55,79]. In an uncertainty analysis, the life cycle emissions were calculated as a function of fuel cell efficiency to determine how much this parameter affects the results. The results of the uncertainty analysis are shown in Figure 8.