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Meta-analysis of life-cycle assessment studies into future zero-emission shipping technologies

Evers, V.H.M.

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Meta-Analysis of Life-Cycle Assessment Studies into Future Zero-Emission Shipping Technologies

By V.H.M. Evers (0862091)

Eindhoven University of Technology & Future Proof Shipping
Department of Sustainable Energy Technology & Innovation Sciences

ASSESSMENT COMMITTEE

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Prof. Heleen de Coninck	Industrial Engineering and Innovation Sciences
Prof. David Smeulders	Mechanical Engineering

Daily supervision by Arjan Kirkels, Milinko Godjevac & Prasanna Colluru

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Eindhoven, July 15, 2021

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Executive Summary

This report presents a meta-study into the CO_2 emissions of alternative marine fuels and propulsion systems. Maritime transportation is responsible for roughly 3% of global greenhouse gas emissions. Despite ever more stringent regulations, these emissions are projected to grow towards 2050. A transition towards alternative shipping fuels is therefore required, in order to achieved deep decarbonization and to meet ambitious international climate goals.

An extensive body of Life-Cycle Assessment (LCA) studies has assessed the possible CO_2 emissions of alternative fuels and conversions systems. However, analytical inconsistencies complicate comparisons, which consequently makes it difficult to draw definitive conclusions regarding environmental impacts. Therefore, this research assesses the carbon footprint of system alternatives from a full life-cycle perspective. It identifies the most promising options, and presents an analysis of the key impacts areas, life-cycle uncertainties, and system dynamics. Possible practical implications of the results are explored in a system-level context.

A mixed method meta-analysis is employed, which is based on a quantitative and qualitative review of existing LCA literature. A full life-cycle perspective is adopted, which includes the operational phase, the fuel production phase, and the system component manufacturing phase. The research explores different scenarios based on hydrogen and ammonia fuel, in combination with fuel cell technology. The scenarios are explored around the case of Future Proof Shipping (FPS), who work towards providing solutions for zero-emission inland shipping.

The review shows that a maximum 93% reduction in 30-year emissions can be achieved by vessels based on hydrogen fuel cells, provided that hydrogen is produced via renewable electrolysis. The fuel production phase is by far the most relevant in all alternative scenarios, accounting for 81-98% of total life-cycle CO_2 emissions. The review shows the increasing relevance of upstream and downstream emissions, especially in scenarios based on fuel production via renewable energy. Most relevant are the primary energy sources, the fuel distribution method, the manufacturing process of system components, and the construction of sustainable power plants.

Significant uncertainties remain present in the life-cycle results. These are primarily caused by the aggregation of data, and a lack of transparency with respect to methodological assumptions. Despite these uncertainties, this research shows that a meta-review can provide sufficiently conclusive results to enable strategic decision-making on crucial life-cycle aspects. This improves the practical utility of LCA studies for stakeholders such as Future Proof Shipping.

For future research it is recommended to assess the feasibility of promising decarbonization pathways in more detail. Special attention should be paid to system-level aspects such as renewable energy availability, infrastructure, costs, regulations and governing structures. From a methodological point of view, it is urged to continue efforts into the standardization of LCA methodologies.

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List of Abbreviations

NH_3	Ammonia
BoP	Balance-of-Plant
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
CO	Carbon Monoxide
EU	European Union
FC	Fuel Cell
FPS	Future Proof Shipping
GDL	Gas Diffusion Layer
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
H_2	Hydrogen
ICE	Internal Combustion Engine
IMO	International Maritime Organization
LCA	Life-Cycle Assessment
LBG	Liquefied Biogas
LNG	Liquefied Natural Gas
MGO	Marine Gas Oil
MSR	Methane Steam Reforming
MCFC	Molten Carbonate Fuel Cell
N_2	Molecular Nitrogen
NO_x	Nitrogen Oxides
PM	Particulate Matter
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
SOFC	Solid Oxide Fuel Cell
SO_x	Sulfur Oxides
TEU	Twenty-Foot Equivalent Unit

Chapter 1

Introduction & Problem Exploration

In this first introductory chapter, the context, purpose and goals of the research are presented and elaborated upon. Section 1.1 provides the context relating to the issue of emissions in the Dutch inland shipping sector. Section 1.2 introduces Future Proof Shipping, the commissioner and primary stakeholder of this research. Section 1.3 provides an overview of the most relevant and recent innovations in alternative maritime fuels and conversion systems. Finally, Sections 1.4 and 1.5 present the problem definition, research question and the intended results of the study presented in this report.

1.1 Inland Shipping & The Environment

Maritime transport represents 80-90% of international trade by volume (Walker et al., 2018; Hansson et al., 2019). Currently, an estimated 3% of annual anthropogenic greenhouse gas (GHG) emissions is attributed to the shipping sector. This is a result of the heavy reliance on fossil fuels such as heavy fuel oil (HFO) and marine gas oil (MGO) (Lindstad & Eskeland, 2015). More importantly, however, emissions from shipping are projected to grow by a substantial 150-250% towards 2050, if no measures are taken to limit emissions (Lindstad & Eskeland, 2015; I. N. Brown & Aldridge, 2019). Therefore, both the Dutch Governments and the International Maritime Organization (IMO) have formulated targets to reduce the CO_2 emissions from shipping by at least 40-50% by 2050 (Green Deal, 2019; IMO, 2020). At the same time, concerns relating to the effects of local pollutants such as nitrogen oxides (NO_x), sulfur oxides (SO_x) and particulate matter (PM), are being addressed by the implementation of Emissions Control Areas (Spoof-Tuomi & Niemi, 2020; IMO, 2020).

These regulations have contributed to innovations in fossil fuel composition and combustion engine efficiency, which resulted in considerable reductions of local emissions in Dutch inland waterways. The desulfurization of marine fuels in particular has had substantial effects on the reduction in SO_x (99%) and PM emissions (36%) (Wever D et al., 2018; CBS, 2021). However, improvements in fuel combustion and shipping efficiency have not had the same effect on emissions of CO_2. Carbon emissions from shipping are still predicted to grow, despite a projected decelerating effect resulting from regulations (UNEP et al., 2012). In order to achieve deep decarbonization, the current regulatory measures need to be complemented by a transition towards alternative fuels and conversion systems with drastically lower carbon emissions.

Among these potential alternative fuels are carbon-containing fuels such as liquefied natural gas (LNG), liquefied biogas (LBG) and methanol, or carbon-free alternatives such ammonia (NH_3) and hydrogen (H_2) from various sources and production methods (Brynolf et al., 2014; DNV GL, 2019b). The related energy conversion systems may include the traditional internal combustion engine (ICE), or several types of fuel cells such as the Proton Exchange Membrane Fuel Cell

(PEMFC) or the Solid Oxide Fuel Cell (SOFC) (van Biert et al., 2016). Different combinations of fuel and conversion system may lead to different levels of decarbonization. Batteries may be used to store energy from renewable sources and to power an on-board electric motor at a later time. When it comes to the suitability of each of these alternatives, stakeholders are challenged with weighing a set of complex factors relating to investment costs, technological maturity, regulations and environmental performance, among others (Hansson et al., 2019). The academic field of Systems Engineering is particularly concerned with balancing these considerations, and assessing the techno-economic feasibility of complex emerging systems (Keating et al., 2003).

With respect to environmental performance, however, the Life-Cycle Assessment (LCA) is the most notable methodology for assessing environmental impacts (Guinée et al., 2004). The LCA methodology is widely used to compare environmental impacts of different design alternatives and, as such, may assist in decision-making processes. Ideally, an LCA adopts a life-cycle perspective which encompasses all environmental impacts, from all relevant life-cycle-stages, for every component of the system under consideration. Because of the analytical complexity and time-consuming nature of such a comprehensive assessment, real life-cycle impact studies will often consider a more simplified scope. LCAs may be employed to analyze the impacts of existing systems, after they have been deployed. However, ex-ante LCA applications are growing in importance, especially for market stakeholders who are interested in a wide variety of possible future system configurations (Cucurachi et al., 2018; van der Giesen et al., 2020).

1.2 Future Proof Shipping

One such stakeholder is the Dutch company Future Proof Shipping (FPS), the commissioner of this research. Based in Rotterdam, FPS works towards providing solutions for zero-emissions marine transportation. FPS aims to build a fleet consisting of at least ten zero-emission inland vessels in the next 5-10 years. Their strategy is based on retrofitting conventional diesel-based vessels. Currently, FPS are retrofitting their very first vessel, the Maas, to a hydrogen fuel cell-based power system. This this done in collaboration with BCTN Network of Container Terminals and the Holland Shipyards Group. The retrofitted vessels are to be chartered to cargo owners on a long term basis. Additionally, FPS assists maritime stakeholders in transitioning to zero-emission alternatives, by consulting on technological, financial and commercial aspects.

Figure 1.1: *Photo of the Maas in operation. Image taken from Schuitemaker (2020).*

Due to the novel and emerging nature of the zero-emission shipping sector, FPS are still interested in a wide variety of pathways towards zero-emissions shipping. For this type of stakeholder, it is important to be able to easily conduct comparative assessments of a range of different alternatives.

It is therefore argued that the LCA provides a useful approach to the assessment of system alternatives considered by FPS.

1.3 Sustainable Shipping Innovation

Studies have shown that the environmental impacts of a vessel may be improved in a range of different ways. This section provides a brief overview of regulations and innovations that have contributed to recent improvement. Moreover, it presents an overview of the most promising technologies for continued future improvement, with a focus on alternative fuels and their related conversion systems.

1.3.1 Regulations

Heavy Fuel Oil (HFO) is by far the most dominant global shipping fuel, making up just short of 80% of consumption in 2018 (IMO, 2020). The combination of HFO's high sulfur contents, high carbon contents and its high combustion temperatures, results in environmentally harmful emissions of CO_2, SO_x, NO_x and PM. In 2008, the MARPOL Annex VI for prevention of air pollution was adopted to address these issues. (Čampara et al., 2018). MARPOL Annex VI dictates a progressive reduction of SO_x, NO_x and PM emissions, which has currently entered its final and most stringent phase. Under these regulations, the maximum sulfur contents of marine fuels are reduced from 3.5 to 0.5% in 2020. In so-called emissions-control areas, sulfur content is restricted even further, to a maximum of 0.1%. NO_x emissions are regulated based on the specific power output of an individual diesel engine.

In order to comply with the progressively more demanding regulations, the maritime industry has been prompted to consider alternative power systems and fuels to limit emissions (IMO, 2020; MARPOL & Julian, 2000). Most recently, this has caused a slight shift away from HFO fuel and towards low-sulphur alternatives such marine gas oil (MGO) (IMO, 2020). As a result, SO_x emissions in Dutch inland waterways have been reduced by an impressive 99%. At the same time, innovations in combustion technology have contributed to reductions in emissions of NO_x and CO_2. While continued innovation may result in a continued reduction of shipping emissions, global CO_2 emissions from shipping are still increasing (5.6% from 2012 to 2018) (IMO, 2020; van Biert et al., 2016). Therefore, improving fossil fuel-based systems alone is not sufficient, in order to work towards zero-emissions shipping (IMO, 2020).

1.3.2 Technological Developments

Technological developments in alternative fuels and conversion systems have resulted in a range of possible future replacements for HFO, MDO and MGO. Hydrogen fuel is considered to be one of the most attractive alternatives, since its oxidation process in a fuel cell is free of harmful emissions. A range of different hydrogen fuel cells has been developed, each with their own distinct characteristics. The Polymer Electrolyte Membrane Fuel Cell (PEMFC) and the Solid Oxide Fuel Cell (SOFC) are considered the most promising for shipping applications (DNV GL, 2019b). The PEMFC in particular achieves high power densities, rapid start-up times and transient response, and low operating temperatures (65-200 degrees Celsius), making it especially interesting for transportation purposes (van Biert et al., 2016).

Fuel cells may operate on the input of (nearly) pure hydrogen fuel. Alternatively, hydrogen-containing fuels may be reformed internally into pure hydrogen. Ammonia (NH_3), for example, may be reformed into H_2 under the influence of high temperatures in an SOFC, without emitting any CO_2. However, NO_x emissions may still occur, due to the combination of the high-temperature environment of the fuel cell and the presence of nitrogen in fuel and air. Carbon-containing fuels such as LNG may also be internally reformed into hydrogen. However, carbon monoxide (CO) is formed in the process, which is consequently oxidized and emitted as CO_2. PEMFCs are currently unsuitable for internal reforming, due to the high purity requirements of hydrogen. PEMFCs are particularly vulnerable to CO, since CO adsorption to the platinum catalyst causes degradation of the fuel cell, which severely affects performance and lifetime (Hidai et al., 2012). High temperature alternatives such as the SOFC do not suffer from this issue, since SOFCs do not require a platinum catalyst and utilize CO as a fuel. High-temperature PEMFCs are being developed in order to deal with the downside of low-temperature PEMFC's ' inability to handle fuel impurities (Cinti et al., 2020).

Liquefied Natural Gas (LNG) is currently the only alternative shipping fuel whose supply surpasses the global maritime energy demand, meaning that a global switch to LNG is theoretically possible today (DNV GL, 2019b). LNG is compatible with both ICEs and high temperature fuel cells and has the lowest carbon content of all fossil fuel alternatives. As such, LNG has the potential to reduce CO_2 emissions in the short term. However, the use of LNG will always be associated with carbon dioxide emissions, due to its inherent physical properties. Additionally, the reforming of LNG in a fuel cell is associated with the release of uncombusted methane (methane slip), which is another potent greenhouse gas (DNV GL, 2019a).

Hydrogen and ammonia fuel cells are thus the most promising zero-emissions shipping systems. However, over 95% of hydrogen and ammonia is currently produced from non-renewable fossil fuel sources, most notably Methane Steam Reforming (MSR) and the Haber-Bosch process (Detz et al., 2019). Substantial improvements in production capacity of renewable hydrogen and ammonia are therefore required. Renewable alternatives of H_2 production may be based on biomass gasification or water electrolysis. Electrolysis is a strong contender because of the maturity of the technology and the high production efficiencies (60-80%). However, the high cost of electrolysis is still one of the major challenges: approximately 6.00 \$/kg, compared to 1.00-2.30 \$/kg for MSR (Shiva Kumar & Himabindu, 2019). It is estimated that the price of electrolysis could be reduced to about 2.60 \$/kg H_2, by the year 2030 (Hydrogen Council, 2020).

1.4 Problem Definition

In the past two decades, a vast body of LCA literature into alternative shipping fuels and power systems has been developed (Valente et al., 2017). Despite the wealth of available research, a perception of inconclusiveness relating to "true" environmental impacts is still prevalent among decisions-makers (Brandão et al., 2012; Lifset, 2012). Discrepancies in results, ambiguity in methodology, and inconsistencies in recommendations are among the main causes. Based on a preliminary review of the LCA literature, the following underlying causes of uncertainty may be observed.

Firstly, hydrogen and ammonia fuel cells have been identified as some of the most promising and sustainable alternative power systems for marine applications. This is primarily based on the zero-emission operation of these systems. However, additional emissions do occur in other life-cycle phases, and these are not consistently taken into account. When upstream and downstream emissions are taken into account, however, large discrepancies in impact results are observed.

Additionally, a disproportionate number of studies focuses on the impacts of the fuel production phase of the life-cycle. Impacts related to component manufacturing, maintenance and end-of-life phases of the energy converters are largely disregarded. This stands in stark contrast with LCA studies into alternative power systems of passenger vehicles (Evangelisti et al., 2017; Lombardi et al., 2017; Bauer et al., 2015). The limited number of comparative LCA studies that do include the manufacturing, maintenance and end-of-life phases, do so for very specific cases. These cases do not include some of the more state-of-the-art or emerging power systems that are of current interest to researchers and market parties.

From a methodological point of view, it is observed that the existing LCA studies present results at a low level of detail. Impacts are generally presented as aggregated impacts, without clear distinction between different life-cycle stages. Additionally, a lack of transparency with respect to used data, boundary conditions and other situation-specific assumptions is observed. These methodological ambiguities complicate the identification of key environmental impact areas and make it more difficult to understand the nature of discrepancies in LCA results. In turn, this impairs comparisons between different systems. As a result, no definitive conclusions regarding CO_2 emissions can be drawn, which complicates strategic decision-making.

Finally, the comparative LCAs are based on data-intensive and time-consuming processes. Collecting high quality data for a wide range of emerging technologies is particularly challenging. This severely complicates the comparison of a wide range of alternatives in a quick and easy manner. This is an issue for market stakeholders and policymakers, who wish to make decisions on the basis of comprehensive and conclusive analyses. Secondary LCA data from literature may be used to estimate impacts in a streamlined manner. The accuracy of such estimates is up for debate, however, and depends strongly on the methodological assumptions and underlying uncertainties.

1.5 Intended Results & Research Question

As a result of the analytical inconsistencies and methodological ambiguities in the existing body of LCA literature, drawing definitive conclusions regarding environmental impacts is severely complicated. The goal of this research is address aforementioned uncertainties and to clarify impact magnitudes of marine power systems. In order to achieve this goal, this research aims to arrive at the following three results.

Firstly, it intends to provide a comparative analysis of the environmental impacts of some of the most promising future maritime power systems. This is a comprehensive analysis from a full life-cycle perspective, with a focus on CO_2 emissions. Rather than conducting a bottom-up assessment based on primary data, this comparison is based on a meta-review of data from existing literature.

Secondly, this research aims to provide an overview of the most significant impact categories and life-cycle stages, as well as an analysis of major uncertainties. The key impact areas provide insight into the most environmentally relevant system elements. In turn, this provides guidance with respect to practical focus areas for potential future improvements in environmental performance. The analysis of uncertainties improves the understanding of key system parameters, as well as the most relevant methodological choices. As a result, it provides guidance with respect to possible methodological improvements in the LCA process. Additionally, it identifies specific knowledge gaps in the life-cycles of alternative maritime systems that may require additional research.

Finally, the results are interpreted to arrive at recommendations for FPS. The interpretation focuses primarily on practical recommendations, relating to choices that may enhance the environmental performance of the FPS fleet. The implications of the results are also explored from a system-level perspective, in order to put the zero-emission challenge of FPS in a wider perspective.

In short, this research presents an exploratory review into the environmental impacts of alternative marine propulsion systems. This research distinguishes itself from bottom-up LCA research in that it aims to explore and interpret an emerging system, based on a meta-review of existing LCA studies. The results are interpreted on a system-level and the implications for FPS are discussed and synthesized into practical recommendations. A detailed justification of this approach is presented in Chapter 4. The goals and intended results of this study are captured in the following primary research question:

*What are the **key environmental impacts** and **uncertainties** in the life-cycle of alternative maritime propulsion systems, based on Life-Cycle Assessment data from literature, and what are the **implications** for Future Proof Shipping?*

Chapter 2

Literature Review: LCA

This chapter presents a literature review relating to the LCA methodology in general, and the existing body of LCAs into marine power system in particular. First, Section 2.1 presents an overview of the LCA process and introduces its key concepts. Second, Section 2.2 presents a review of the existing LCA literature and details on its shortcomings. Finally, Section 2.3 elaborates on the limitations of the LCA methodology, and argues in favor of employing a meta-analysis for the purpose of this study.

2.1 Life-Cycle Assessment (LCA)

The method for assessing full life-cycle impacts and identifying key impact areas in this study is based on the review of Life-Cycle Assessment (LCA) literature. The LCA is the most widely used tool for assessing environmental impacts of products, processes or activities throughout all stages of its life cycle (Guinée et al., 2004). In the vast majority of cases, LCAs are employed to assess the relative impacts of one system compared to one or more alternative systems (Heijungs et al., 2019). This comparative approach is particularly useful for identifying key impact areas and life-cycle hot spots. Especially in a decision-making context, this comparative approach to conducting LCAs has proven to be a suitable and valuable tool (Guinée et al., 2011). This makes an LCA particularly interesting for stakeholders such as FPS, who wish to implement and scale technologies with the least possible environmental impacts.

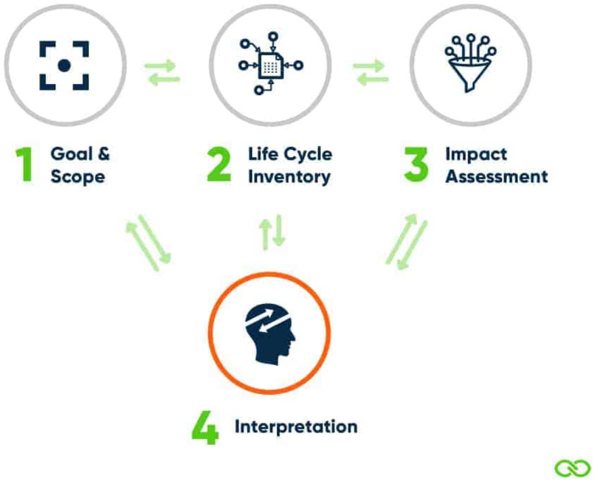

Figure 2.1: *Schematic representation of the four stages of the LCA methodology. Image taken from Liebsch (2019).*

The LCA process is commonly described as a four-step process, consisting of 1) a goal and scope definition, 2) a life-cycle inventory analysis, 3) an impact assessment, and 4) an interpretation phase. This process is typically presented as a semi-linear process, meaning that the first three steps are taken consecutively, while the interpretation phase is continuous. Within this semi-linear process, there is room for reiteration, whenever this is deemed necessary due to newly acquired information. The process is schematically shown in Figure 2.1.

During the first phase of the research, the goal and scope definition, the initial choices and assumptions with respect to the researched system are defined. Among the elements defined in this phase are the research question, intended application of the LCA, objects of analysis, functional units, technological alternatives and boundary conditions (Guinée et al., 2004). While choices relating to the scope are ideally based on thorough research and scientific literature, subjective judgments by LCA practitioners are unavoidable (Matthews et al., 2019). The wide variety of scoping choices encountered in LCAs of hydrogen energy systems was comprehensively mapped by Valente et al. (2017). As argued in the problem definition (Section 1.4), these differences significantly impact the direction of the research, and may have decisive effects on the final results (Hetherington et al., 2014; Rebitzer et al., 2004; SAIC, 2006; Weidema et al., 2004). Awareness and transparency with respect to assumptions are thus crucial when communicating the findings and limitations of an LCA study.

Within the defined scope, an overview of relevant materials, processes and flows is constructed (Step 2). This overview may be referred to as an Inventory, Reference Flows or the Bill-of-Materials. The inventory should include all the relevant processes and material flows of the researched system, within the previously defined boundary conditions. These may include material flows, energy flows and emissions flows. An inventory may be constructed based on data from literature, LCA databases, or first-hand data provided by manufacturers and other relevant parties. Since LCA databases are not available to FPS and the researcher of this study, the inventory is primarily based on literature, and validated by manufacturers whenever possible.

When the inventory of the systems is satisfactorily constructed, the impact of the system can be assessed. This is done by means of so-called emission factors (also referred to as embodied emissions, embedded emissions or emission intensity). Emission factors express the rate of emissions as a function of a reference flow (M. Ashby, 2012). Examples include tonnes of CO2 per trip, kilograms of SO_x per kilogram of material, or grams of NO_x per kilowatt-hour of electrical output. In the presence of an accurate and comprehensive system inventory, emission factors can easily be used to translate inventory data into emission impact data. Optionally, emission data may be weighed and translated into relevant impact categories, such as Global Warming Potential, Acidification Potential or Human Health Impact. This step is not performed in this review.

Parallel to each of these LCA phases runs the interpretation phase. The interpretation phase serves to continuously reflect upon the methodological choices that are made in the LCA process, and to reiterate the methods or scope whenever this is required after critical reflection. Perhaps even more importantly in the context of this study is to identify the key impact areas, key differences and key uncertainties, and to interpret the practical implications of the findings for FPS. The exact way in which this study dealt with these interpretive aspects is elaborated upon in the upcoming sections (2.2 and 2.3).

2.2 Existing LCAs on Alternative Shipping

With respect to marine power systems, the vast majority of LCA studies are focused on fuel production and power system operation. DNV GL (2019b), for instance, have performed an LCA study into the GHG emissions of power systems based on HFO, hydrogen, ammonia, methanol and fully electric alternatives. For this assessment a well-to-wake scope was adopted, which included emissions from production, transport and storage of each fuel, as well as combustion/conversion to mechanical energy on board the vessels. Similar well-to-wake LCA studies have been performed by Bengtson et al. (2011), who only considered fossil fuel alternatives, and Brynolf et al. (2014), who also considered liquefied biogas and bio-methanol alternatives. Deniz & Zincir (2016) used a matrix-based assessment method to compare environmental and economic impacts of methanol, ethanol, LNG and hydrogen alternatives. In this study, the scope was limited to the impacts of on board use. Finally, Lloyd's Register & UMAS (2020) and Gilbert et al. (2018) estimated the CO2 impacts of the production of a wide range of low carbon fuels from a "full life-cycle" perspective. This scope included both upstream emissions related to fuel production/acquisition, as well as operational impacts (including transportation, bunkering and storage). Gilbert et al. (2018) also consider different possible scenarios for 2050.

The aforementioned studies all share a fuel-centered approach to assessing impacts of marine power systems. Other life-cycle phases, such as the manufacturing, maintenance and end-of-life phases of the power system components, are largely outside of the scope of existing literature. Gilbert et al. (2017), argue that low carbon shipping research focuses too strongly on energy efficiency and mitigation measures related to operations, while largely disregarding the impacts relating to material efficiency and manufacturing. Despite the limited academic attention towards materials efficiency, several studies in relation to material efficiency in the maritime industry have still been identified. Bicer & Dincer (2018) researched the environmental impacts of power systems based on hydrogen and ammonia. The manufacturing and maintenance phase of the entire vessel are accounted for in this study. What is not considered, however, is how the impacts of the manufacturing process of the energy converters differ for each of the power systems. Instead, a generic vessel is assumed, irrespective of the power system that is used. As a result, it is not possible to assess the differences in environmental impacts in the manufacturing, maintenance and end-of-life phases of the two power systems.

Generally, the impact allocation in the existing body of LCAs is conducted at a high level of aggregation. This means that the impacts of several life-cycle stages are simplified into a single impact indicator. The most common allocation procedure in literature is based on a distinction between operational and upstream emissions (Balcombe et al., 2019; Gilbert et al., 2018; Lloyd's Register, 2019). Occasionally, other sub-stages of the life-cycle are distinguished, but their comparability is low due to significant differences in assumed life-cycle boundaries. When boundary conditions of the different life-cycle phases are ambiguously defined or presented based on black-box methodologies, impacts allocation is complicated even further (Mehmeti et al., 2018).

Ling-Chin & Roskilly (2016) conducted a comparative LCA based on a bottom-up assessment for individual power system components. The study considered two alternative power system scenarios: a retrofit power system based on lithium ion batteries and PV systems, and a new-build all-electric power system. The inventory analysis results showed that both retrofit and new-build systems consumed less fuels and released less emissions (5.2–16.6% and 29.7–55.5% respectively) during operation, whilst more resources were consumed during manufacture, dismantling and the end of life. By including a comprehensive inventory analysis of the power systems, the study effectively deals with some of the shortcomings relating to aggregation of impacts. However, the specificity of the cases considered in this study limits the transferability of results to other power systems and vessel types.

Finally, Favi et al. (2018) have proposed a data framework for assessing the environmental impacts of vessels based on detailed design information. The study presents an effective method for assessing the impacts of the materials in the manufacturing phase, provided that detailed data on the life-cycle inventory is available. However, the applied method assumes a high level of detail which is time consuming, making it unsuitable for a quick exploratory comparison of a wide range of alternatives.

2.3 LCA Limitations & Uncertainties

As argued in the previous section, the comparative LCA methodology is a useful tool for assessing relative impacts and identifying key environmental problem areas and hot spots. However, this report has noted that the LCA methodology is subject to significant methodological limitations, which increase uncertainties in results. These limitations and uncertainties have received widespread attention in academic literature on the LCA methodology (Cherubini et al., 2018; Finnveden, 2000; Heijungs & Huijbregts, 2004; Ross et al., 2002; van der Giesen et al., 2020).

Firstly, the effect of subjective scoping choices on final results is generally accepted as a source of discrepancies among LCA studies (Matthews et al., 2019; Rebitzer et al., 2004). As such, the widely observed ambiguity relating to methodological assumptions in LCA literature has been cited as a major source of uncertainties, which limits comparability of results (Cherubini et al., 2018; Roßmann et al., 2019). Secondly, distinctions between different life-cycle phases are often lacking as a result of impact aggregation. This leads to (overly) generalized results, which in turn may lead to misleading conclusions and misguided recommendations (Cherubini et al., 2018). More detailed analyses are required to better understand the situation specific conditions that cause discrepancies (Ross et al., 2002). Thirdly, LCA literature is likely to consider system configurations that differ from the configuration of the researched system. Harmonization of these differences on the basis of literature is complex, if at all possible, and further limits comparability (Corsten et al., 2013). Finally, LCAs require large amounts of inventory and process data. When data quality is poor, the reliability of results is significantly affected (Finnveden, 2000). This applies in particular to emerging technologies, where high quality data is not readily available (Hetherington et al., 2014; van der Giesen et al., 2020).

Combined, these uncertainties may result in a perception of inconclusiveness with respect to “true” environmental impacts. Strategies to deal with these uncertainties have focused on *increasing methodological transparency* (Ross et al., 2002; van der Giesen et al., 2020; Hetherington et al., 2014), *employing statistical approaches to quantify uncertainties* (Cherubini et al., 2018; Guo & Murphy, 2012; Heijungs & Huijbregts, 2004), and *qualitative assessments of assumptions* (Igos et al., 2019; Leroy & Froelich, 2010). The use of qualitative methods has received particular attention in recent years, since it is argued that they create invaluable situation-specific insights for decision-makers (Igos et al., 2019; van der Giesen et al., 2020; Bałdowska-Witos et al., 2020; Alyaseri & Zhou, 2019).

An alternative approach is based on a meta-analysis of existing LCA literature (Lifset, 2012). Meta-reviews may provide valuable contributions to a body of research, by solidifying or challenging assumptions and theories with respect to system dynamics (Zamagni et al., 2012). In the context of LCA research, the meta-analysis creates quantitative and qualitative insights into the relative importance of different sub-systems. Moreover, it aims to better understand crucial uncertainties and system parameters, with the goal of uncovering the specific sources of discrepancies in impact results (Post et al., 2020). The ultimate goal of such a review-based LCA is to harmonize seemingly conflicting data and to better understand underlying system dynamics (Brandão et al., 2012). This meta-level research approach has recently gained popularity and has been employed in a variety of different industries, including the *food sector* (Henriksson et al., 2021), *waste processing* (Gentil et al., 2010), *building industry* (Abd Rashid & Yusoff, 2015), *solar PV manufacturing* (Muteri et al., 2020), and *Carbon Capture and Storage* (Corsten et al., 2013). This widespread application of the meta-analysis points to the prevalence of uncertainties in LCA research, and illustrates an existing need to make sense of conflicting results. It is argued that the quantitative and qualitative insights produced by a meta-review of LCA studies, will make the existing body of LCA studies more useful to decisions makers.

Chapter 3

Literature Review: Alternative Fuels & Conversion Technologies

In this chapter, the system alternatives considered in this study are introduced in more detail. Some of their most interesting properties are discussed in order to justify their inclusion in this study. Whenever necessary, this chapter provides the appropriate technical background for understanding the relations between alternative fuels and their associated power system are provided. In Section 3.1, the most promising alternative fuels and conversion systems are elaborated upon. Section 3.2 explores the different options for transporting these fuels from their production plant to the bunkering stations in a port. Finally, Section 3.3 explains how the fuels are utilized by the on board energy converter. This explanation focuses on the case of hydrogen utilization in a Proton Exchange Membrane Fuel Cell (PEMFC). Details on the utilization of diesel fuels in an ICE are presented in Appendix A.

3.1 Alternative Fuel Choices

Several promising alternative fuels have been identified in Sections 1.3 and 2.2 of this report. Fuel cell technology in combination with hydrogen or ammonia fuel has been introduced as a particularly promising alternative. Figure 3.1[1] presents an overview of the different combinations of fuel and conversion technology that are taken into account in this study. Note that this selection is by no means exhaustive. It does, however, reflect a range of existing and novel pathways, with realistic potential for implementation in the maritime industry in the next decade (DNV GL, 2019b).

A total of 10 different pathways are considered in this research. Each of these pathways starts with an energy source that is processed into an energy carrier and subsequently utilized in a power conversion system. Pathway 1 represents the base-case that is representative of the incumbent system and serves as a reference to the current fossil fuel-dominated situation. In this pathway, crude oil is processed into HFO, MDO or MGO via complex refinery processes (Bredeson et al., 2010; Johnson & Vadenbo, 2020; Jungbluth et al., 2018). The use MGO is assumed in this study, and hereinafter referred to simply as diesel. Upon delivery onto a vessel, the diesel fuel is combusted in an ICE to deliver power.

Pathways 2 to 5 are based on utilization of hydrogen fuel in a PEMFC. Four different hydrogen production pathways are taken into consideration. Pathways 2 and 3 are based on the steam reforming of natural gas, commonly referred to as Methane Steam Reforming (MSR) (Bareiß et al., 2019). Pathway 2 represents the MSR method which is currently by far the most common method for producing hydrogen. Pathway 3 explores MSR in combination with Carbon Capture and Storage (CCS) technology. This is currently only a marginal technology. Pathways 4 and 5 are based on hydrogen production via electrolysis of water. A wide variety of electrolysis methods may

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[1] The figure is an abstract visualization of the considered pathways, not a representation of actual material or energy flows. For more details on fuel cycle flows, please refer to Appendix B.

be considered (Dincer, 2012; Dincer & Acar, 2014). In this study, the proton exchange membrane (PEM) process is assumed. Both grid electricity and renewable electricity are considered as inputs of the electrolysis process. The produced hydrogen is compressed or liquefied at the production plant and later used as a fuel in a PEMFC fuel cell.

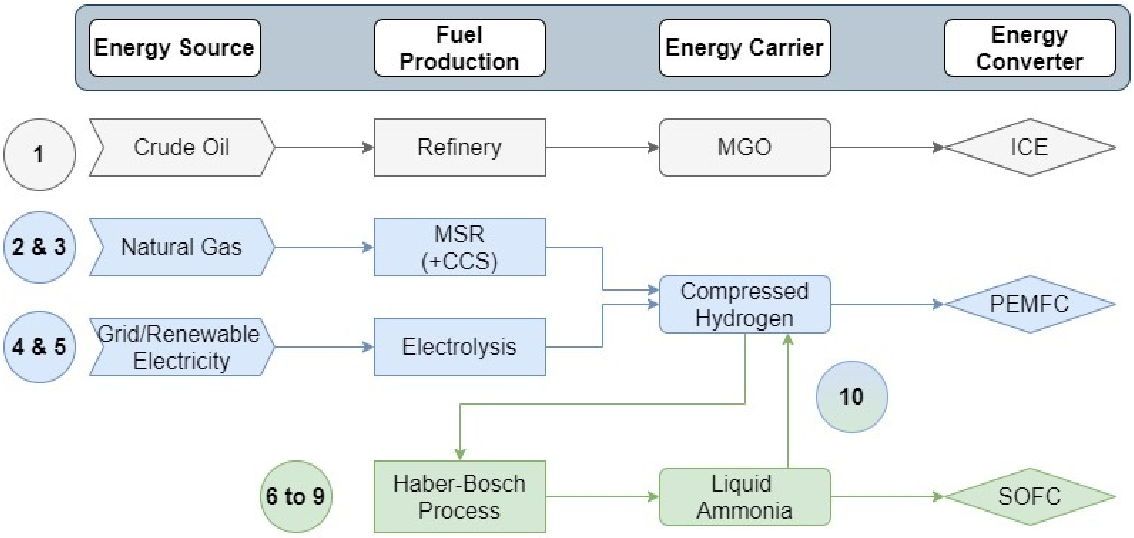

Figure 3.1: *The ten different scenarios considered in this research, with variations in primary energy source, fuel production process, energy carrier and energy converter.*

Pathways 6 to 9 are based on the production and use of ammonia fuel in an SOFC. Ammonia is produced in the so-called Haber-Bosch process, which requires hydrogen and nitrogen as essential feedstocks (Cheema & Krewer, 2018). The hydrogen production processes of Pathways 2 to 5 are thus also an integral part of the ammonia production pathways. As such, ammonia may also be looked at as a carrier or temporary storage of atomic hydrogen.

Ammonia is most effectively utilized when applied directly in high temperature SOFCs (Jeerh et al., 2021; Lan & Tao, 2014). Under the influence of high temperatures in the SOFC, ammonia is internally reformed into hydrogen, nitrogen (N_2), and traces of NO_x. The resulting hydrogen is subsequently used as fuel, while N_2 and NO_x are emitted to the air.

Alternatively, the reforming of ammonia may be performed externally, prior to entering the fuel cell. The resulting hydrogen is suitable of applications in a PEMFC. In this scenario, ammonia acts as a temporary storage mechanism for hydrogen. This alternative is shown as Pathway 10 in Figure 3.1. However, direct ammonia applications are incompatible with PEMFCs, due to the low operating temperatures.

3.2 Transportation & Distribution Options

After the production process, hydrogen fuels may be stored and distributed to end-users in several different ways. Each of the distribution scenarios is associated with a different set of advantages and disadvantages, due to the different physical properties of the stored fuels. The relevant properties are presented in Table 3.1. Liquid NH_3 is considered a hydrogen transportation mechanism as well, since NH_3 is a carrier of atomic hydrogen. MGO properties are included as a reference to the base-case system.

For the distribution by means of storage tanks (trucks, trailer or vessel), the energy density is a crucial parameter. Table 3.1 shows that the energy density of hydrogen and ammonia fuels is substantially lower than that of conventional MGO fuel. This means that more on-board fuel stor-

Table 3.1: *Physical properties of different energy storage systems/fuels.*

Storage Method	Pressurization (bar)	Energy Density (MJ/L)	Specific Energy (MJ/kg)	Liquification Temperature (C)
MGO	N/A	38.6	45.6	N/A
Compressed H_2	300	2.4	120	N/A
Liquid H_2	1.013	8.5	120	-253
Liquid NH_3	1.013	11.5	18.6	-33
Battery Electricity	N/A	0.9	0.4	N/A

age space is required in the alternative scenarios, as compared to the base-case scenario. This is important for vessel owners, who wish to maximize the on-board storage capacity for transporting cargo. However, limiting the fuel storage capacity has detrimental effects on the shipping range of vessels. A trade-off in either cargo capacity or fuel capacity (and sailing range) is therefore likely necessary when switching to alternative scenarios.

Additionally, a trade-off in storage efficiency and process efficiency is likely required as well. The energy density of ammonia is substantially higher than that of hydrogen compressed to 300 bar, and slightly higher than that of liquefied hydrogen. This means that hydrogen energy is most efficiently stored and transported by means of liquid ammonia, based on spacial storage requirements. However, the production of liquid ammonia requires additional processes steps, most notably Cryogenic Air Separation and the Haber-Bosch process, which limit the the overall energy efficiency of its life-cycle. With respect to liquid hydrogen, the liquefaction process requires a large amount of energy due to the low temperature requirements. The energy requirements are roughly equal to 35% of the chemical energy of hydrogen and thus limit the overall energy efficiency (Elgowainy et al., 2017). The energy requirements for the compression of a kilogram of H_2 to 300 bar are only around 5%. However, the energy density is substantially lower compared to the other alternatives.

In addition to distribution via storage tanks mounted on trucks, trailers or vessels, hydrogen may also be distributed via pipelines. Pipeline distribution of hydrogen is similar to the distribution of natural gas via pipelines. As such, the natural gas grid in the Netherlands provides great potential for distributing large volumes of hydrogen in the future. Pipeline distribution requires lower pressurization than storage in compression tanks: 70-100 bar compared to 300 bar (Wulf et al., 2018). The environmental effects of each option are not yet know at this point in time. By assessing the pathways of Figure 3.1 from a full life-cycle perspective, this study aims to gain more insight into the environmental trade-offs that may play a role in the choice of storage and distribution options.

3.3 Working Principle Hydrogen Fuel Cell

Hydrogen fuel cells (FC) are devices which generate electrical power via electrochemical reactions, rather than mechanical power through combustion. The basic fuel cell principle is based on the conversion of chemical energy of hydrogen fuel and oxygen, into an electric DC current which is fed to an external circuit. In this process, only heat and pure water are generated as “waste” products. Fuel cells may be employed to power electric motors for the propulsion of vessel and thus provide an emission-free alternative to the fossil fuel-based ICE.

3.3.1 Fuel Cell Types

A wide variety of different hydrogen fuel cell types and applications may be distinguished. Among these are the proton exchange membrane fuel cell (PEMFC), the solid oxide fuel cell (SOFC), and the molten carbonate fuel cell (MCFC). The preferred application of each fuel cell type depends on its unique characteristics.

In the context of maritime applications, the PEMFCs are among the most promising options. Firstly, PEMFCs enjoy high volumetric power densities at low mass, which makes them suitable for mobile applications. Additionally, PEMFCs operate at low temperatures, typically below 100 degrees Celsius. This allows for rapid start-up times and excellent load following, which in turn allows for quick variations in electrical output. This is ideal for inland shipping and other mobile applications. Finally, PEMFCs enjoy long operating lifetimes of over 20000 hours. Disadvantages include the required use of expensive (platinum) catalysts and the limited tolerance to fuel impurities, particularly of carbon monoxide (CO) (van Biert et al., 2016; Wang et al., 2020).

SOFCs may provide an alternative to PEMFCs because of their much higher operating temperatures (500-1000 degrees Celsius). At these temperatures, CO poisoning does not occur, and the use of the expensive platinum catalyst is not required. With a maximum electrical efficiency of 40-60%, the SOFC achieves efficiencies similar to the PEMFC. However, the gravimetric and volumetric power densities are substantially lower, meaning that greater volumes are required for a similar power output. This is a significant drawback for inland shipping applications, where on-board vessel space is limited. Additional disadvantages are the long start-up times and slower transient response compared to the PEMFC.

3.3.2 Working Principle

While varieties of fuel cells are different in terms of operation and characteristics, they all share the same basic components: two flow plates, two sealing gaskets, two electrodes (anode and cathode), and an electrolyte (Figure 3.2). In this section, the fuel cell working principles are explained based on the example of the PEMFC.

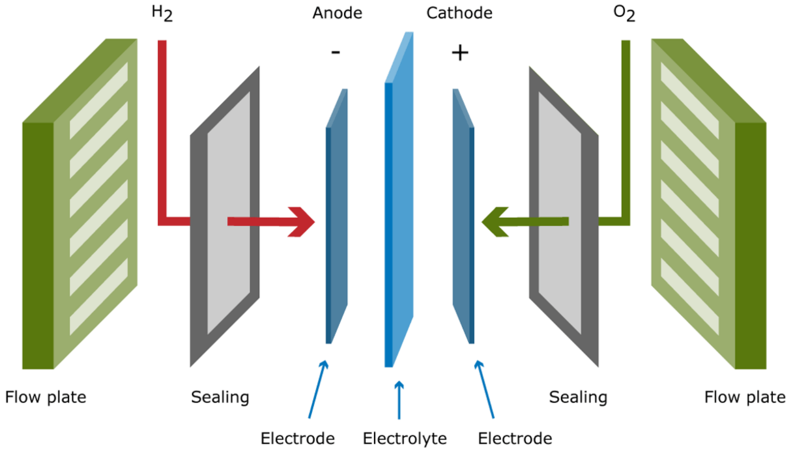

Figure 3.2: *Basic fuel cell components. Image taken from NedStack (2021).*

The channels in the graphite flow plates are used to conduct hydrogen fuel and oxygen to the electrodes on either side of the fuel cell. The gasket sealing provides an airtight environment that prevents any leaking of hydrogen or oxygen. At the anode, a platinum catalyst causes the hydrogen (H2) molecule to split, creating hydrogen ions (H+) and electrons (e-):

$$2H_2 \rightarrow 4H^+ + 4e^- \tag{1}$$

The Polymer Electrolyte Membrane (PEM) at the center of the fuel cell is designed to conduct the positively charged hydrogen ions from the anode to the cathode. Simultaneously, it acts as an insulator to electrons and a reactant barrier to oxygen and hydrogen. Electrons are consequently forced to the cathode though an external circuit, in which they provide a source of electrical power. The electrically conductive pathway for current collection is provided by a so-called Gas Diffusion Layer (GDL), which sits on the electrolyte surface. The GDL also facilitates the passage and removal of reactants, water and heat, and protects the catalyst layer against erosion and corrosion. After passing through the external circuit, the electrons combine with the hydrogen ions and oxygen at the cathode to form pure water (H_2O):

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{2}$$

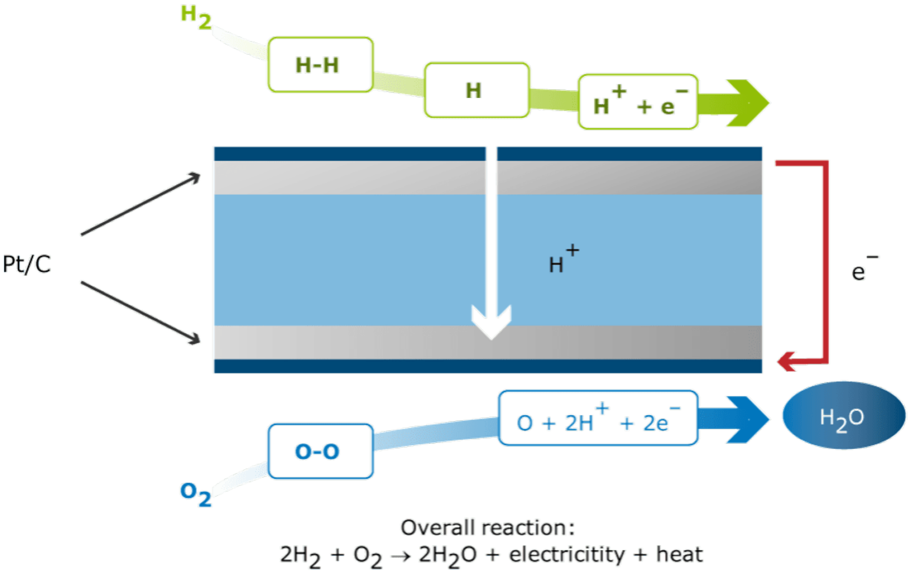

Figure 3.3: *Schematic representation of the half reactions in the hydrogen PEMFC. Image taken from NedStack (2021).*

This entire process is schematically represented in Figure 3.3. Combining the half reactions in equation 1 and 2, leads to the following total reaction:

$$2H_2 + O_2 \rightarrow 2H_2O \tag{3}$$

Fuel cells are processed into a fuel cell stacks in order to increase the voltage of the system and provide adequate power for operational purposes. Such a stack is created by connecting individual fuel cells in series. In this stack assembly, the flow plates serve the additional purpose of conducting the electrical current from one cell to the next. This is visually represented in Figure 3.4.

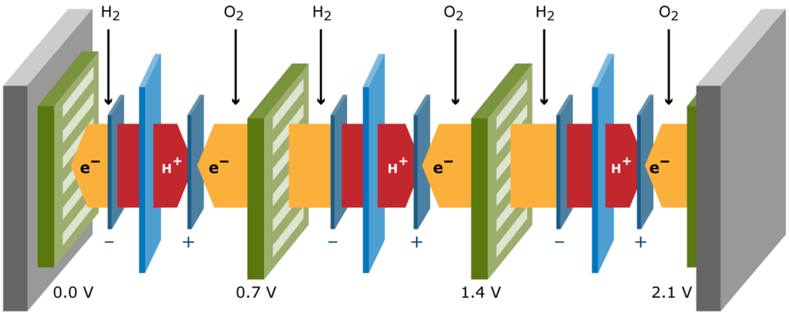

Figure 3.4: *Schematic representation of a fuel cell stack consisting of three fuel cells in series. Image taken from NedStack (2021).*

The fuel cell stack is completed by its Balance of Plant (BoP). The BoP refers to all components that are required for proper functioning, apart from the fuel cell stack itself. These include pumps, sensors, humidifiers, the fuel management system, among others (Miotti et al., 2017a).

Chapter 4

Methodology

In this chapter, the methodology for arriving at the the intended results of this research are elaborated upon. Section 4.1 sets out the general approach to the life-cycle assessment employed in this study. Consequent sections provide details with respect to the specifics of each assessment stage: a quantitative meta-review (4.1.1), a detailing review (4.1.2), and a system-level analysis (4.1.3). Section 4.2 elaborates on specific scoping choices, including the system boundaries (4.2.1), functional unit (4.2.2), and the analyzed systems (4.2.3).

4.1 Assessment Approach

This study employs a research approach which combines elements of different LCA approaches, and is based on both quantitative and qualitative assessment methods. The goal of this mixed-method approach to acquire and compare environmental impacts in a quick and easy manner, with sufficient accuracy to enable strategic decision-making. Figure 4.1 schematically represents the structure of the research, as well as the individual element elements that combine to arrive at the intended results (Section 1.5).

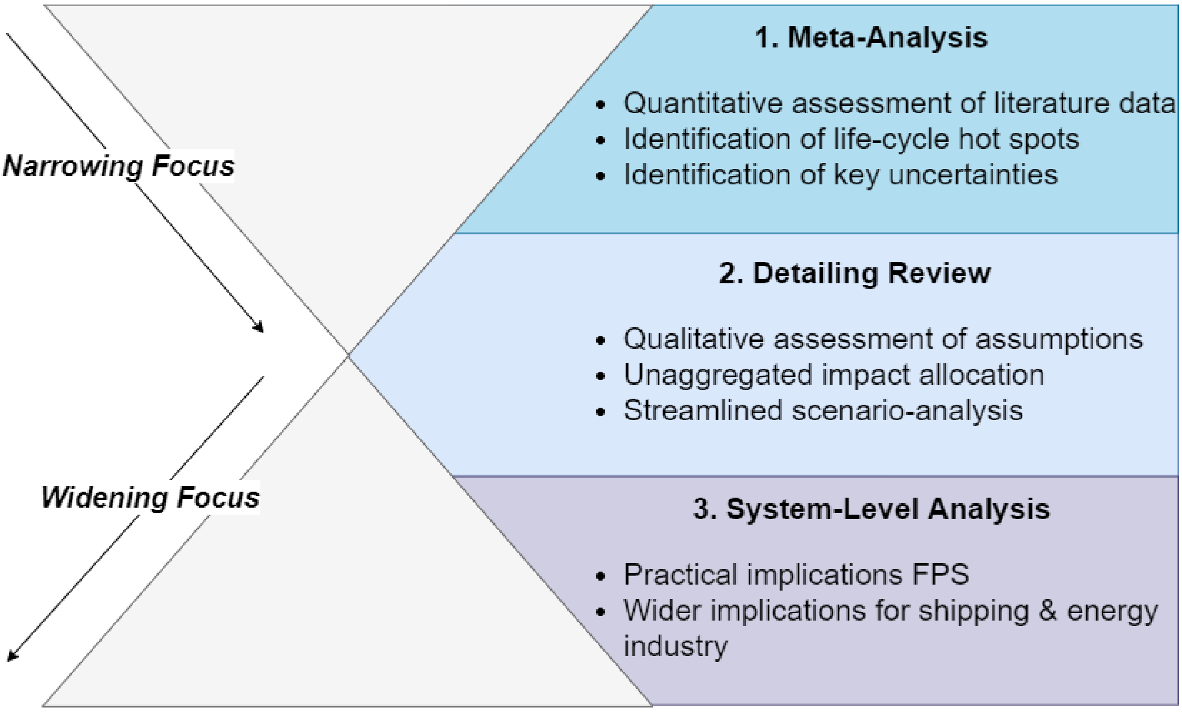

Figure 4.1: *Schematic representation of methodological approach taken in this study.*

First, a comparative assessment is conducted on the basis of a meta-analysis of existing LCA literature. This assessment is of a quantitative nature and aims to estimate life-cycle impacts of some of the most interesting system alternatives. In addition, it identifies key environmental hot spots the life-cycles of the system alternatives, which are deserving of a more detailed analysis. Finally, it aims to identify the key uncertainties in life-cycles, by assessing the relative spread and differences in impact assessment values by different LCA studies. A large relative spread in reported impacts is considered an indicator of significant underlying uncertainties (Igos et al., 2019). As such, the quantitative meta-review identifies specific life-cycle hot-spots and uncertainties that are targeted by a more comprehensive qualitative detailing review.

This detailing review is based on a qualitative assessment of underlying assumptions, boundary conditions, scoping choices, or any other factors that may contribute to uncertainty in results. The goal of this review is to come to a better understanding of the system dynamics that influence that result of an LCA. The primary aim is not to assess the “correctness” of one set of assumptions over the other. Rather, this study embraces the philosophy set forth by Roßmann et al. (2019), which calls for the recognition and acceptance of plurality in LCA methodologies. It is argued here that, in addition to being an assessment tool, the LCA has an important function in inspiring and promoting learning, discussion and critical thinking.

In addition, the detailing review aims to allocate life-cycle impacts at a lower level of aggregation (greater level of detail). This is first based on the qualitative analysis of inventory data in LCA literature. If the qualitative review fails to provide sufficient insight or detail, streamlined quantitative LCA calculations are performed. The streamlined LCA uses inventory data from additional sources to estimate impacts for different system scenarios (Arena et al., 2013). The streamlined LCA calculations is also referred to, in different methodological variations, as an eco-audit (M. F. Ashby, 2013), a screening LCA (Hochschorner & Finnveden, 2003), or a prospective LCA (Arvidsson et al., 2018; Mendoza Beltran et al., 2020).

After acquiring life-cycle impacts data at the desired level of detail, a system-level analysis is performed to assess the practical implications of the results for the case of FPS. The goal is to arrive at practical recommendations that assist their decision-making process. In addition, the most important implications for the wider shipping and energy system are discussed. The goal of this system-level interpretation is to explore the potential for widespread adoption of the most environmentally promising system alternatives.

The strength of the mixed-method approach employed in this report is manifold. Firstly, the approach builds on the existing body of LCA literature and provides a much more targeted approach for identifying knowledge gaps in the life-cycle of emerging systems. As such, this approach relies much less on the collection of original data for bottom-up life-cycle assessments. Especially in the case of emerging technologies and systems, these assessments are characterized by long and cumbersome data collection processes, which do not necessarily lead to significantly more accurate results.

Secondly, as a result, more time and resources are available towards qualitatively understanding the dynamics, leverage points and uncertainties that impact the system and drive results. In the uncertain context of emerging systems, these qualitative aspects are considered of greater value than a purely quantitative evaluation. As such, this report is not just another study in the already vast and confusing body of LCA research. Rather, it contributes an improved understanding of the critical system parameters.

Finally, the detailed qualitative assessment of LCA methodologies allows for the identification of trends in methodologies and assumptions in the reviewed LCA studies (Corsten et al., 2013). This can be used to draw conclusions with respect to the strengths, limitations and possible improvements of the LCA methodology.

4.1.1 Quantitative Meta-Analysis

For the quantitative meta-analysis, academic LCA literature is selected from a variety of sources including ScienceDirect, ResearchGate, Scopus and Google Scholar. Keywords used in the search query include *life cycle assessment*, *life cycle impact*, *environmental impact assessment* and *carbon footprint*. These are combined with key words relating to the analyzed systems, which include (combinations of) *diesel engine*, *(PEM) fuel cell*, *hydrogen*, *ammonia*, *battery*, and *electrolysis*, among many others. The relevance of the resulting articles to the research question is assessed by reviewing the titles, abstracts, citations, and publication dates.

Environmental impacts of different life-cycle phases are derived from the selected literature and scaled to the appropriate functional unit defined in this study (see Section 4.2.2). The exact method of scaling depends on the way in which impact data is presented in the consulted literature. This review results in a range of possible emissions on a high level of aggregation. The average impacts are determined to get a first estimation of life-time CO_2 emissions. The relative spread in the reported emissions is estimated by determining the standard deviation in the impact data. The standard deviation is significantly impacted by data outliers and extreme values. A large standard deviation thus indicates that data is spread over a wide range. As such, it is considered an indicator for significant inconsistency in literature data, which in turn points to possible uncertainties.

While this method initially lacks the level of detail required for impact allocation on an individual component level, it is proven to be successful in identifying life-cycle hot spots, key impacts areas and uncertainties in a streamlined way (Arena et al., 2013; Arvidsson et al., 2018; Corsten et al., 2013). This is exactly the purpose of the meta-review.

4.1.2 Qualitative & Quantitative Detailing Review

A detailed qualitative review of the identified literature is conducted, with a focus on the key impacts areas and uncertainties identified in the scoping review. Firstly, an analysis of methodological assumptions is conducted to arrive at a better understanding of the impact discrepancies of the meta-review and possible underlying uncertainties. Special attention is paid to spatial and temporal variability, boundary conditions, data aggregation level, data gaps, and representatives of the reference system (Igos et al., 2019; Leroy & Froelich, 2010).

Secondly, a detailed analysis of inventory data reported in the previously identified literature is conducted. This analysis is based on a thorough assessment of processes, material flows and emission factors. The goal of this analysis is to break generic and aggregated impact data down to a greater level of detail, and to allocate them to specific sub-stages in the system life-cycle. This more detailed allocation allows for the exploration of different scenarios, for example with respect to fuel distribution, which in turn results in a deeper understanding of the key impact areas and system sensitivities. Moreover, it allows for the exploration of different scenarios, which may be of practical interest to FPS.

Depending on data quality in the selected LCA literature, the qualitative detailing review may be insufficient for allocating impacts to specific life-cycle stages. Whenever this is the case, original inventory and emission data is collected for this specific life-cycle stage. This data is collected from different literature sources such as scientific articles and industry reports. Search queries will thus include keywords targeted at specific elements in this life-cycle stage. These key words cannot yet be determined at this point, since they depend on the results of the initial review. The collected data is used to perform streamlined calculations which estimate life-cycle impacts that are not sufficiently addressed in existing LCA literature. As such, these calculations target specific knowledge gaps identified in literature, or provide additional detail where a thorough breakdown of LCA literature is unable to do so.

4.1.3 System Level Analysis

Finally, the results of the meta-review and detailing review are interpreted from a system-level perspective. The practical implications for the zero-emission ambitions of FPS are discussed throughout the report, and the advantages and disadvantages of different scenarios examined. Whenever appropriate, specific recommendations are made for preferred scenarios or choices.

In addition, a system-level interpretation of the results is presented. This assessment explores the feasibility of widespread implementation of the most promising alternative. This analysis is based on the concepts of *quantitative exploratory scenario analysis* (Mahony, 2014; Moallemi et al., 2017), and *normative quantitative scenario analysis* (Maier et al., 2016). These concepts use quantitative assessments methods in order to identify the circumstances under which crucial system requirements can or cannot be satisfied. Back-of-the-envelope type calculations are performed to put the alternative system requirements into perspective (MacKay, 2010). Special attention is paid to the availability of renewable energy sources and infrastructural requirements, and the necessary orders of magnitude for decarbonization of the Dutch inland shipping sector.

The systems level interpretation is based on reviews of meta-studies regarding the possible role of alternative fuels in the Netherlands. The goal of this review is not to accurately predict future demand or required sustainable energy capacity. Rather, it aims to put the results and the decarbonization challenge into perspective, while identifying possible crucial bottlenecks for future implementation.

4.2 Scoping Framework

Chapter 2 argued on the importance of transparently defining the scope of an LCA. A common way of communicating LCA scoping choices and assumption is by drafting a so-called Goal and Scope report (Guinée et al., 2004). In it, the goal and scope of the research are defined as comprehensive and unambiguous as possible from the onset. This framework is based on a review of several standard works on LCAs and contains information on the most relevant scoping choices and assumptions (Curran, 2017; Guinée et al., 2004; Grant, 2009; Weidema et al., 2004). The full Goal & Scope Report is presented in Appendix C. In this section, the most relevant aspects of this report are presented and justified: the system boundaries (4.2.1), the functional unit (4.2.2), and the analyzed systems (4.2.3).

4.2.1 System Boundaries

The need to assess marine power systems from a full life-cycle perspective was argued based on the shortcomings in the existing LCA literature into the impacts of marine power systems (Chapter 2.2). Analyzing all relevant subsystems related to the energy system is considered crucial, since environmental impacts may occur in different parts of the system, depending on the operation the different alternatives (Finnveden, 2000). In accordance with the GREET life-cycle model for "Greenhouse Gas Emissions in Fuel and Vehicle Technologies", the scope is defined to include the operational phase, the fuel production phase and power system/converter manufacturing phase (Elgowainy et al., 2017). These phases encompass the raw materials acquisition phase, the processing of raw materials into final products, the distribution of final products, the use phase, and finally the end-of-life phase. These life-cycle phases, as well as their interconnections, are schematically represented in Figure 4.2.

Due to limitations in available resources and time, it is not feasible to assess each of the life cycle stages in unlimited detail. It is therefore decided to only consider primary reference flows. These are the flows that serve as a direct input to the processes presented in Figure 4.2. This excludes the manufacturing of capital goods from the analysis. Due to the previously introduced issue of data aggregation, there is no guarantee that literature-based data can be harmonized perfectly with the scope of Figure 4.2.

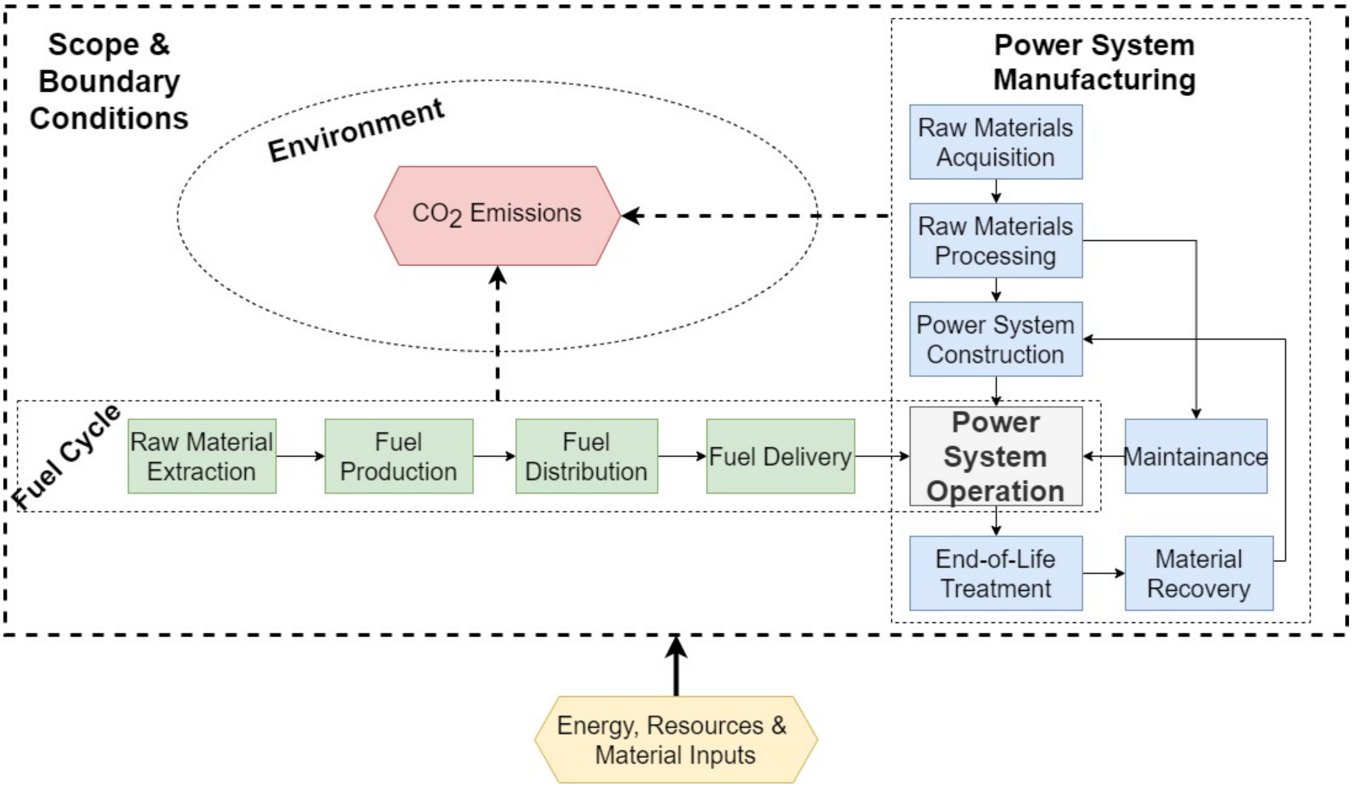

Figure 4.2: *The full life-scope considered in this study, along with the corresponding boundary conditions.*

4.2.2 Functional Unit

The functional unit is a unique feature of the LCA methodology, which was introduced in order to facilitate comparisons between complex systems (Guinée et al., 2004). By rendering two different systems functionally equivalent, impact data may be harmonized despite large differences in methodological choices (Corsten et al., 2013). Perfect harmonization is only possible, however, when all assumptions and data are transparently presented in LCA studies. The literature review has already shown that this is rarely the case. This means uncertainties in comparisons may arise, despite a properly defined functional unit.

In this study, the functional unit of the power systems is based on their shared function of propelling the MAAS. The Maas is an inland shipping vessel categorized as a standard container ship with a maximum tonnage greater than 1500 tonnes. The Maas represents a practical case-study for the purposes of Future Proof Shipping. Moreover, the Maas is representative of about 40% of the inland shipping fleet in the Netherlands (CBS, 2017). Details on the specifications of the Maas are provided in the top half of Table 4.1. Its average trip characteristics, as reported by FPS, are provided in the bottom half of Table 4.1.

The definition of the functional unit in LCAs on alternative energy system is most commonly defined based on the mass of consumed fuel, the energy of consumed fuel, or the distance traveled by a vehicle (Valente et al., 2017). Neither one of these definitions are suitable to capture the full scope of the system considered in this study. This is due to the fundamentally different nature of processes outputs, in the system manufacturing cycle, compared to the fuel production cycle. In order to capture both life-cycle elements in a single functional unit, the functional unit is formulated in more generalized way:

The propulsion of 1 Maas vessel traveling the same route for the course of 30 years, under the conditions defined in Table 4.1.

Table 4.1: *Physical parameters of the Maas in the current base-case situation (top). The characteristics of an average voyage by the Maas (bottom).*

The Maas – Vessel Characteristics	
Length (m)	110
Width (m)	11.45
Draught (m)	3.50
Cargo Capacity (TEU)	200
Maximum Tonnage	3041
Diesel Tank Capacity Stern (L)	75000
The Maas – Average Trip Characteristics	
Departure	Eemhaven (NL)
Arrival	Meerhout (BE)
Trip Distance (km)	200
Trip Frequency (trips/year)	220
Average Cargo (TEU)	160
Average Tonnage	2000

By defining the functional unit in this way, output flows required for fulfilling this function may be identified. In case of the fuel cycle, these outputs are the 30-year fuel consumption required for the operation of the system. In case of the power system manufacturing cycle, these outputs include all materials, components and machinery required for 30-year operation. All the related life-cycle processes, energies and materials for arriving at these outputs are derived in detailing review, which was explained in Section 4.1.2. This functional unit can be translated to other functional units such as fuel use, provided that the 30-year fuel use is known.

4.2.3 Analyzed Systems

Chapter 3 elaborated in detail on the different alternative shipping fuels and power systems. Figure 4.3 presents a detailed overview of the analyzed systems and their corresponding system components within the scope. Note that these system components do not necessarily represent all system components. For the sake of limiting complexity, only essential system components are taken into account.

The system manufacturing phase of the LCA takes into account the emissions resulting from the manufacturing and assembling of the system components of Figure 4.3. The required materials and process energies of the manufacturing phase are determined in large part by the life-times of the components in question: shorter life-times result in higher process demands, while longer life-times result in lower process demands. Table 4.2 presents the assumed lifetimes of the main system components, as well as the required number of components during the 30-year scope of this study. It is assumed that a full refit of a system component is required at the end of the life-time.

Table 4.2: *Lifetimes of the energy system components, along with the required number of components in a 30-year scope.*

Component	**Lifetime (years)**	**Number of components (per 30 years)**
Diesel Engine	30	1
Fuel Cell: Stack	7	4
Fuel Cell: Balance-of-Plant	30	1
Fuel Storage Tanks	20	2
Li-ion Battery	10	3

Each of the systems in Figure 4.3 is responsible for vessel propulsion according to the functional

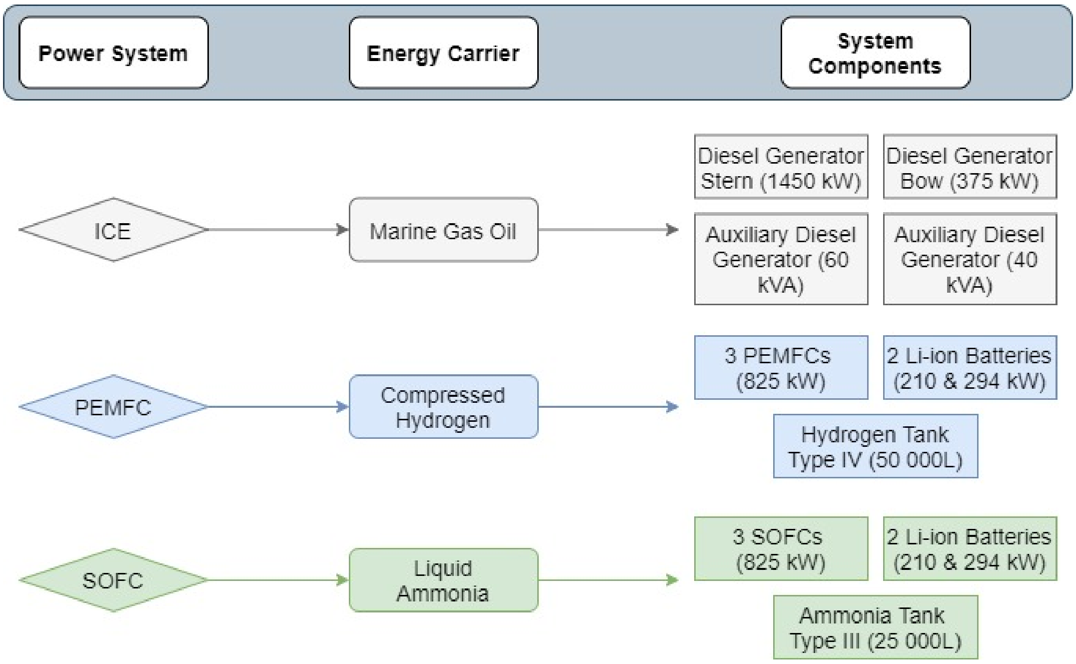

Figure 4.3: *The three different power system configurations considered in the base-case (grey) and alternative scenarios (blue and green).*

unit. Most of the power is consumed by a stern propeller shaft (in the diesel situation), or by a stern thruster (in the fuel cell scenario). A smaller fraction of power is consumed by the bow thruster, which serves to improve maneuverability at low shipping speeds. Finally, hotel electric power is required for a range of auxiliary operations. These operations include lighting, communications, HVAC, refrigeration, and a range of other purposes outside of propulsion. For a detailed overview of energy flows in each system, please refer to the Sankey diagrams in Appendix D.

Base-Case Diesel Scenario (ICE)

The diesel-based ICE power system serves as a representative case of the vast majority of inland shipping vessels and, as such, is treated as the benchmark base-case. In this conventional diesel-powered scenario, each of the three sub-systems (stern, bow and hotel power) requires a separate engine or generator. In case of the Maas, power for propulsion of the vessel is delivered by a 1450 kW Caterpillar 3516 diesel generator. This generator is directly coupled to the shaft and, as such, provides mechanical power directly to the propeller. A smaller 375 kW Caterpillar 3408 is used for the operation of the bow thruster. Finally, the auxiliary electric hotel power is delivered by two small John Deere generators (40 and 60 kVA). When in a port, the vessel's power system may be connected to the electricity grid, in which case the hotel power is delivered by the grid.

Hydrogen Fuel Cell Scenario (PEMFC)

In the hydrogen fuel cell scenario, all of the previously described subsystems are powered electrically, either by fuel cells or batteries. It is assumed that the fuel cells operate on compressed hydrogen at 300 bar. Two different operational modes may be distinguished in this case. Firstly, the shipping mode, in which the velocity of the vessel is non-zero, and secondly the port mode, in which the vessel is in a port and its velocity is equal to zero. In shipping mode, both the stern and bow thruster as well as the hotel applications are powered by three 275 kW PEMFCs. These fuel cells operate on a load sharing basis, meaning that each of the fuel cell provides one third of the load power at any given time. Li-ion batteries (210 and 294 kWh) may serve as a backup power source in shipping mode, in case a defect occurs in one of the PEMFCs. Moreover, the batteries may be used for peak shaving. In port mode, when vessel velocity is zero, the thrusters do not require any power. In this case, the electric hotel power is provided by Li-ion batteries, or by grid electricity. It is assumed that hydrogen is stored on-board in type IV hydrogen storage tanks with a total storage capacity of 50000 L, enough for at least two 200 km trips.

Ammonia Fuel Cell Scenario (SOFC)

The operation of the ammonia fuel cell scenario is largely similar to the hydrogen fuel cell scenario. Onboard power is delivered by three 275 kW SOFCs. These SOFCs also operate on a load sharing basis and provide electrical power to each of the three subsystems. Two Li-ion batteries (210 and 294 kWh) provide backup power when necessary and hotel power in port mode. Due to the longer start-up times and slower transient response of the SOFC compared to the PEMFC, batteries may also provide short bursts of (start-up) energy when required. Liquid ammonia is stored in 25000 L storage tanks, which provide enough volume for at least four 200 km trips. Because of the limited availability of ammonia storage tank data, the closest alternative is assumed which is a Type III storage tank. Due to its higher energy density, the ammonia storage tank is assumed smaller compared to the hydrogen tank. This saves on-board space which can be used for cargo. If desired, the storage tank volume could be increased to 50000 L. This increases the shipping range of a single tank, at a cost of 25000 L of on-board cargo space.

Chapter 5

Results & Discussion

This chapter presents the results of the Life-Cycle Assessment of promising future zero-emission shipping systems. Figure 5.1 presents an overview of the structure of this chapter, in relation to the defined scope and the different life-cycle stages. First, Section 5.1 presents the key results of the meta review[1] from a full life-cycle perspective. Key impact areas are identified and special attention is paid to the most important findings and their practical implications. Based on these findings, some of the most promising future pathways for FPS are identified.

Subsequent sections present the result of the detailing into the key findings identified in the meta review. This review presents a deeper exploration of the most promising pathways, as well as an analysis of methodological choices that impact uncertainties[2]. The detailing review is presented on the level of individual life-cycle stages: the operational phase (5.2), the fuel production phase (5.3), and the manufacturing phase (5.4). This structure allows for an in-depth and critical discussion of the results and their underlying specifics and uncertainties. Moreover, it allows for the exploration of various scenarios within a specific life-cycle stage.

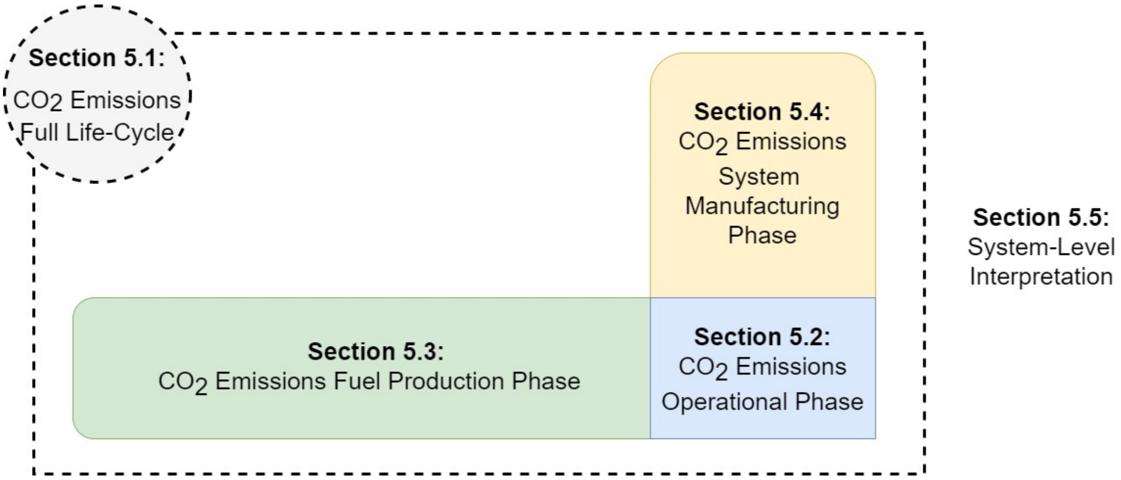

Figure 5.1: *The structure and topics of the sections in this chapter, in relation to the previously defined LCA scope.*

In Section 5.5 the possible implications of the findings for the inland shipping sector are discussed from a system-level perspective. Special attention is paid to the issues of availability of renewable energy sources, and the required distribution infrastructure.

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[1] For the literature consulted in the meta review, please refer to Appendix E.

[2] For the literature and original data used in the detailing review, please refer to Appendix F.

5.1 Full Life-Cycle CO_2 Emissions

Figure 5.2 presents the results of the meta-analysis of the full life-cycle of each of the scenarios defined in the scope (Section 4.2.3). These scenarios include the diesel fuel base-case, four hydrogen PEMFC scenarios and four ammonia SOFC scenarios. The bar charts represent the average CO_2 impacts based on data from the meta analysis, scaled to the Maas' system size. The standard deviation in the same data set is represented by the error bars.

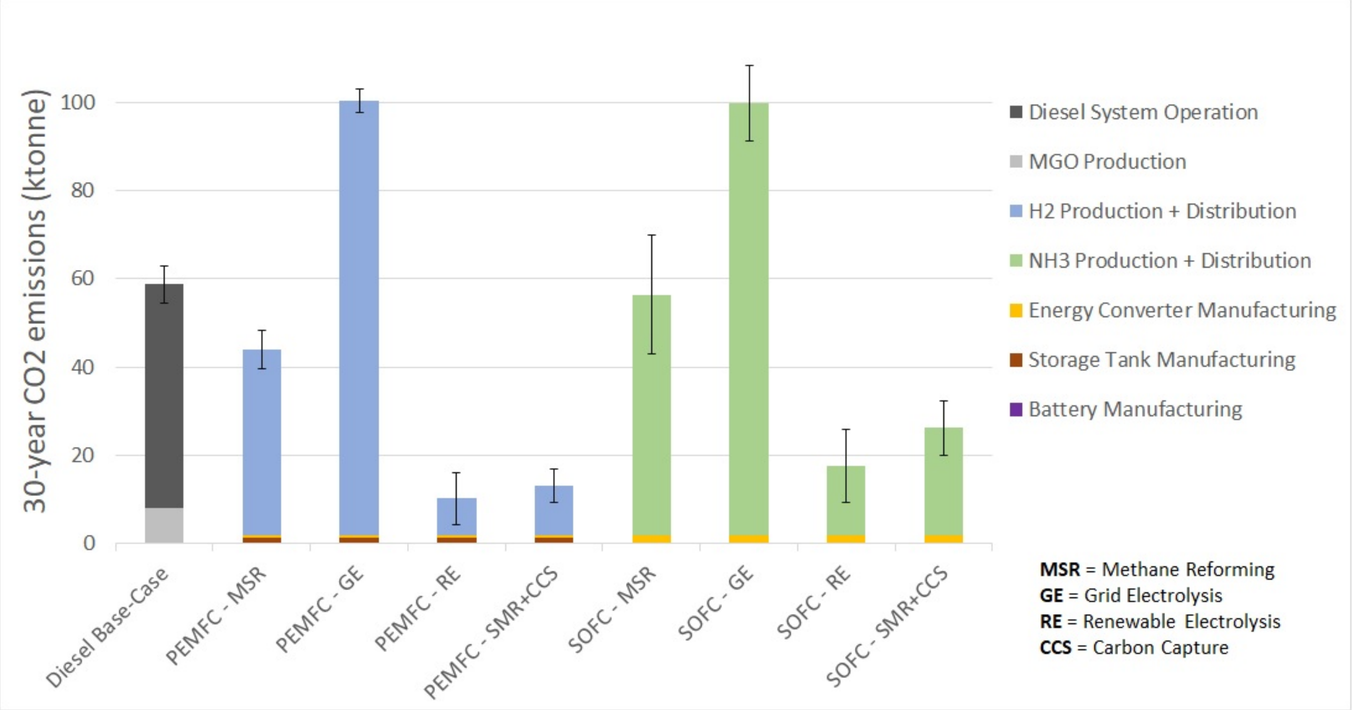

Figure 5.2: *The average 30-year CO_2 emissions for different alternative power system scenarios, based on the average data derived from the meta-analysis. Error bars represent the standard deviation in the data set of the meta-analysis.*

Figure 5.2 shows that the diesel-based base-case scenario produces a total of 58.6 ± 4.2 ktonnes of CO_2 in all life-cycle phases, over the course of the 30 year life-time. The alternative scenarios based on fuel production via MSR produce CO_2 emissions in a comparable range: 44.0 ± 4.3 ktonnes of CO_2 in the hydrogen-based MSR scenario, and 56.7 ± 13.4 ktonnes in the ammonia-based MSR scenario. Real significant reductions in CO_2 emissions are achieved by the pathways based on fuel production via renewable electrolysis, or MSR combined with CCS. In these scenarios, carbon impacts are reduced to levels as high as 32.3 tonnes, and as low as 4.3 ktonnes in 30 years. With an average of 9.7 ± 5.7 ktonnes of CO_2 in 30 years, the pathway based on renewable electrolysis of hydrogen presents the most promising alternative. The pathways based on fuel production via grid electrolysis result in a significant increases compared to the base-case: 100.2 ± 2.6 ktonnes for the hydrogen PEMFC scenario and 100.1 ± 13.4 ktonnes for the ammonia SOFC scenario.

Figure 5.3 presents the distribution of the average CO_2 impacts of each life-cycle phase, relative to the the total impacts. This figure is based on the same averages as presented in Figure 5.2. The figure shows that 86% of these diesel base-case emissions are attributed to the combustion of MGO fuel during the operational phase. The remaining 14% of life-cycle emissions result from the fuel production process, which includes the acquisition of crude oil feed stock and complex refinery processes (Bengtson et al., 2011; Altmann et al., 2004; Spoof-Tuomi & Niemi, 2020). Only a negligible 0.2% of emissions is attributed to the manufacturing of the internal combustion diesel engine. In the alternative scenarios, no operational emissions are produced. However, an overwhelming 81-98% of all life cycle emissions originate in the hydrogen and ammonia fuel production

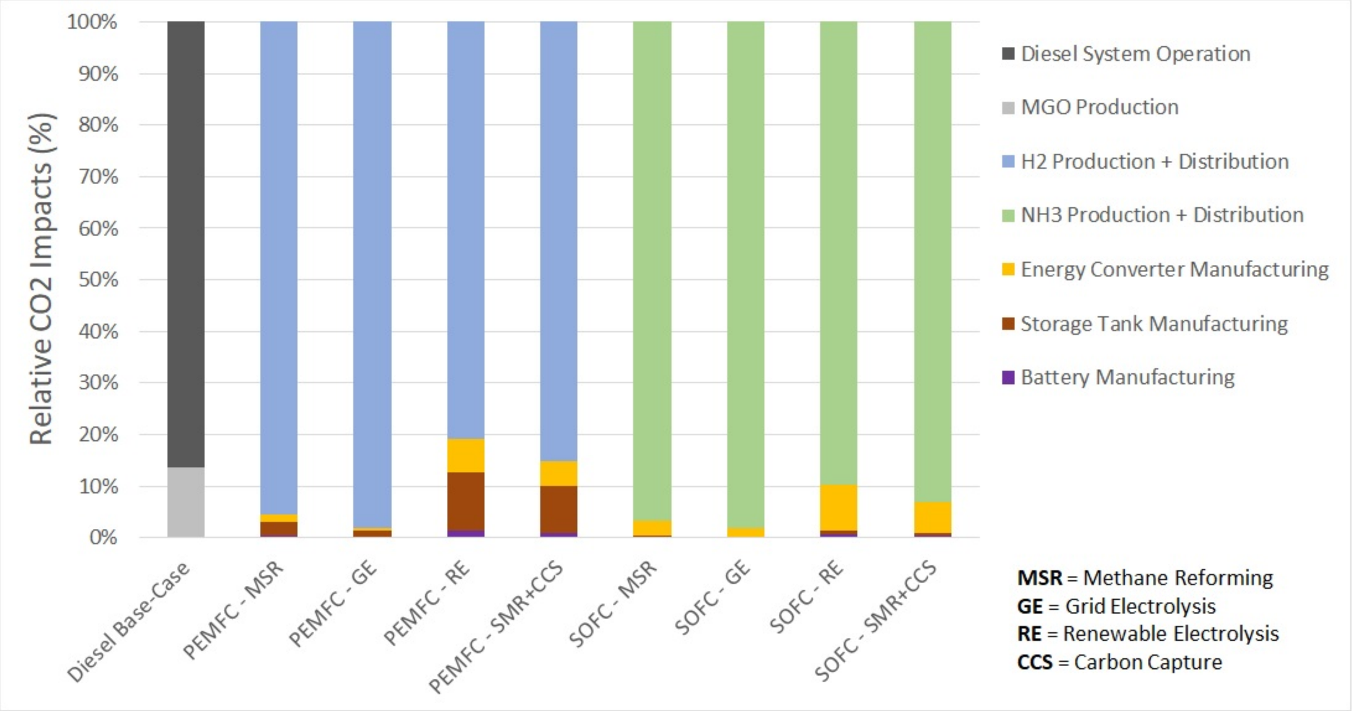

Figure 5.3: *The relative contribution of each life-cycle stage to the total 30-year CO_2. Based on the average impacts derived in the meta-analysis.*

processes. The share of emissions attributed to component manufacturing for fuel cells, batteries and fuel storage tanks range from 2-19%.

Based on the results of the meta review presented in Figures 5.2 and 5.3, six key findings are formulated and their practical implications are discussed below.

1. Fuel production method is key: renewable electrolysis most promising

The first major finding is that 30-year life-cycle impacts of alternative shipping systems are dominated by the CO_2 emissions of the fuel production cycle. An overwhelming 81-98% of life cycle emissions in alternative scenarios originate from the hydrogen and ammonia fuel production processes (5.3). The fuel production method is a thus crucial process in the environmental performance of the explored system alternatives. This is illustrated by the wide range of possible life-cycle emissions resulting from differences in fuel production scenarios (Figure 5.2).

The most promising fuel production method is based on fuel production via renewable electrolysis. Especially in the hydrogen PEMFC scenario, an impressive average reduction of 84% may be achieved: from of 58.7 ktonnes of CO_2 in the base-case, to an average of 10.1 ktonnes of CO_2 in 30 years. Uncertainties in the renewable hydrogen scenario are still relatively large, however, as indicated by the large standard deviation: 47-57%. Details relating to these uncertainties are discussed in the detailing review of Section 5.3.

2. Availability of renewable energy is crucial

Renewable electrolysis is currently only a marginal technology in the global hydrogen economy. Considerable investments into renewable electrolysis and sustainable electricity generation technologies are thus required to enable extensive zero-emission fuel production. Electrolysis via grid electricity could provide a solution to issue of renewable energy availability. However, Figure 5.2 shows that 30-year CO2 emissions increase dramatically in this scenario. This is a result of the large carbon intensity of the average European grid, whose electricity is produced primarily by fossil fuels (64-76%), including the very polluting coal fuels (Gilbert et al., 2018; Dufour et al., 2012; Mehmeti et al., 2018).

Grid electrolysis in regions with carbon intensive electricity grids is thus to be avoided in the long term. From an environmental perspective, a near-term switch to a grid-based electrolysis scenarios can only be justified by the expectation of increased decarbonization of the electricity grid in the next couple of decades[3]. In that case, the increase in CO_2 emissions could be considered an unavoidable temporary side-effect in the process of developing a mature hydrogen electrolysis industry.

3. Uncertain potential of MSR & CCS

Alternative scenarios based on fuel production via MSR result in 30-year impacts comparable to the diesel base-case scenario. This is relevant since MSR currently represents nearly 70% of the hydrogen production processes globally, and close to a 100% in the Netherlands (Weeda & Segers, 2020). Due to its technological maturity, MSR scenarios appear to represent the most feasible large-scale alternative to diesel scenarios in the present. However, the short-term environmental benefits of switching to alternative fuels based on MSR are only limited at best. In the ammonia-based scenario, MSR may even result in increased emissions compared to the base-case.

MSR may be combined with Carbon Capture and Storage (CCS) technology to abate carbon emissions in the MSR process. Theoretically, between 85 and 98% of carbon emissions can be captured by this technology (Dufour et al., 2012; The Hydrogen Council, 2021). However, real CO_2 abatement levels are closer to 70%, due to an increased consumption of (carbon-intensive) electricity (Hauck, 2020). Consequently, CCS reduces life-cycle CO_2 emissions of MSR pathways to 13.0 ± 3.8 ktonnes in the hydrogen scenario, and 26.6 ± 6.1 ktonnes in the ammonia scenario. While this is significantly lower than the emissions in the base-case diesel system, the CCS scenario relies on technologies that have not yet been deployed at a large enough scale to enable extensive zero-emission fuel production. As of 2020, only 0.1% of carbon emissions from industrial processes was captured (Bui et al., 2018; Kearns et al., 2021; Gilbert et al., 2018). Therefore, a switch to a MSR-based hydrogen scenario will have limited effects on emissions in the short term. In the long term, it may result in significant CO_2 reductions, provided that CCS will be adopted at a large scale. As such, the MSR scenario may be treated as a transition pathway towards more renewable hydrogen.

4. Manufacturing emissions may grow in relevance

The manufacturing phase has a limited effect on the 30-year emissions in each of the alternative scenarios, compared to the fuel production phase. The share of manufacturing emissions with respect to total CO_2 emissions ranges from a negligible 2% to a more significant 19%, depending on the employed fuel production method (Figure 5.3. The relative impacts of the manufacturing cycle in renewable scenarios is comparatively large, as a result of lower emissions in the fuel production cycle. As such, the impacts of the manufacturing process are expected to become more relevant as the decarbonization of fuel production progresses.

At the present, the limited impact of the manufacturing cycle has an important implication for FPS, who wish to retrofit existing diesel-based vessels into fuel cell-based vessels. The results of the meta review show that the avoided CO_2 emissions from switching to renewable fuel cell systems, far outweigh the additional CO_2 emissions resulting from retrofit-related manufacturing. CO_2 emissions for the fuel cell manufacturing phase represent less than 5% of the total 30-year base-case emissions. This means that retrofit-related emissions are equivalent to only about 1.5 years of shipping in the base-case. FPS can thus take significant steps towards providing zero-emissions shipping services, by retrofitting as soon as possible and by guaranteeing the use of certified green hydrogen (Gmucova, 2021).

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[3] Please refer to Appendix G for more details on possible grid decarbonization scenarios.

5. Hydrogen versus ammonia: no clear advantage

While the overall differences in CO_2 emissions between alternative scenarios is large, Figure 5.2 suggests a correlation between the different hydrogen production methods and their corresponding ammonia counterparts. This is a logical result, since hydrogen is a major feed stock in the ammonia production (Haber-Bosch) process, and responsible for 80-90% of the energy consumption in the ammonia production process (Smith et al., 2020).

Hydrogen scenarios slightly outperform their ammonia counterparts, due to the more efficient production process. However, taking into account the standard deviation, there are no overwhelming environmental advantages in the hydrogen pathways, compared to the ammonia counterparts. The choice between hydrogen or ammonia as primary fuel may therefore be decided by other factors such as costs, safety, or storage and distribution properties. These factors may justify a trade-off in environmental performance under specific circumstances. As of today, however, ammonia fuel is not ready for commercial deployment.

6. Zero-emission shipping not yet possible

From a full life-cycle perspective, true zero-emissions shipping is currently not yet possible. The results in Figure 5.1 show that life-cycle emissions may be reduced to a minimum of 4.3 tkonnes of CO_2, which is a reduction of 93% compared to the base case. However, due to the use of fossil fuels in upstream processes, some carbon emissions will still remain. Decarbonization of the wider energy system is thus a requirement for true zero-emissions shipping in the future. Decarbonization of upstream emissions is currently outside of the direct control of FPS. Subsequent sections discuss the relevant upstream and downstream processes in more detail.

5.2 Operational Phase CO_2 Emissions

The zero-emission operation of hydrogen and ammonia fuel cells was introduced as one of the most favorable attributes of the alternative pathways considered in this study. The results of Section 5.1 have shown that the zero-emissions operation may significantly reduce the total 30-year emissions CO_2, when compared to the base-case diesel scenario.

Since operational CO_2 emissions of fuel cell systems are already zero, they cannot be reduced any further. However, significant improvements in the operational efficiency of fuel cells may reduce the operational demand for hydrogen or ammonia fuel. This, in turn, reduces the demand for fuel production, which has advantageous effects on the carbon impacts of the fuel production cycle. In this study, fuel demand for a single 200 km trip was estimated at 516 kg H_2 or 3805 kg NH_3. This translates to a 30-year demand of 3403 tonne H_2 or 25113 kg NH_3. This demand was derived on on the assumptions of a 50% fuel cell efficiency and a specific fuel consumption that increases linearly with engine load (Verstraete et al., 2012). Due to matters of confidentiality, the exact FPS fuel cell specifics are not presented in this report.

With respect to the diesel base-case scenario, 30-year operational emissions amount to 50.7 ± 3.3 ktonnes of CO_2. These impacts are calculated using fuel consumption data, as well as real-time engine performance data[4]. Uncertainties in these impacts are small and generally originate from two different sources. Firstly, emissions factors may differ slightly, depending on the exact carbon content of the assumed diesel fuel. Secondly, the operational profile of the engine, and hence the fuel consumption, may differ depending on the assumed engine parameters.

Lindstad & Eskeland (2015) suggest that fuel consumption, and hence operational emissions, may also be reduced by optimizing shipping parameters such as shipping speed, hull slenderness and vessel size. However, the contribution of such improvements to CO_2eduction in the base-case is expected to be very limited. A transition away from fossil fuels is thus undoubtedly necessary in striving towards zero-emission shipping (I. N. Brown & Aldridge, 2019).

5.3 Fuel Production CO_2 Emissions

Section 5.1 of this chapter presented an overwhelming case for the relevance of the fuel cycle in contributing to the 30-year life-cycle CO2 emissions. Moreover, results pointed convincingly towards the hydrogen PEMFC scenario as being one of the most promising alternatives. However, significant uncertainties still exist within this scenario, as was illustrated by the large standard deviation: 47-57%. Additionally, the allocation of fuel production impacts into specific sub-stages of the fuel-cycle was not possible based on the meta analysis. This is a result of the use of aggregated impact data, on which the majority of the LCA literature relies to a more or lesser extent.

A qualitative detailing review of methodological assumptions is thus conducted in order to better understand the source of uncertainties. Section 5.3.1 will show that impacts of renewable electrolysis pathways differ significantly, depending on the assumed source of primary energy. Additionally, upstream emissions relating to power generation facilities are shown to play a significant role in explaining the relatively wide range in results.

The issue of data aggregation is tackled by performing original streamlined calculations based on inventory data from additional sources. Section 5.3.2 presents a detailed breakdown of fuel cycle emissions for an electrolysis scenario based on wind power. Streamlined calculations will show that the fuel distribution phase of the fuel cycle may be considered a key impact parameter.

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[4] Please refer to Appendix A for a detailed elaboration on these calculations.

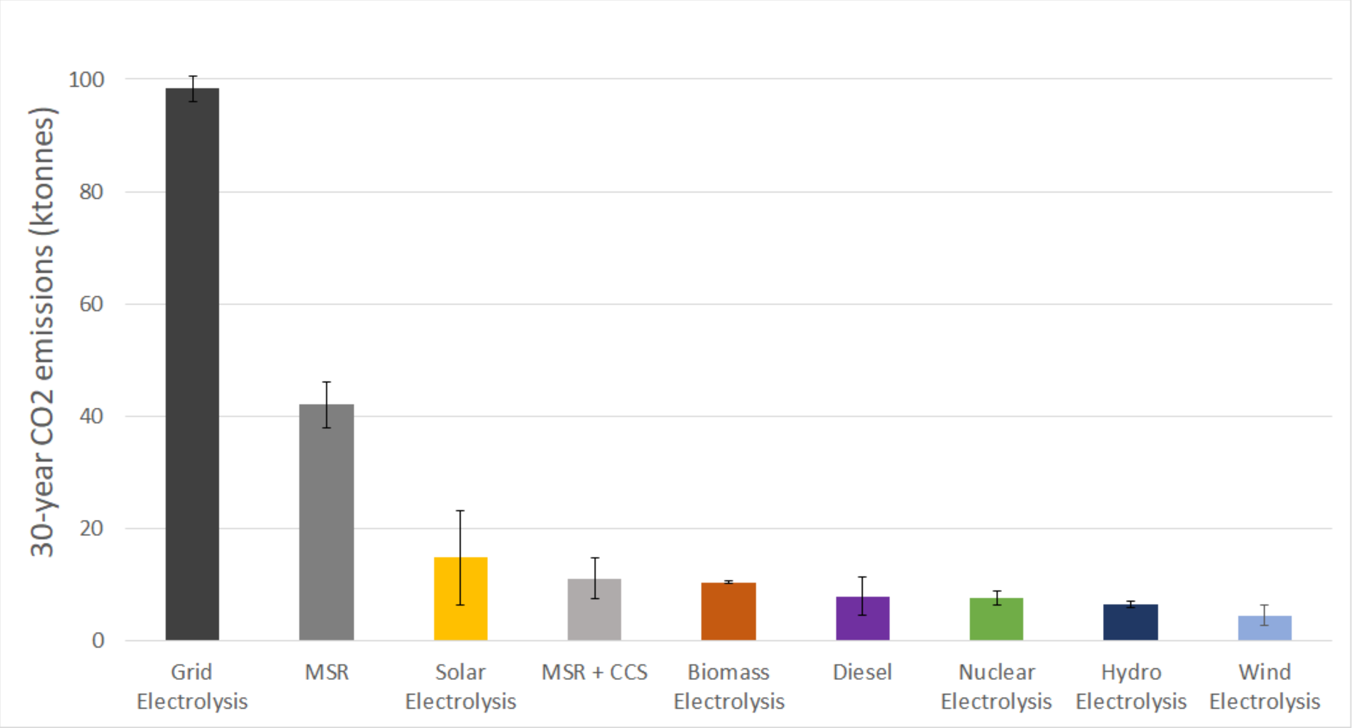

Figure 5.4: *The 30-year CO_2 emissions of the fuel hydrogen production cycle. Bar charts represent the average values found in the meta-analysis. Error bars represent the standard deviation in the data of the meta-analysis. Emission from diesel production are added as a reference.*

5.3.1 Upstream Emissions: Primary Energy & Plant Construction

Figure 5.4 presents the 30-year CO_2 impacts resulting from the fuel production cycle, derived from the meta review. The figure presents electrolysis scenarios based on different primary energy sources. It also includes both MSR pathways and the diesel production scenario as a reference. The bar charts represent the average 30-year emissions based on the detailing review, and the error bars represent the standard deviation.

Firstly, the figure shows significant differences between the emissions of grid electrolysis and renewable electrolysis scenarios. Since water electrolysis itself is a zero-emissions process, this points to the significant role of primary energy sources in the electricity generation process. The current predominant use of carbon intensive fossil fuels for producing grid electricity results in significantly larger upstream emissions for this scenario (Gilbert et al., 2018; Dufour et al., 2012; Mehmeti et al., 2018).

With respect to renewable electrolysis, the figure shows that the 30-year CO_2 emissions may range from values as high as 23.2 ktonnes in case of solar electrolysis (Dufour et al., 2012), to as low as 2.6 ktonnes in case of wind electrolysis (Bhandari et al., 2014). Since renewable scenarios do not depend on fossil fuels for electricity generation, the differences between pathways originate even further upstream the fuel production cycle. A careful inspection of methodological assumptions reveals that the majority of renewable electrolysis LCAs consulted in the meta review, explicitly take these upstream emissions into account (Mehmeti et al., 2018; Utgikar & Thiesen, 2006; Ozbilen et al., 2011; Bhandari et al., 2014; Cetinkaya et al., 2012; Dufour et al., 2012; Gilbert et al., 2018).

However, only the studies by Cetinkaya et al. (2012), Bhandari et al. (2014) and Utgikar & Thiesen

(2006) provide detailed unaggregated impact data. This data suggests that 63-78% of total fuel cycle emissions is likely to originate from the manufacturing and decommissioning of electricity generation plants (wind farms, solar PV plants and nuclear power plants). Differences between CO_2 impacts of renewable pathways are thus likely caused by differences in upstream material usage and processes relating to power plant manufacturing. This is also illustrated by the large relative uncertainties in solar PV pathways, which are caused by differences in assumptions relating to upstream processes. Cetinkaya et al. (2012), for instance, assume a PV panel life-time of 30 years, whereas Dufour et al. (2012) assume a life-time of just over 10 years (30.000 sun hours). This factor 3 difference in PV panel life-time is reflected in the factor 2.8 difference in fuel-cycle impacts (8.2 ktonnes according to Cetinkaya et al. (2012) and 23.0 according to Dufour et al. (2012)).

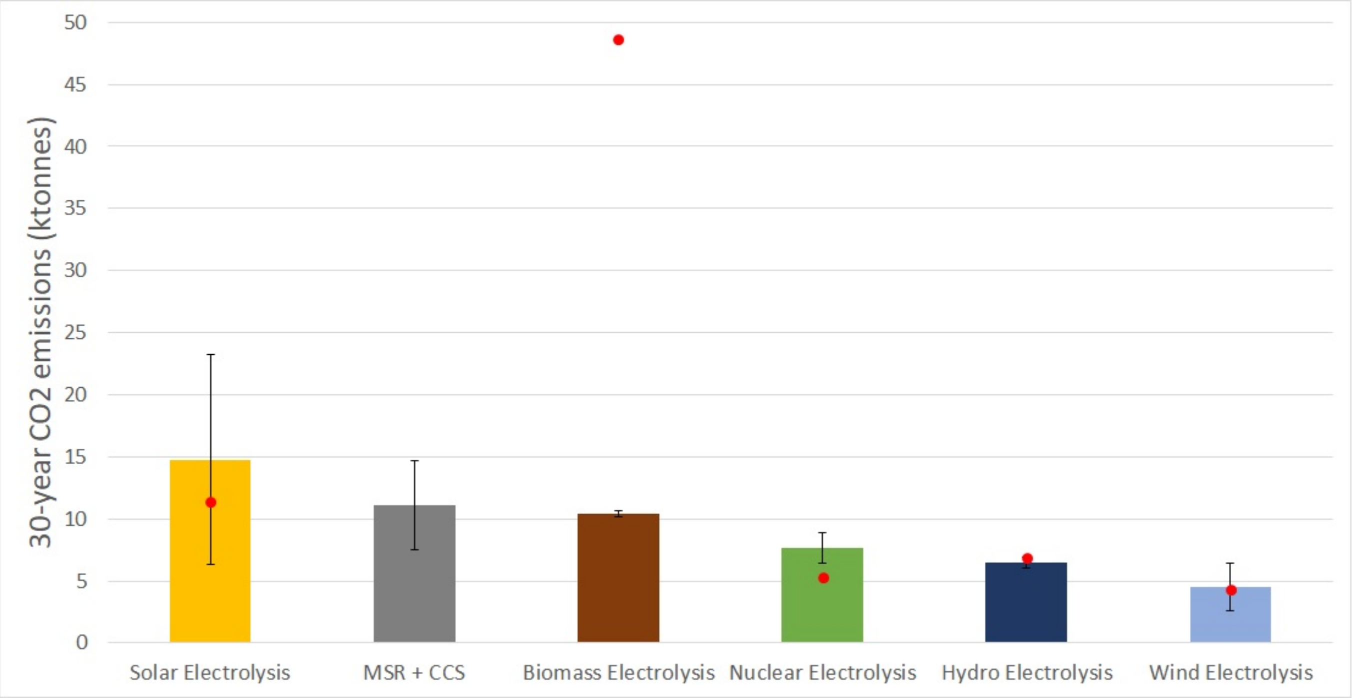

Figure 5.5: *The 30-year CO_2 emissions of the renewable hydrogen fuel production cycles. Bar charts and error bars respectively represent the average values and standard deviation found in the meta-analysis. Red dots represent the values of original calculations in the detailing review.*

Figure 5.5 compares the results from the qualitative meta review of renewable electrolysis pathways with the original streamlined calculations of the quantitative detailing review. The bar charts and corresponding error bars represent the results derived from the detailed analysis of LCA literature. The red dots represent the result of the calculations based on original inventory data. The figure shows that the original calculations generally fall within the standard deviation found in literature. The MSR + CCS scenario is only added as a reference.

The most notable exception is the biomass electrolysis pathway, whose calculation results in an overestimation of almost 500% compared to literature values. These differences are likely explained by differences in assumed accounting methodologies. The disagreement relating to carbon accounting methodologies is especially relevant for biomass, and relates to contentious claims of carbon neutral combustion of biomass (Norton et al., 2019). In the consulted literature, no details regarding emission factors and inventories are provided (Utgikar & Thiesen, 2006; Ozbilen et al., 2011). In the original calculations in this report, a value of 230 g CO2/kWh is assumed (Moomaw et al., 2011).

Finally, with respect to MGO, the meta-analysis suggests that impacts from diesel production results in 30-year CO_2 emissions of 7.9 ktonnes. However, most recent data suggests that this may be an underestimation, and that the 30-year impacts may be closer to 10-11 ktonnes (Spoof-Tuomi & Niemi, 2020; Hoekstra, 2020). This is a result of the more comprehensive life-cycle scope attempted in these recent studies, which include crude oil extraction and processing, crude oil transportation, refining of crude oil, fuel distribution, storage and bunkering. However, the inclusion of well exploration, well drilling, refinery manufacturing, and waste product treatment ambiguous. It is therefore not unlikely that the emissions are still higher than 10-11 ktonnes. A final cause of uncertainty is the impact allocation method of complex refinery process. Especially in multi-output processes, different allocation procedures may be employed, which each have an effect on final results (Bredeson et al., 2010; Johnson & Vadenbo, 2020).

5.3.2 Downstream Emissions: Fuel Distribution

The majority of LCA studies consulted in the meta review assess the fuel production cycle holistically, resulting in aggregated impacts rather than impacts at specific sub-stage level. The identification CO_2 hot spots within the fuel production cycle is therefore complicated. It is argued that a more detailed breakdown is desirable, however, considering the large contribution of the fuel production process to life-time impacts. Since a qualitative review of methodological assumptions does not allow for a sufficiently detailed analysis, original calculations are performed based on inventory data from additional sources.

For this purpose, the fuel cycle impacts are divided into five different phases: pretreatment, fuel production (electrolysis and/or Haber-Bosch), fuel storage, fuel distribution and fuel delivery. For the fuel distribution phase, several different scenarios are considered, due to the wide range of distribution options. These scenarios consider different storage options (compressed hydrogen, liquid hydrogen and ammonia), as well as different distribution distances (100-400 km) [5].

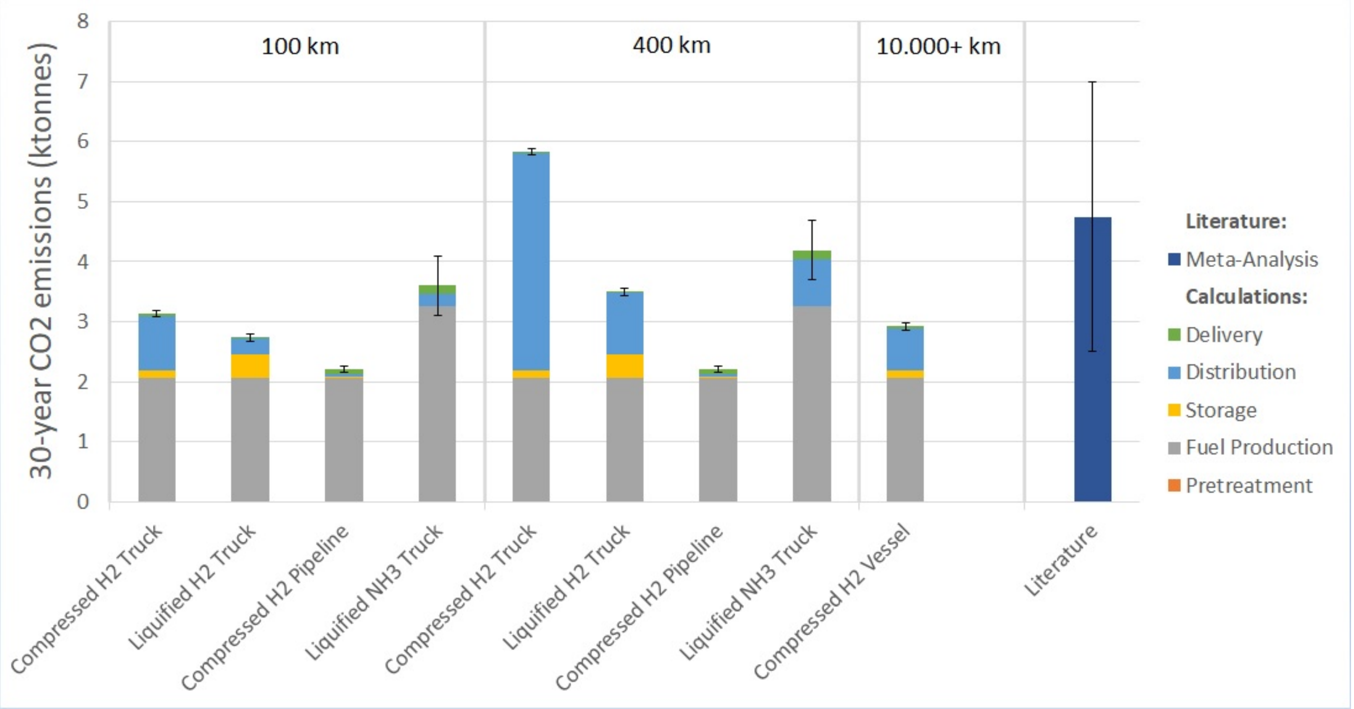

Figure 5.6: *A breakdown of the 30-year CO_2 impacts of the wind electrolysis pathway of the hydrogen fuel cycle, for different distribution scenarios at different distribution distances. Values from the meta-analysis are added as a reference.*

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[5] Details on the inventories and scenarios are presented in Appendix F.

Figure 5.6 shows the results of the calculations for the renewable wind electrolysis scenario. In this scenario, it is assumed that all electric processes are powered by wind turbines. The bar charts represent the averages results of the original calculations. The error bars represent the standard deviation resulting from differences in inventory data. The bar labeled "Literature" represents the impacts based on the meta review and serves as a reference point to validate the calculations.

Firstly, Figure 5.6 shows that compression and distribution via pipelines is the preferred distribution scenario, from a carbon footprint perspective. Distribution emissions in this scenario make up only 6% of fuel cycle emissions and result in a 30-year total of 2.7 ktonnes of CO2. More importantly, these emission are nearly independent of distribution distance and depend instead on the flow rate of the distribution grid (Wulf et al., 2018). The flow rate is determined by the cumulative hydrogen production rate of all production plants connected to the grid and expressed in tonnes of transported hydrogen per day.

In scenarios based on truck driving, on the other hand, emissions increase linearly with distribution distance. This effect is strongest for fuels with low energy densities (compressed H_2), which are distributed less efficiently by trucks than fuels with a high energy densities (liquid H_2 or NH_3). However, the more energy dense liquid hydrogen and ammonia emit more CO_2 as a result of the energy requirements in the storage phase (liquefaction) and fuel production phase, respectively. Figure 5.6 shows that these emissions are fairly balanced at distances around 100 km. However, at distances around 400 km, the transportation inefficiencies associated with compressed hydrogen result in significantly larger emissions, compared to the other alternatives.

Secondly, Figure 5.6 shows that the shipping of compressed hydrogen at distances larger than 10000 km results in emissions similar to 100 km of truck driving. Bulk import of renewable hydrogen from areas with abundant renewable energy sources may therefore be preferred over the purchase of Dutch hydrogen at distances greater than 100 km. Especially in the short term, where the supply of Dutch renewable hydrogen is insufficient, and pipeline infrastructure is deficient.

Finally, Figure 5.6 shows that the range in 30-year CO2 impacts of the different scenarios reflects the range of emissions found in literature. Additionally, the figure shows that the standard deviation within each of the different hydrogen distribution scenarios is very small (1-2%) compared to the standard deviation in the aggregated life cycle impacts (47%). This finding suggest that the wide range in impacts found in literature results from implicit differences in assumed distribution scenarios. This hypothesis is supported by the fact that most of the consulted LCA have included the distribution phase in the fuel cycle, without providing any inventories or details relating to assumptions (Altmann et al., 2004; Bhandari et al., 2014; Cetinkaya et al., 2012; Gilbert et al., 2018).

5.3.3 Discussion & Implications

The results in the section show that primary energy sources, upstream manufacturing processes, and the fuel distribution method an distances are key determinants for CO_2 emissions in the fuel production cycle. As such, uncertainties and implicit assumptions relating to these parameters are likely to be at the basis of the discrepancies observed in the meta-analysis. The qualitative analysis of scoping choices suggested that manufacturing emissions may account for 63-78% of total fuel cycle emissions. The streamlined calculations, however, suggested that the fuel distribution emissions may dominate the fuel cycle emissions when transportation distances approach 400 km. These results thus show that uncertainties with respect to the exact allocation of emissions are likely to continue to be present, as long as assumption are not made explicit (Brandão et al., 2012).

Despite these uncertainties, the key insights formulated in Section 5.1 are still valid. This illustrates the strength of the meta-analysis in identifying key impacts areas of the life-cycle of this particular case. This strength is also cited as an important attribute of the meta-analysis in other LCA meta-reviews (Corsten et al., 2013; Gentil et al., 2010; Muteri et al., 2020). In addition, it is shown that key impacts and uncertainties found in the meta-review provide a solid basis for a targeted detailing review based on streamlined calculations. The calculations have identified the distribution phase as a key life-cycle area and provided valuable insights into system dynamics. This was previously not discovered by the meta-analysis or the qualitative review of LCA literature.

With respect to the fuel production cycle, centralized renewable electrolysis in combination with pipeline distribution is the found to be the preferred system configuration for the long term. In the short term, however, higher distribution emissions are likely to be an unavoidable side-effect, resulting from large truck driving distances in a decentralized transition-system. In the short term, this may lead to life-cycle CO_2 emissions that temporarily exceed the levels of the fossil fuel base-case, particualy in a compressed hydrogen scenario. The use of liquid hydrogen or ammonia may therefore be preferred in the short term. Alternatively, hydrogen import from countries with abundant renewable energy may be adopted as a short-term strategy.

5.4 System Manufacturing Phase CO_2 Emissions

The results of Section 5.1 of this chapter revealed that the manufacturing of alternative power system components accounts for 2-19% of total life-cycle emissions. As fuel production process decarbonizes further, the relative impacts of system manufacturing may gradually exceed 19%. As such, the power system manufacturing phase is expected to contribute more significantly to total CO_2 emissions in the future. Additional insight into the key impacts of the manufacturing cycle will therefore become increasingly relevant.

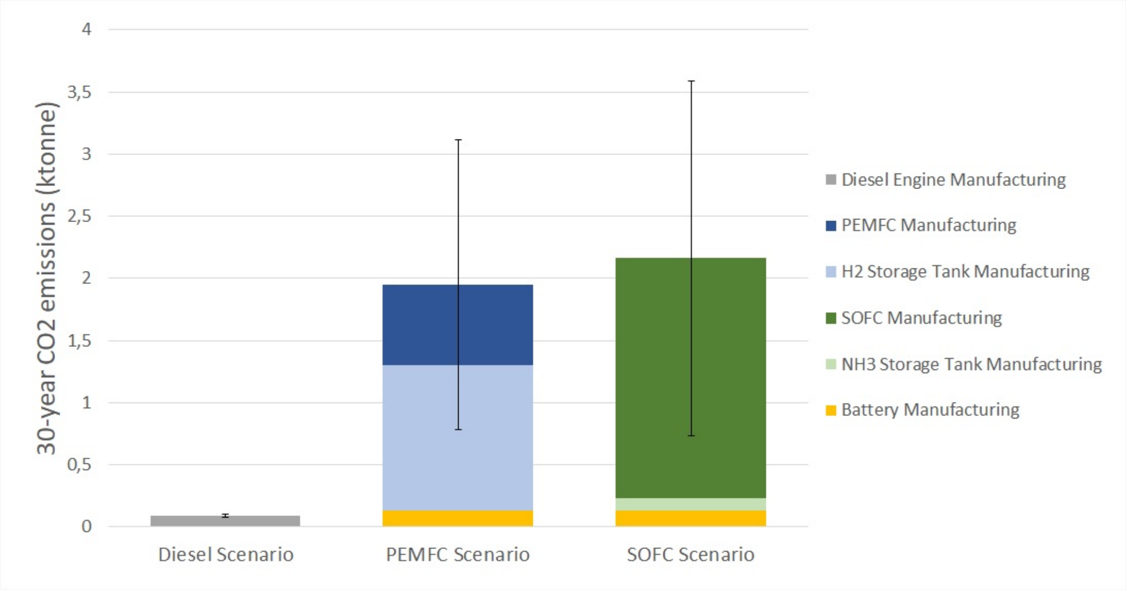

Figure 5.7: *The 30-year CO_2 impacts of the manufacturing phase in the diesel-based, PEMFC-based and SOFC-based scenarios. Bars charts and error bars are respectively based on the average values and the standard deviation found in the meta-analysis.*

Figure 5.7 shows bar charts representing the average manufacturing emissions derived from the meta-analysis of LCA literature. The error bars represent the standard deviation in the literature values. The figure shows that the manufacturing of the diesel engine results in CO_2 emissions of 91 ± 12 tonnes in the course of 30 years. In the fuel cell scenarios, these emissions are significantly higher. Emissions for manufacturing the fuel cells, storage tanks and batteries amount to a 30-year total of 1951 ± 1167 tonnes of CO_2 in the PEMFC scenario, and 2162 ± 1428 tonnes of CO_2 in the SOFC scenario.

Based on the averages, Figure 5.7 suggests that the relative impacts of different manufacturing phases may differ strongly depending on the fuel cell technology, which results in slightly higher

Table 5.1: *Key materials and processes in the manufacturing phase of the PEMFC, SOFC, H_2 storage tank, NH_3 storage tank and the Li-ion batteries.*

Key Material/ Process	Unit	30-Year Demand	Embodied Emissions (kg CO_2/Unit)	Source
PEMFC				
Platinum	kg	2,6 ± 10%	21743 ± 44%	[1],[2],[3]
Nafion	kg	131 ± 64%	781 ± 6%	[1],[2]
Graphite	kg	11604 ± 48%	0,0523 ± 63%	[1],[2],[3]
Thermoset Plastic	kg	2910 ± 35%	4,0 ± 16%	[1],[2],[4]
Steel	kg	2898 ± 83%	3,0 ± 48%	[1],[2],[3]
Plant Electricity	MWh	24 ± 113%	344 ± 72%	[1],[2],[3]
SOFC				
Electronic Components	kg	924	154	[4]
Stainless Steel	kg	15763 ± 72%	2.8 ± 59%	[1],[4],[7]
Zinc Oxide	kg	7739 ± 105%	4,6	[4],[7]
Plant Electricity	MWh	977 ± 36%	344 ± 72%	[4],[7]
H_2 STORAGE TANK (TYPE IV)				
Carbon Fibre	kg	16620 ± 17%	33,8 ± 70%	[1],[5],[6]
HDPE	kg	7558 ± 123%	2,0	[5],[6]
Epoxy Resin	kg	7474 ± 27%	7,3 ± 8%	[5],[6]
NH_3 STORAGE TANK (TYPE III)				
Carbon Fibre	kg	8016 ± 49%	33,8 ± 70%	[5],[8]
Aluminium	kg	9568 ± 49%	8,3 ± 13%	[2],[4],[5],[8]
Epoxy Resin	kg	5344 ± 49%	7,3 ± 8%	[5],[8]
LI-ION BATTERY				
Cathode	kg	1512 ± 26%	-	[9],[10],[11]
Anode	kg	789 ± 21%	-	[9],[10],[11]
Process Energy	MWh	337 ± 101%	-	[10],[12]

[1] Miotti et al. (2017b); [2] Stropnik et al. (2019); [3] Lotrič et al. (2020); [4] Staffell et al. (2012); [5] Agostini et al. (2018); [6] Benitez et al. (2021); [7] Bicer & Khalid (2020); [8] Gerboni et al. (2004); [9] Dehghani-Sanij et al. (2019); [10] Dai et al. (2019); [11] Sullivan & Gaines (2011); [12] Ellingsen et al. (2014)

emissions in the SOFC scenario compared to the PEMFC scenario. Most importantly, however, the figure shows that the standard deviation in literature-based values is very large (60-66%). This suggests that there are substantial uncertainties in the data found in the meta-review of LCA studies.

5.4.1 Key Materials & Processes

In order to better understand these uncertainties, Table 5.1 presents an overview of the most environmentally significant materials and processes in the manufacturing phase. Materials are considered key impact parameters when the embodied emissions of a material are large, due to the energy intensity of its upstream manufacturing processes, or when material is required in large quantities. A combination of both characteristics is also certain to result in large impacts. The overview of Figure 5.1 is based on a thorough review of inventory data from the consulted LCA literature and presents the 30-year demand for key materials and processes, as well as embodied emissions factors.

The table reveals that there are substantial variations in the inventories presented in the consulted LCA literature. This results in significant uncertainties in impact data, which is reflected in the wide standard deviation in Figure 5.7. Despite the large uncertainties, literature generally agrees on the relative contributions of platinum in the 30-year PEMFC manufacturing cycle: 22-40% (Pehnt, 2001; Miotti et al., 2017a; Stropnik et al., 2019). The relative impacts of the Nafion membrane are substantial as well (23-66%), since both the quantities and embodied emissions are relatively high (Miotti et al., 2017a; Stropnik et al., 2019). Original streamlined calculations are performed for the PEMFC manufacturing emissions, based on an inventory that was validated by Nedstack[6]. The results suggest that the combined relative contribution of platinum and Nafion is 71% of total PEMFC manufacturing emissions.

In the SOFC scenario, the electrical components contribute substantially to the overall 30-year impacts of the manufacturing phase. Carbon fiber is the most CO_2-intensive material in the manufacturing cycle of the H_2 and NH_3 storage tanks, due to its relatively large embodied emissions (Miotti et al., 2017b; Agostini et al., 2018; Benitez et al., 2021; Gerboni et al., 2004). The consulted literature relating to the manufacturing of batteries only provides aggregated inventory data, where the anode and cathode are responsible for the largest impacts. Embodied emissions factors are not provided, so specific key materials are not identified (Dehghani-Sanij et al., 2019; Dai et al., 2019; Sullivan & Gaines, 2011; Ellingsen et al., 2014).

With respect to processes impacts, the results show that the consumption of electricity is a significant contributor to CO_2 emissions as well. In the SOFC scenario, requirements are substantially larger, compared to the PEMFC scenario (Staffell et al., 2012; Miotti et al., 2017b). From literature, it is unclear which specific processes contribute to this difference, due to the aggregation of consumption data. What is clear, however, is that manufacturing emissions will benefit from improved energy efficiency, and the projected trend of decarbonization of the global energy supply.

5.4.2 End-of-Life Phase

The overall CO_2 impacts of the production phase may be reduced by employing circular end-of-life pathways, which reduce overall demand for materials. These pathways include the recovering, recycling and reusing of materials. Circular treatment of the previously identified critical materials (Table 5.1) is of particular interest. In case of PEMFCs, a theoretical end-of-life recovery rate of 76-100% may be achieved for the critical materials platinum, Nafion and graphite. At these rates, an estimated 12-16% of CO_2 emissions may be avoided in the manufacturing phase (Stropnik et al., 2019, 2018; Lotrič et al., 2020). It is noted, however, that current recycling rates of platinum are no higher than 0-5% (Miotti et al., 2017a; Stropnik et al., 2018). Achieving the theoretical recycling rates will therefore require considerable improvements in end-of-life infrastructure, as well as overcoming a wide range of technical and market challenges (Hagelüken, 2012). In the short term, PEMFC recycling rates of 41% are considered realistic. In the case of the SOFC, CO2 reductions of 8-11% may be achieved as a result of the recycling of electrical components and steel in the balance-of-plant (Staffell et al., 2012).

With respect to the storage tanks, it is noted that the recycling of carbon fiber is not currently considered feasible (Miotti et al., 2017a). Reducing the energy intensity of the carbon fiber production process is considered the best future strategy, since it may result in a 41% reduction of storage tank manufacturing emissions (Benitez et al., 2021). With respect to the Li-ion batteries, a reduction in process energy of 50% may be achieved as a result of recycling (Gaines et al., 2010). At present, however, Li-ion recycling rates are only about 3%, due to the immature end-of-life collection infrastructure (Dehghani-Sanij et al., 2019).

5.4.3 Discussion & Implications

The previous section has shown that variations in data used for manufacturing inventories can be large, both in terms of material quantities and assumed emission factors. A thorough qualitative review of LCA data shows that these discrepancies arise as a result of situation specific differences that are (implicitly) embedded in inventory data. Firstly, the manufacturing location is shown to indirectly affect several important local parameters parameters. These include the local energy mix, efficiency of manufacturing, the transportation distances, and the local abundance or

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[6] Please refer to Appendix H for details on this inventory.

scarcity of raw materials. In addition, different manufacturers may employ a range of different manufacturing processes, which affect process energies and materials usage. Second is the assumed application and size of the reference system. In the example of fuel cells, the installed reference capacity in literature may range from 1 to 250 kW. An analysis of available inventory data from literature suggests that the relative demand for critical materials (kg materials per kW of installed capacity) is higher in the larger systems. This is true for both the membranes (Nafion) and the platinum loadin. (Lotrič et al., 2020; Miotti et al., 2017a; Stropnik et al., 2019; Pehnt, 2001). The reference system for constructing the bill-of-materials may thus impact the inventory, and by extension the emission estimations. Similar scaling-related effects are found in the storage tank and battery inventories as well.

Ambiguity with respect to the situation specific assumptions underpinning the inventory data is thus causing uncertainties with respect to impact results. It is argued that a more transparent and standardized approach to performing and communicating LCA processes could benefit the LCA methodology. The traceability of inventory data and methodological assumptions should be given special attention in such approach, since it allows for a more comprehensive assessment of data quality (Valente et al., 2017). Presenting data on a subsystem level, rather than aggregated into a single indicator, should also improve transparency.

Despite the existing uncertainties, the results in this chapter have shown that the meta-analysis is useful in interpreting the impact magnitudes of the component manufacturing phase. Moreover, some key materials and processes have been identified, which act as crucial parameters influencing the impact results. In the short term, these key materials have limited effect on the overall 30-year CO_2 emissions, due to the overwhelming relevance of the fuel production phase. In the mid-long term, however, the results provide important guidance with respect to focus areas for improving the supply chain. Improved energy efficiency, increased decarbonization of the energy supply, and more circular end-of-life treatment of key materials are the most important of these focus areas.

5.5 System Level Implications

In this section, the implications of the results of this report are discussed from a broader system-level perspective. This sections focuses on the feasibility of the renewable hydrogen electrolysis scenario, which was shown to have the greatest potential for CO_2 reductions. Please note that the MSR and CCS scenario also provides significant potential for CO_2 reductions. However, due to limitations in available time and resources, it was decided to focus only on the scenario with the most potential according to the meta-analysis.

Special attention is paid to the availability of sustainable energy sources, because of the overwhelming importance of renewable energy availability in reducing CO_2 emissions of fuel cell-based systems. Additionally, this section focuses on the infrastructural requirements for large-scale distribution. Other relevant system elements such as costs, regulations, market dynamics and policy, are outside the scope and not considered in this section. The primary goal of this section is to assess the feasibility of a zero-emissions Dutch shipping sector, by exploring orders of magnitude based and approximate data from meta-studies. As such, the numbers presented in this section should not be considered accurate predictions for future markets or systems.

5.5.1 Renewable Energy Requirements

A total of 47000 Mtkm of freight was shipped on Dutch inland waterways in 2018 (CCNR, 2019). In order to meet the energy demand for shipping this freight with hydrogen PEMFC systems, a minimum of 60.6 ktonnes of hydrogen are required annually. A minimum of 3.71 TWh of renewable energy is required every year, in order to sustainably produce this amount of hydrogen via electrolysis.

Table 5.2: *Current Dutch installed capacity of low-carbon energy generation compared to the required capacity for zero-emission shipping in the Netherlands. The table assumes that only one energy source contributes to production at a time.*

Energy Source	Capacity Factor Netherlands (%)	Minimum Required Capacity (GW)	Installed Capacity NL 2018 (GW)
Onshore Wind	24.1	1.76	3.44
Offshore Wind	39.6	1.07	0.96
Industrial Solar PV	9.6	4.41	1.40
Nuclear Power Plant	84.9	0.5	0.485

Table 5.2 presents an overview of the current installed capacity of low-carbon energy generation in the Netherlands, along with their capacity factor (CBS Statline, 2021a,b,c,d). The table also presents the minimum required installed capacity in order to meet a demand of 60.6 ktonnes of hydrogen per year. For each energy source, the table assumes that this energy source is the only source contributing to production. The calculations show that the capacity of onshore wind is already twice as high as the required minimum. Offshore wind and nuclear energy each provide almost exactly enough energy to meet the annual requirements. Only industrial PV capacity is well below the minimum required capacity.

Based on these numbers alone, it is arithmetically possible to produce enough hydrogen for the entire Dutch inland shipping sector today. This finding is only theoretical, however, since the current installed capacity already accommodates an existing demand for sustainable energy. Additional sustainable energy generation would thus be required. In the Netherlands, at least three major sustainable offshore wind electrolysis projects have been commissioned for the next couple of decades: VoltH2 (100 MW), Port of Rotterdam (250 MW), and NortH2 (4 GW). These projects roughly amount to a 450% increase in existing offshore wind capacity.

Figure 5.8 shows how these projects may contribute to reaching the minimum annual energy requirement of 3.71 TWh. Three scenarios are presented, in which different shares of the produced hydrogen are allocated to the inland shipping sector. In case 100% of the produced hydrogen is allocated to the inland shipping sector, the minimum requirements are comfortably exceeded by 2030. If the allocation is 10%, the requirements are only just met by 2040. When an allocation of 1% is assumed, the commissioned projects only meet 10% of the minimum requirements. Please note that the scenarios in Figure 1.1 do not take into account a likely growth in minimum energy requirements, due to projected growth in inland freight transport (Lindstad & Eskeland, 2015; I. N. Brown & Aldridge, 2019).

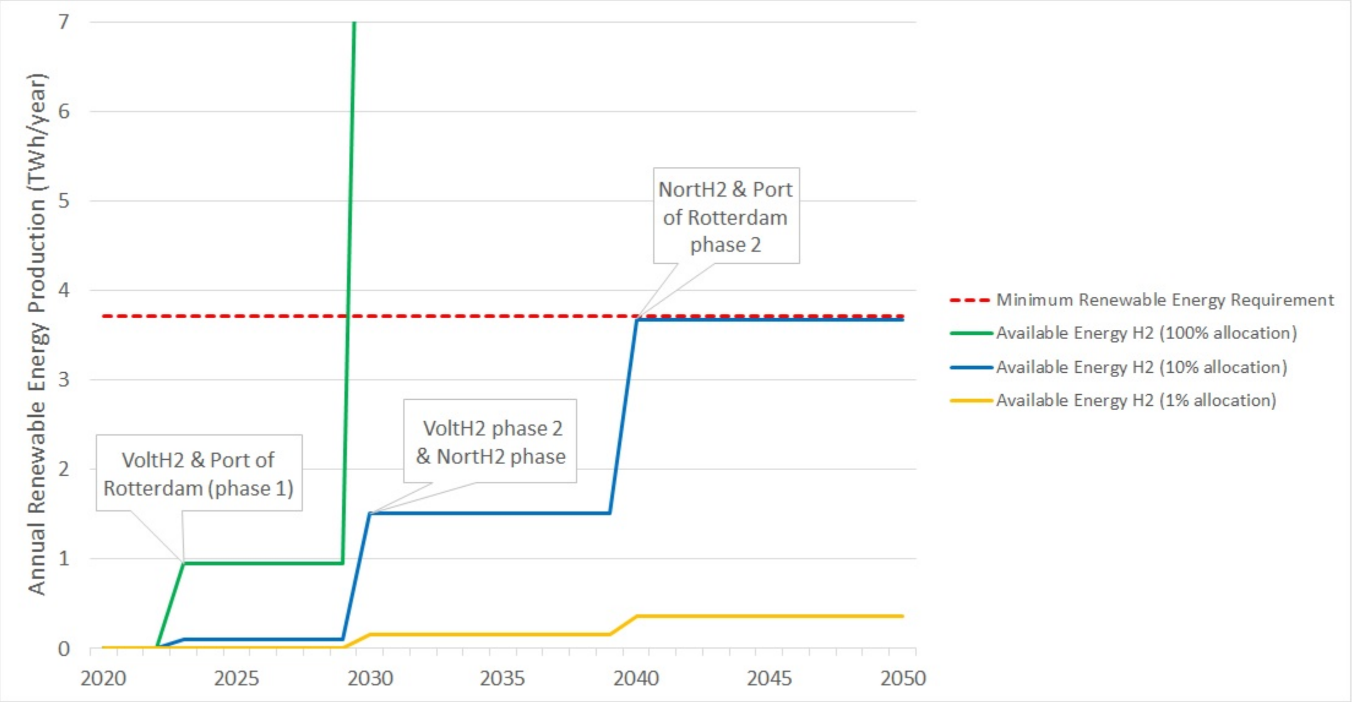

Figure 5.8: *The effect of future Dutch wind farms on the availability of renewable energy for hydrogen production. The dotted red line represents the minimum annual requirement for providing zero-emission hydrogen to entire the Dutch inland shipping sector. The unbroken lines represent the share of available energy allocated to the inland shipping sector.*

Several meta-studies have been examined in order to put the renewable electrolysis scenarios into perspective. Based on this review, the average estimate of the Dutch hydrogen economy in 2050 is 5.8 Mtonnes annually (Gasunie, 2019; Meindert et al., 2018; Detz et al., 2019; Noordelijke InnovationBoard, 2017). The share of inland shipping in this scenario is roughly 1% (60.6 ktonne), assuming no significant growth in inland freight transport. Figure 5.8 shows that the commissioned projects fall short in providing sufficient renewable energy in this 1%-scenario.

Additional renewable hydrogen projects may therefore be required in the future. However, the Netherlands suffers from inherent limitations with respect to natural conditions for renewable energy generation, as well as space availability (MacKay, 2010; Smil, 2016). Importing green hydrogen from areas with abundant renewable energy sources should therefore be considered as a serious addition to domestic production (Notermans et al., 2020; RVO & Topsector Energy, 2021). Section 5.3.2 has shown that hydrogen import via sea does not result in substantial environmental penalties.

5.5.2 Infrastructure Requirements

In addition to sufficient renewable hydrogen sources, a mature hydrogen distribution infrastructure is required to achieve large-scale hydrogen-based shipping. This section will provide an exploratory assessment of the orders of magnitude required for large scale hydrogen distribution, with a focus on the hydrogen distribution infrastructure and refill stations. For these calculations compressed hydrogen at 300 bar is assumed, which is in accordance with the specifications of the fuel used by FPS.

The infrastructural distribution requirements for transporting the annual hydrogen demand depend on the mode of distribution. A seagoing vessel carrying hydrogen as cargo can transport roughly 50 ktonnes of hydrogen in a single trip (Lloyd's Register, 2019). The annual hydrogen demand may therefore be imported by just two vessels. About nine vessels are required to import an equivalent 447 tkonnes in the ammonia scenario. In case of distribution via truck-driven compression tanks 128-151 trucks are required daily, based on truck capacities of 1100-1300 kg (Wulf et al., 2018; Demir & Dincer, 2018). In case of liquid hydrogen, only 36-43 trucks are required daily due to the substantially higher density of the liquid. In case of liquid ammonia, only 30-37 trucks are required. In case of ammonia, transportation benefits due to higher mass densities are largely offset by the lower specifc energy, as compared to hydrogen.

With respect to pipeline distribution, the Netherlands already has an excellent natural gas distribution infrastructure in place. This network of pipelines transported 78.7 Gm^3 in 2020, which comfortably exceeds the requirement for meeting hydrogen demands for inland shipping (Gasunie, 2020). While several technological challenges still need to be overcome (Kim et al., 2014), it is expected that “parallel pipelines” in the grid may be used for hydrogen transport in the short term, as demand for natural gas declines. In 2030, a 1400 km hydrogen ”backbone” should be developed, which connects the major industrial areas in the Netherlands (RVO & Topsector Energy, 2021).

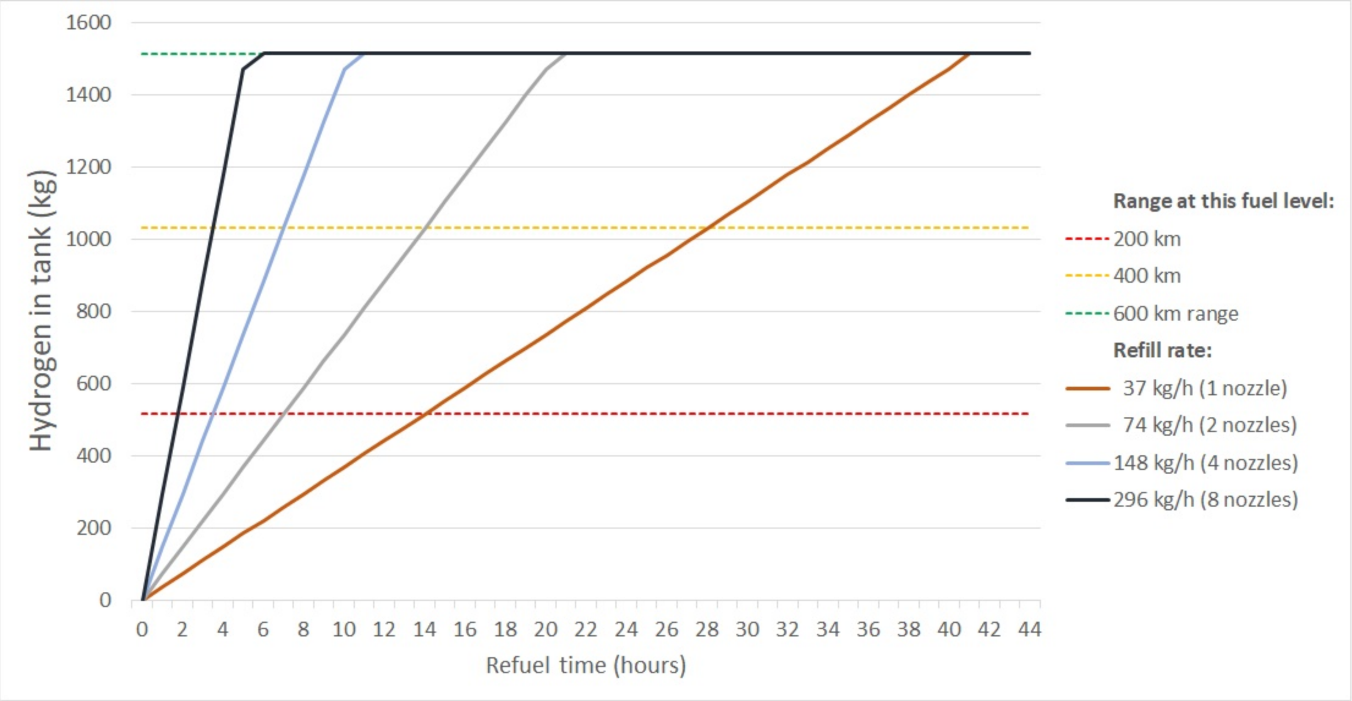

Figure 5.9: *The effect of the amount of refuel nozzles on the refill time of the MSC Maas. Dotted lines represent the hydrogen content corresponding to a shipping range of 200, 400 and 600 km.*

With respect to refueling infrastructure, the average refill rate of existing hydrogen refuel stations is 800-1000 kg per day (Van Hoecke et al., 2021; Demir & Dincer, 2018; Wulf et al., 2018). The exact refueling method (shore-to-ship, ship-to-ship) is not specified. With an average daily hydrogen demand of 116 tonnes (based on 60.6 ktonnes annually), a theoretical minimum of 116-145 hydrogen refill stations is required in the Netherlands. However, this does not take into account any dynamic temporal variations in hydrogen demand. Additional research is therefore required to determine the appropriate number of refueling stations for meeting hydrogen demand at all times. Differences in demand between larger and smaller terminals should be taken into account as well. Currently, 38 shipping terminals are located in the Netherlands (Rotterdam Transport, 2021). The port of Rotterdam is by far the largest bunkering port and this should be reflected in the geographical distribution of refueling stations.

At the aforementioned refuel rate of 800-1000 kg per day, it takes around 28 hours to fill a 50000 L fuel tank (equivalent to 1500 kg H_2). Figure 5.9 shows how the refuel rate may be increased by deploying more refueling units/nozzles. Horizontal lines represent the fuel tank content of 500, 1000 and 1500 kg, which respectively correspond with sailing ranges of around 200, 400 and 600 km. The figure illustrates the trade-offs that can be made between storage tank fuel capacity, shipping range and system complexity. Larger fuel storage volumes result in longer shipping ranges, but reduce cargo space and increase emissions resulting from storage tank manufacturing. Deploying additional nozzles may significantly decrease refueling time, but this increases the scale of the refueling infrastructure, which results in higher costs and greater complexity (Van Hoecke et al., 2021). Finally, the fuel tank may be filled to fractions of its total capacity. While this may significantly decrease the refueling times, it also decreases the shipping range to a similar extent. Additional research is required to determine appropriate trade-offs per situation.

As a final alternative, compressed hydrogen tanks may be mounted inside a standard 1 or 2 TEU container (Van Hoecke et al., 2021). These so-called cassette-type fuel storage systems can fairly easily be discharged and reloaded onto a vessel. This allows for a quick exchange between an empty and full storage tank in port. As such, an empty storage tank can be refueled, while the vessel continues it voyage to another port. Based on the average round-trip voyage of the Maas (around 400 km), the critical refuel time of the cassette-type system is approximately 18 hours. Based on the data of Figure 5.9, this requires at least two nozzles per cassette system at the refuel locations.

Chapter 6

Conclusions

This report has presented an exploratory meta-analysis into the CO_2 emissions of alternative marine fuels and propulsion systems. The goal of this research was to address the major shortcomings in the existing body of LCA literature, and to answer the following research question:

*What are the **key environmental impacts** and **uncertainties** in the life-cycle of alternative maritime propulsion systems, based on Life-Cycle Assessment data from literature, and what are the **implications** for Future Proof Shipping?*

This research question was answered by employing a mixed research methodology, which was based on a quantitative and qualitative analysis of existing LCA literature. A quantitative meta-analysis of LCA literature provided the foundation of this approach. Consequently, a more targeted detailing review was conducted into the key findings of the meta-analysis. This was based on a qualitative assessment of LCA methodologies and assumptions, as well as several quantitative streamlined scenario analyses. Subsequently, these findings and their implications were interpreted at a system-level.

By employing this approach, the research arrived at the following three results. Firstly, a comparative analysis of CO_2 impacts of some of the most promising future maritime power systems was presented from a full life-cycle perspective. The most promising pathways towards zero-emission shipping were derived from this comparison. Secondly, a detailed analysis of life-cycle impacts was conducted, which resulted in a more comprehensive understanding of key environmental impacts, uncertainties and system dynamics. Thirdly, the possible practical implications of the results were explored in the context of FPS, as well as the context of the the wider shipping industry. Based on this assessment, practical recommendations were provided throughout the report.

In this concluding chapter, the main contributions of the research are presented, and the results are synthesized into key takeaways (Section 6.1). Next, a critical reflection on the strengths and limitations of the employed research method is presented (Section 6.2). Finally, recommendations for future research are made (Section 6.3).

6.1 Key Contributions & Practical Takeaways

Key Contributions

CO_2 emissions of alternative shipping technologies have been considered holistically for the first time, by performing a meta-analysis of the CO_2 impacts in the operational phase, fuel production phase and system manufacturing phase. This study found that the CO_2 emissions of the fuel production phase are responsible for 81-98% of total life-cycle impacts. Fuel production method is thus a key life-cycle element that strongly determines final impact results. Two of the most feasible pathways towards zero-emissions shipping are based on the renewable electrolysis of hydrogen, or hydrogen production based on MSR in combination with CCS. The hydrogen-based

PEMFC system was found to be the most promising alternative pathway for zero-emission shipping. A CO_2 reduction of up to 93% of the base-case can be achieved in this scenario, provided that hydrogen is produced via renewable electrolysis.

By conducting a qualitative and quantitative detailing review, life-cycle results of key impact areas were derived at a greater level of detail as compared to literature. This resulted in a more comprehensive understanding of life-cycle impacts, system sensitivities and dynamics. Quantitative streamlined LCA calculations of different fuel production scenarios revealed that system emissions are (highly) sensitive to upstream and downstream parameters. Of particular relevance are the primary energy sources in the fuel production phase, and the transportation distances in the fuel distribution phase. A qualitative review of inventory data found that the system is also sensitive to assumptions relating to upstream manufacturing processes. Construction of power plants and material quantities for component manufacturing were found to be key parameters.

A qualitative review of methodological choices and inventory data uncovered a trend in LCA literature to present data a high levels of aggregation. This was identified as a significant source of ambiguity and uncertainty, since aggregation complicates the allocation of impacts to specific subsystems. Methodological choices, boundary conditions, and other situation specific assumptions are generally ill-defined, despite significantly affecting the outcome of the impact assessments. This complicates harmonization of LCA data from different studies.

Finally, this study revealed several future challenges and potentially crucial system trade-offs, by exploring possible future scenarios and analyzing them from a system-level perspective. The availability of renewable energy sources was shown to be crucial and a potential bottleneck for the decarbonization of the Dutch inland shipping sector.

Key Practical Takeaways for Future Proof Shipping

FPS shipping can achieve substantial reductions in life-cycle CO_2 emissions by switching to a hydrogen PEMFC system. A crucial condition, however, is that hydrogen electrolysis is based on renewable primary energy sources. Preferably, hydrogen from hydro or wind powered production is used. In these scenarios, total life-cycle CO_2 emissions may be reduced by up to a maximum of 93% compared to the base-case. The primary focus of FPS should thus be on ensuring the use of renewable hydrogen. This may be achieved by participating in so-called “Guarantee of Origin” schemes (Gmucova, 2021). In the absence of renewably produced hydrogen, hydrogen from MSR provides a short-term solution without any environmental penalties, and with long-term decarbonization potential. Hydrogen produced from grid electrolysis is best avoided, as long as the grid is primarily fossil fuel-based.

If the renewable origins of the hydrogen fuel are guaranteed, the relative impacts of upstream and downstream processes to total life-cycle emissions increase. Generally, exerting influence in upstream process is extremely challenging. The most relevant process that may realistically be affected by FPS, is the fuel distribution phase. Ideally, hydrogen is purchased from systems based on pipeline delivery. As long is this is not possible, renewable compressed hydrogen is best imported in bulk via vessels, or transported by trucks over short distances only (<100 km).

With respect to the system manufacturing phase, avoided life-cycle emissions from the use of renewable hydrogen in the operational phase, far outweigh the additional CO_2 emissions resulting from retrofit-related manufacturing. From an environmental point of view, there is thus no reason to postpone a retrofit until the end of the diesel system’s life-time. Improvements in material use, energy efficiency and circular end-of-life pathways are only expected to be relevant as the decarbonization of the fuel cycle is sufficiently progressed. At present, FPS could contribute to a more circular end-of-life phase, by ensuring components are returned to the manufacturer or to recycling companies.

Finally, FPS should carefully weigh the advantages and disadvantages of both hydrogen and ammonia fuel for the future. From a carbon footprint perspective, renewable hydrogen is preferred over renewable ammonia, but not by overwhelming margins. As such, other factors that affect the transition towards zero-emission shipping should be considered as well. These include costs, regulations, market-dynamics, policy and infrastructure, crew safety and technological advancements among others. With respect to infrastructure and distribution, this study has show that ammonia fuel may have some advantages over hydrogen fuel. As of today, however, ammonia fuel is not ready for commercial deployment.

6.2 Reflection on Methodological Strengths & Limitations

A meta-review of existing lCA literature was employed in combination with a detailing review based on qualitative and quantitative assessments. This study argued that a meta-review can contribute to the existing body of LCA research, by advancing the understanding of the analyzed system and the underlying parameters that drive its environmental performance. Moreover, it was claimed that this increased understanding could be used to harmonize results and increase practical applicability of existing LCA studies.

This study has shown that a quantitative meta-analysis can be successful at arriving at the intended results of this research. Average values of the life-cycle CO_2 impacts have successfully revealed the key environmental impacts areas. The standard deviation in the results has proven to be a fitting indicator for identifying underlying uncertainties. As such, the meta-analysis provided a suitable starting point for a more detailed analysis of key parameters and uncertainties. This qualitative assessment resulted in more detailed understanding of system dynamics. However, the assessment suffered from issues relating to data aggregation and ambiguous assumptions, a general trend observed in LCA literature. This trend limited the level of detail reached by the qualitative analysis.

However, streamlined LCA calculations have been useful at analyzing key impacts at greater detail. Moreover, it allowed for the streamlined analysis of specific scenarios, which improved the knowledge of system dynamics. Supplementing the meta-analysis with streamlined LCA calculations thus provides a targeted approach for addressing specific knowledge gaps, without the need for time-consuming bottom-up assessments.

Data related issues will continue to be present, however, especially in literature based LCA reviews. The data used for streamlined assessments suffers itself from issues of ambiguity. As such, the issue of methodological ambiguity is only moved further down the life-cycle chain. It is therefore argued that the LCA methodology will always benefit from increased transparency and methodological harmonization. Nonetheless, the empirical case of FPS has shown that the meta-review has resulted in sufficiently conclusive results to enable strategic decision-making on crucial life-cycle aspects. The meta-analysis can thus improve the practical utility of LCA studies, despite the continuing presence of significant uncertainties.

6.3 Recommendations for Future Research

Due to limitations with respect to available time and resources, the MSR + CCS scenario has not been analyzed at the same level of detail as the renewable electrolysis scenario. However, this scenario presents a promising transition pathway towards zero-emissions shipping, due to its reliance on mature technologies and infrastructures. It is therefore highly recommended to research future feasibility of the MSR + CSS scenario, in comparison to the renewable electrolysis scenarios. Special attention should be paid to systems-level aspects that are not covered in this study. These include factors that may affect large-scale implementation, such as costs, regulations, market-dynamics, policy and governing structures, fuel cell innovation and other scientific developments, and stakeholder acceptance.

With respect to the the renewable electrolysis scenarios, an exploratory review has already uncovered some key challenges. However, this review was by no means comprehensive. It is therefore recommended to build on the research into the energy generation and infrastructural aspects. Special attention should be paid to the global potential of renewable hydrogen, the spacial distribution of refueling stations, the development of a hydrogen pipeline infrastructure and the requirements for matching fuel supply and demand at all times.

This study has focused on the carbon footprint of the analyzed system alternatives. Ideally, the choice of a system alternative is based on a comprehensive consideration of all environmental aspects. It is therefore recommended to extend the LCA research to include aspects such as acidification of soil and water, depletion of (abiotic) resources, human toxicity, and many others.

Finally, from a methodological point of view, it is urged to continue efforts into the standardization of LCA methodologies. Special attention should be paid to the transparency of assumptions and traceability of data. This is particularly relevant for upstream emissions, whose relevance is set to increase as a result of the decarbonization of downstream processes.

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Appendices

A Internal Combustion Engine

In this appendix, the operational characteristics of the diesel Internal Combustion Engine (ICE) are elaborated upon. Special attention is paid the relation between operational parameters and the emissions of CO_2, SO_x, NO_x, and PM. The information in this appendix is aimed at improving the understanding of the base-case diesel scenario considered in this study. Additionally, it elaborates on the calculations performed for determining the base-case emissions.

Engine Parameters

The traditional ICE operation is based on the combustion of fossil fuels, in order to generate mechanical power. In this process, heat and water is produced, as well as a range of (environmentally) harmful emissions. The type and rate of emissions onboard a vessel is affected by a complex interplay of different parameters (Lindstad & Eskeland, 2015). Figure 1 shows one possible representation of these relations (Jalkanen et al., 2012). A close inspection of the figure reveals that a detailed insight into the specific shipping conditions during a voyage (green) are not necessarily required in order to determine operational emissions. Rather, operational emissions are directly related to two different types of parameters: 1) the operational characteristics of the engine (orange), and 2) the ship, engine and fuel properties (blue).

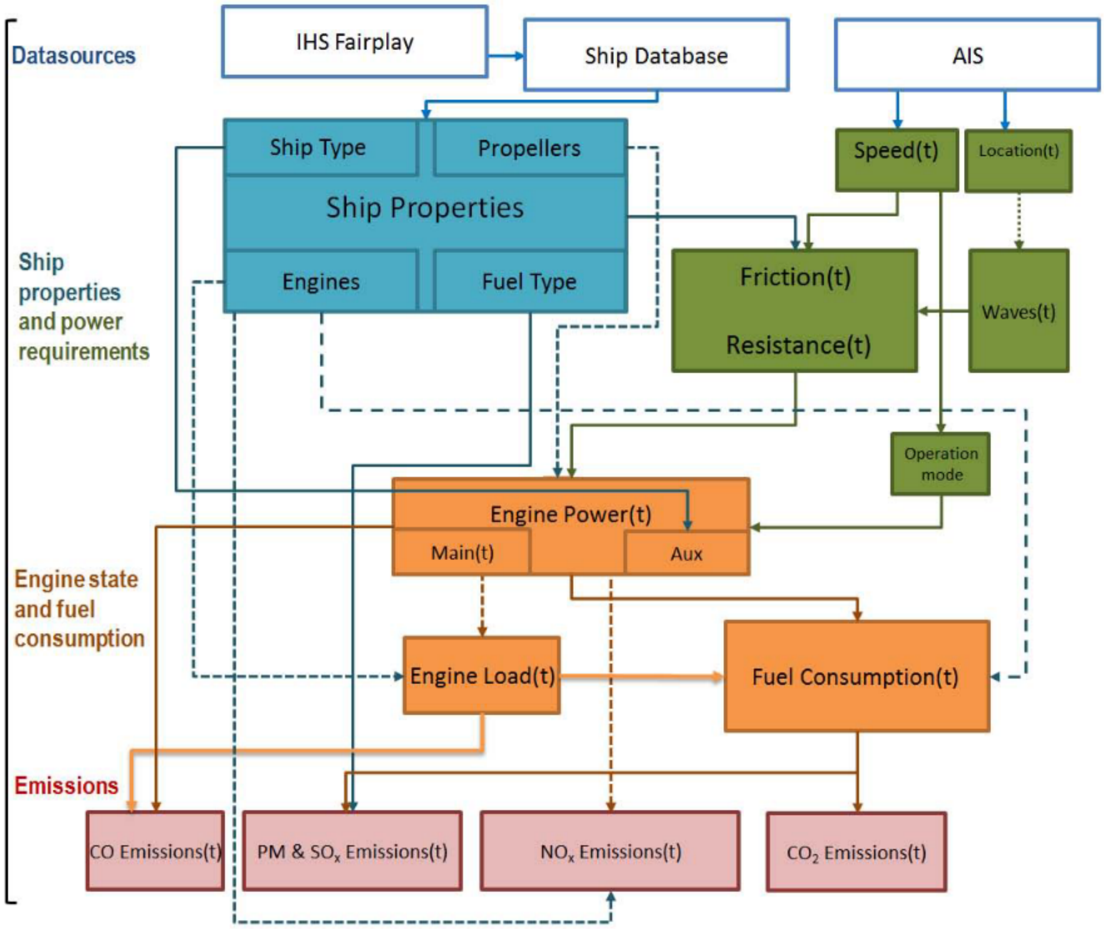

Figure 1: *The relation between operational emissions (red) and vessel parameters (blue), shipping parameters (green) and engine operation (orange). Image taken from Jalkanen et al. (2012).*

The ship, engine and fuel properties are generally known to the manufacturer and user of the vessel, and is easily found in operational manuals or other sources. Operational characteristics, on the other hand, can be derived in different ways. Firstly, they may be derived via direct measurements. Engine power is measured by means of a dynamometer, which measures the torque output and rotational velocity of the engine. The data is consequently converted to engine power data via the following relationship (Kuiken, 2008):

$$P = \frac{\tau \cdot RPM}{9.5488} \tag{1}$$

In this equation, P represents the power in kW, τ is the engine torque in Nm, and RPM is the rotational speed in revolutions per minute.

Fuel consumption, on the other hand, is derived by real-time mass flow measurements during vessel operation, using flow meters. Real-time flow measurements determined the fuel consumption of this a 200 km trip by the MSC Maas in May 2020[1] at 2729 L. Alternatively, fuel consumption may be derived from real-time engine data via a parameter referred to as the Specific Fuel Oil Consumption (SFOC). The SFOC is a measure of the fuel consumption of an engine, relative to the energy output of the engine (grams of fuel per kWh). Figure 2 shows a typical relation between the engine power (load) and the fuel consumption rate. This relationship represents a parabolic function, with a minimum at the rated engine power (Jalkanen et al., 2012):

$$RSOFC = \frac{SOFC}{SOFC_{\text{base}}} = \frac{(0.445EL^2 - 0.71EL + 1.28)}{SOFC_{\text{base}}} \tag{2}$$

In this expression, $RSOFC$ is the dimensionless Relative Fuel Oil Consumption, $SOFC$ is the Specific Fuel Oil Consumption, $SOFC_{base}$ is the Base Fuel Oil Consumption, and EL is the Engine Load. The $\text{SOFC}_{\text{base}}$ fuel oil consummation of the engine at rated power. According to its manual, the $\text{SOFC}_{\text{base}}$ of the MSC Maas' CAT3516 engine is between 200 and 226 g fuel/kWh. The $\text{SOFC}_{\text{base}}$ of the CAT3516 engine was determined more accurately by performing curve-fit simulations, using Equation 2 and the measured fuel consumption data of the MSC Maas for May 2020. This simulation determined the $\text{SOFC}_{\text{base}}$ at 217.7 g fuel/kWh.

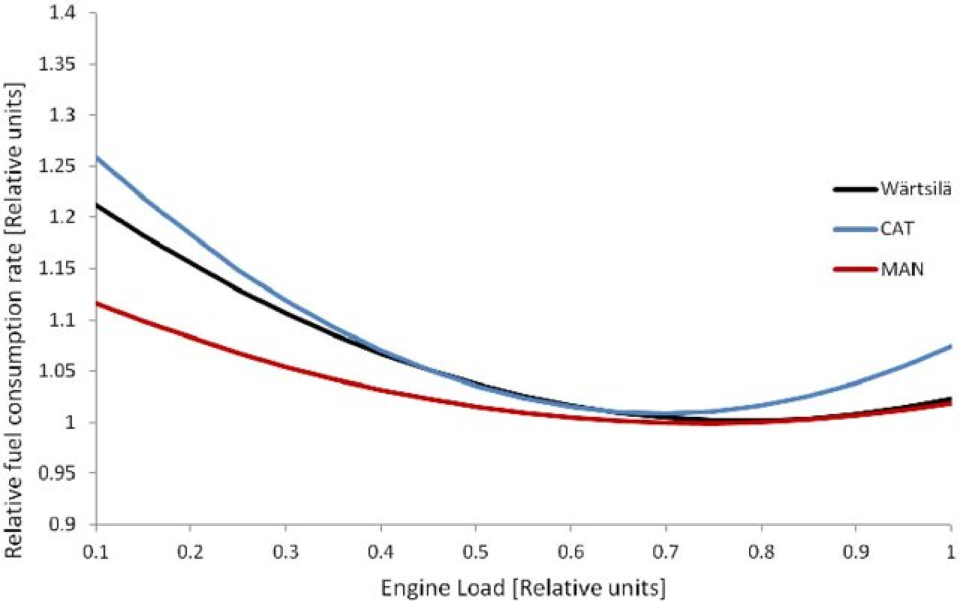

Figure 2: *Typical relation between engine load and the rate of fuel consumption for three different diesel engines. Image taken from Jalkanen et al. (2012).*

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[1] During this voyage, torque, RPM and propeller power were measured at 1-second intervals.

Base-Case Calculations

Operational CO_2 emissions are now determined using either the measured fuel consumption of 2729 L per 200 km trip, or by using the RSOFC relation of Equation 2. Using fuel consumption data and standard emissions factors ranging from 3160 to 3206 g CO_2/kg fuel, the average operational emissions are estimated at 48.8 ktonnes CO_2 in 30 years (Winther et al., 2017; IMO, 2020; Perumal & Timmons, 2017). Using the RSOFC, a time dependent emissions factor may be derived:

$$CO_2(t) = EF_{\mathrm{CO_2}} \cdot RSOFC(t) \cdot E(t) \tag{3}$$

In this equation EF_{CO_2} is the emitted CO_2, *RSOFC(t)* is the Relative Specific Fuel Oil Consumption, and *E(t)* is the energy produced by the engine. These are all values at a specific time *t*. By taking the sum of $CO_2(t)$ at each time *t* during the MSC Maas' voyage, the total operational CO_2 emissions are determined. Use the average emissions factor of 652 g CO_2/kWh, the 30-year CO_2 emissions are estimated at 52.0 tkonnes (Tzannatos et al., 2015; Lloyd's Register & UMAS, 2020; M. F. Ashby, 2013; Winnes & Fridell, 2009).

In addition, the May 2020 shipping data was used to construct an operational CO_2 emission profile of the MSC Maas. This emission profile was constructed using Equation 3 and is presented in Figure 3.

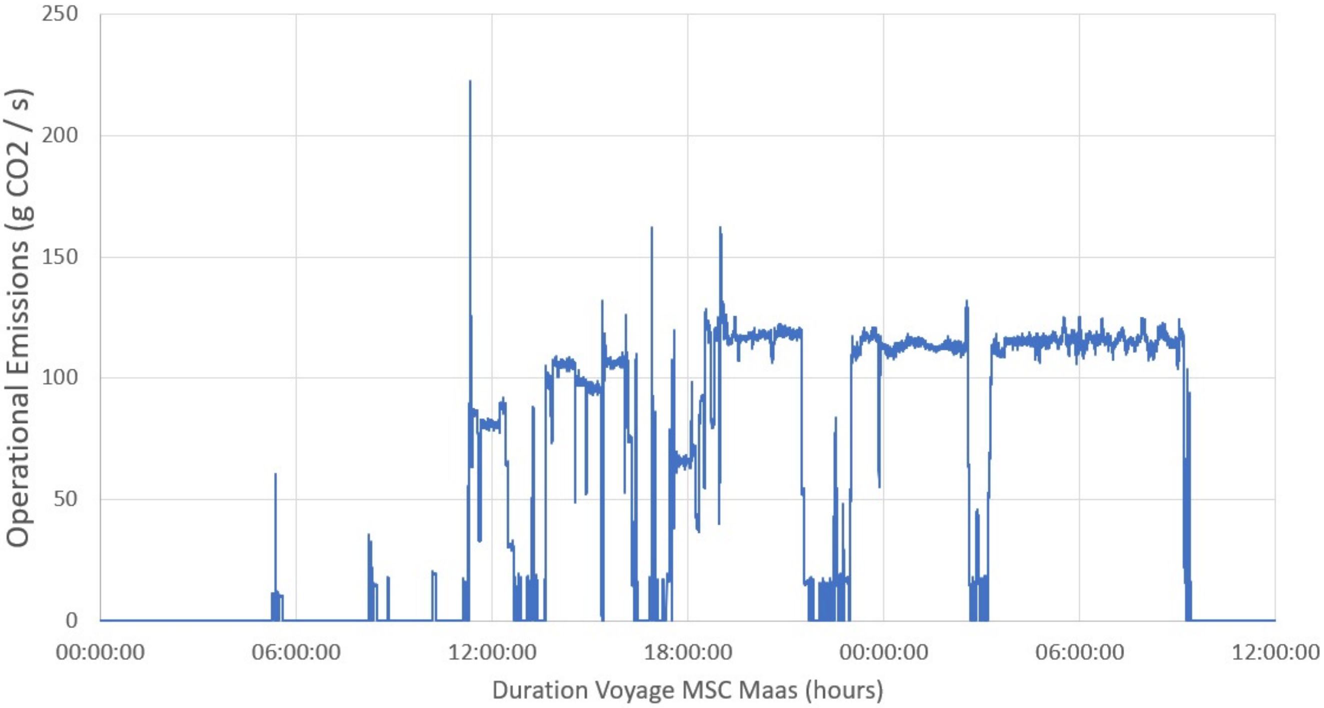

Figure 3: *Operational emissions of the ICE during the 200 km voyage of the MSC Maas in May 2020.*

B Fuel Cycle Process Flows

Section 3.1 of the main part of this report presented a visualization of the ten different scenarios considered in this research. The visualization was an abstraction of several complex life-cycle processes. In this appendix, a more detailed representation of the processes flows in the fuel production cycle are presented (Figure 4). This visualization was made in order to better understand process dependencies and assist the process of collecting original data.

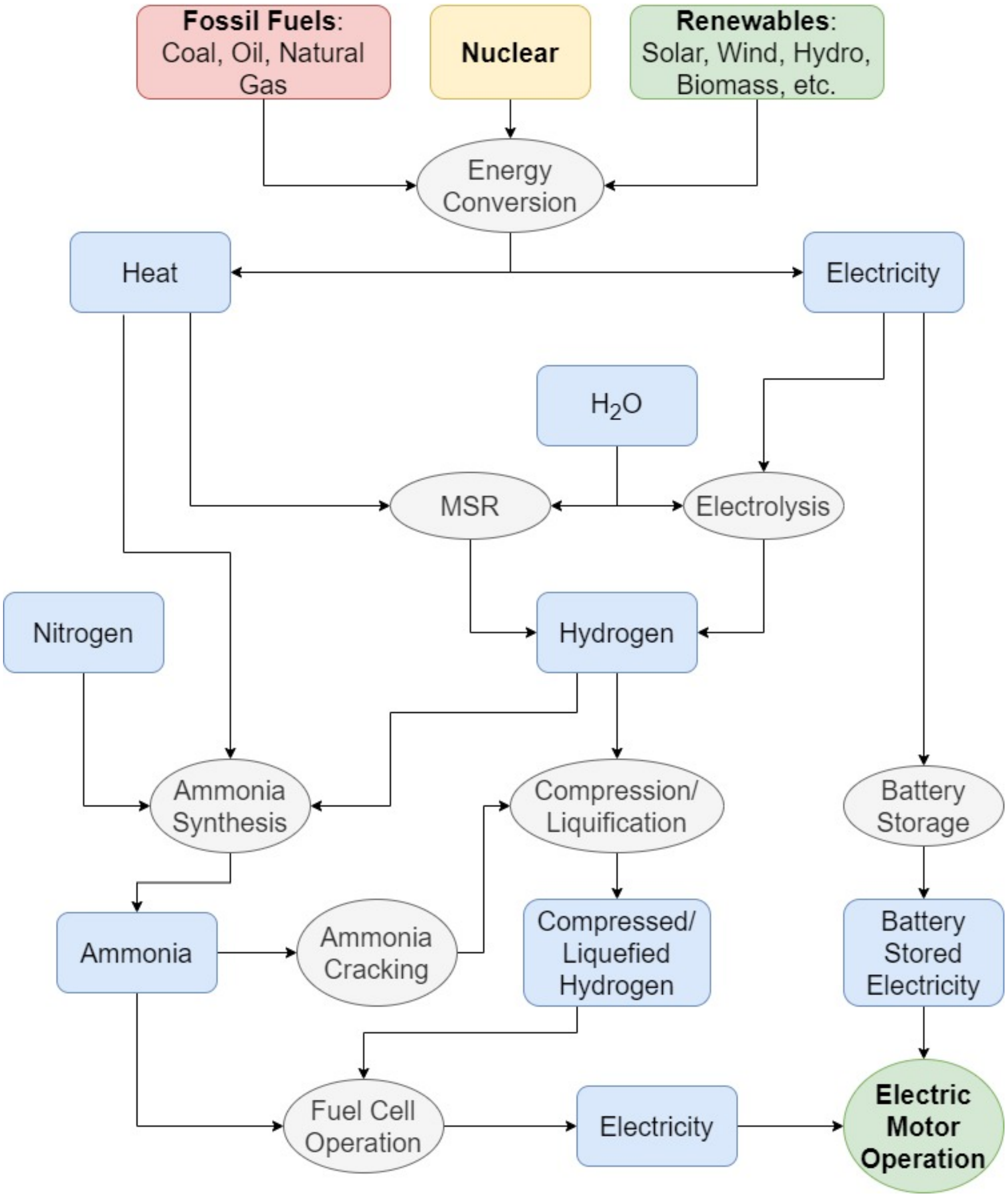

Figure 4: *An overview of the process flow involved in the fuel production cycle, from primary energy carrier to fuel cell operation of the electric motor.*

The colored items in Figure 4 represent different (primary) energy sources. Grey items represents different conversion processes, while blue items represent the inputs to these processes. Please note the that electricity is only explicitly linked to the electrolysis and battery storage processes. However, electricity is also an input to every other conversion process (for example as input to Balance of Plant processes). From Figure 4 is its apparent why the primary energy sources are key parameters in the fuel production process, since every pathway is ultimately traced back to the primary energy source used for heat and electricity production.

C Goal & Scope Report

A Goal & Scope Report is defined transparently and unambiguously define the purpose, scope and assumptions of an LCA study. Table 1 presents the Goal & Scope Report of this study, which is based on a framework presented in several standard works on LCA methodologies (Curran, 2017; Guinée et al., 2004; Grant, 2009; Weidema et al., 2004).

Ideally, this Goal & Scope Report defines the scope of this study comprehensively, unambiguously and definitively from the start of the research. However, as new information emerges during the progression of the research, new insights will often necessitate changes with respect to the original definitions and assumptions (Curran, 2017). This is inherent to the iterative nature of the LCA methodology. The scope presented in Table 1 should therefore not be interpreted prescriptively, but rather as a framework for streamlined and transparent reiteration of the scope.

Table 1: *Goal & Scope Report for the LCA performed in this study: goal definitions (top) and the scope definitions (bottom).*

Goal Definitions	
Research Goal	Identifying the key environmental impact areas and leverage points in the inland shipping industry, by means of an exploratory, iterative and comparative LCA.
Intended Application	Using the results of the LCAs to identify key impacts and uncertainties, which will consequently be used to develop an environmental assessment tool for inland shipping.
Commissioner	Future Proof Shipping
Stakeholders	Future Proof Shipping and Eindhoven University of Technology
Confidentiality	Not confidential
Scope Definitions	
Investigated systems	A base-case marine power system based on diesel fuel, and different alternative scenarios based on hydrogen and ammonia fuel in combination with a PEMFC and SOFC (details in Section 4.2).
Functions of systems	The propulsion of the MSC Maas vessel.
Functional unit	The propulsion of 1 MSC Maas vessel traveling the same 200 km route for the course of 30 years (details in Section 4.2).
System boundaries	Operational phase, fuel production phase and the system component manufacturing phase (details in Section 4.2).
Life-cycle stages	**1. Power System Manufacturing:** Raw Materials Acquisition, Raw Materials Processing, Power System Manufacturing, Maintenance, Material Recovery and End-of-Life. **2. Fuel Production Cycle:** Raw Material Extraction, Fuel Production, Fuel Distribution and Fuel Delivery. **3. Power System Operation:** Fuel Consumption
Data requirements	**Scoping Review:** Aggregated impact data on system level. **Detailing Review:** Unaggregated data impact data on subsystem level; Material reference flows; Process energy requirements; Emission factors
Limitations	LCA software, databases and original data not available
Primary pollutants	Carbon dioxide (CO_2).
Impact categories	Only primary pollutants are considered. Additional impact categories may be flagged whenever results indicate possible significant impacts.

D Operational Energy Flows

This appendix presents Sankey diagrams of the energy flows of the operational phase of the diesel ICE system (Figure 5) and of the PEMFC/SOFC system (Figure 6). The flow sizes represent the energy content of the flow. Grey flows represent the flow of diesel/hydrogen fuel. After conversion, by either the ICE or the fuel cells, the green flows represent useful energy, whereas the red flows represent energy losses. The figures show the inherently different operation of both systems. The base-case system requires four different diesel engine to power the stern propeller, the bow propeller and the hotel appliances. In the fuel cell system , power is provided by all three of the fuel cell on a load sharing basis. The overall energy conversion efficiency of the ICE and fuel cells are approximately 33% and 50%, respectively.

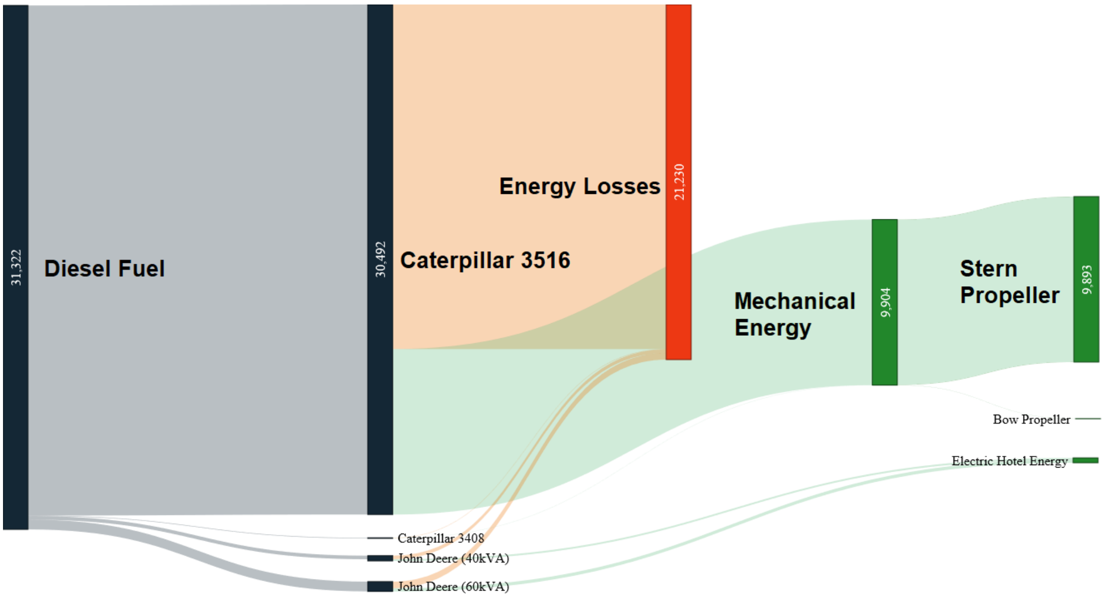

Figure 5: *Sankey diagram of energy flows in MSC Maas power system in the base-case diesel ICE scenario.*

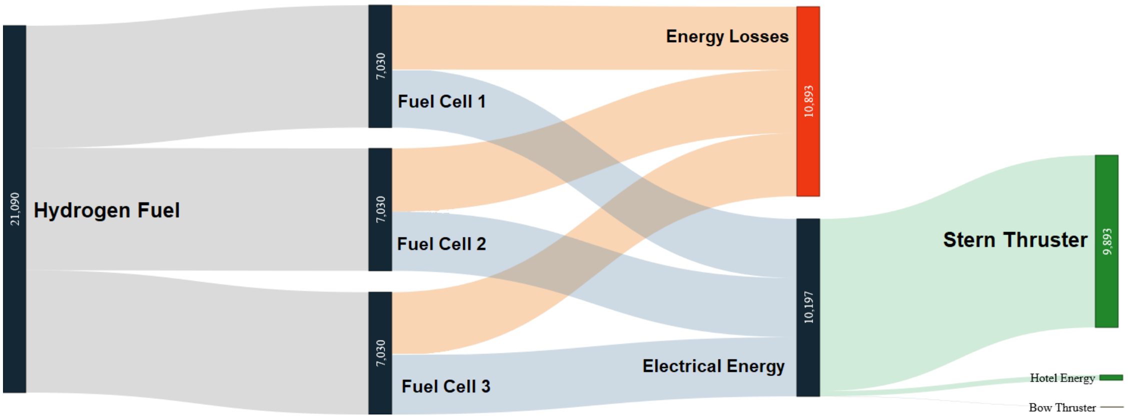

Figure 6: *Sankey diagram of energy flows in MSC Maas power system in the fuel cell scenario.*

E Literature & Data Scoping Review

This appendix presents an overview of the literature consulted in the scoping review of this study, as well as the corresponding data that was used to estimate impacts. The reference values presented in Tables 2 to 2 are the literature values that have been used to estimate total life-cycle CO_2 emissions. In most cases, the references values have already undergone some type of conversion, in order to match the desired functional unit.

Table 2: *Literature consulted in the scoping review of the operational phase, with corresponding reference values.*

Operational Phase				
Source	*Scenario*	*Reference Value*	*Unit*	*Life-Cycle CO_2 (tonnes)*
Tzannatos et al. (2015)	Diesel-base case	692.0	g CO_2 / kWh useful	55145
Lloyd's Register (2019)	Diesel-base case	660.0	g CO_2 / kWh useful	52595
M. Ashby (2012)	Diesel-base case	611.0	g CO_2 / kWh useful	48691
Winnes & Fridell (2009)	Diesel-base case	645.0	g CO_2 / kWh useful	51400
Winther et al. (2017)	Diesel-base case	3160.0	g CO_2 / kg fuel	48376
Perumal & Timmons (2017)	Diesel-base case	3172.0	g CO_2 / kg fuel	48560
IMO (2020)	Diesel-base case	3206.0	kg CO_2 / tonne fuel	49081

Table 3: *Literature consulted in the scoping review of the system component manufacturing phase. with corresponding reference values.*

System Component Manufacturing				
Author	*Component*	*Reference Value*	*Unit*	*Life-Cycle CO_2 (tonnes)*
Li et al. (2013)	Diesel ICE	5.7	kg CO_2 / kg engine	95
Shi et al. (2015)	Diesel ICE	5.36	kg CO_2 / kg engine	89
Dias et al. (2013)	Diesel ICE	4.59	kg CO_2 / kg engine	76
Altmann et al. (2004)	Diesel ICE	57.35	kg CO_2 / kW installed	105
Lotrič et al. (2020)	PEMFC	44.8	kg CO_2 / kW installed	148
Pehnt (2001)	PEMFC	275	kg CO_2 / kW installed	908
Altmann et al. (2004)	PEMFC	356.86	kg CO_2 / kW installed	1178
Stropnik et al. (2019)	PEMFC	112	kg CO_2 / kW installed	370
Bicer & Khalid (2020)	SOFC	0.0242	kg CO_2 / kWhe	1580
Altmann et al. (2004)	SOFC	382	kg CO_2 / kW	1261
Utgikar & Thiesen (2006)	SOFC	0.25	kg CO_2 / kg H_2 consumed	851
Staffell et al. (2012)	SOFC	1218	kg CO_2 / kW installed	4019
Agostini et al. (2018)	H_2 Storage Tank	15.71	kg CO_2 / liter tank	405
Agostini et al. (2018)	H_2 Storage Tank	11.43	kg CO_2 / liter tank	295
Miotti et al. (2017a)	H_2 Storage Tank	276.1	kg CO_2 / kg H_2 content	179
Benitez et al. (2021)	H_2 Storage Tank	70	kg CO_2/ kg carbon fiber	532
Wulf et al. (2018)	H_2 Storage Tank	0.443	kg CO_2 / kg H_2 content	1507
Keoleian et al. (1998)	NH3 Storage Tank	2.52	kg CO_2 / liter tank	65
Dlamini et al. (2011)	NH3 Storage Tank	6.24	kg CO_2 / liter tank	161
Gerboni et al. (2004)	NH3 Storage Tank	2.94	kg CO_2 / liter tank	76
Dehghani-Sanij et al. (2019)	Li-ion Battery	12.5	kg CO_2 / kg battery	135
Ellingsen et al. (2014)	Li-ion Battery	172	kg CO_2 / kWh capacity	87
Dai et al. (2019)	Li-ion Battery	110.2	kg CO_2 / kWh capacity	110
Sullivan & Gaines (2011)	Li-ion Battery	12.5	kg CO_2 / kg battery	150

Table 4: *Literature consulted in the scoping review of the fuel production phase, with corresponding reference values.*

Fuel Production Process				
Author	*Scenario*	*Reference Value*	*Unit*	*Life-Cycle CO_2 (tonnes)*
Bengtson et al. (2011)	MGO: Refinery	291.5	g CO_2/tonne fuel	4617
Altmann et al. (2004)	MGO: Refinery	29.0	g CO_2/kWh fuel	5624
Spoof-Tuomi & Niemi (2020)	MGO: Refinery	14.6	g / MJ fuel	9522
Lloyd's Register (2019)	H_2: MSR	10.7	kg CO_2 / kg fuel	36521
Mehmeti et al. (2018)	H_2: MSR	12.1	kg CO_2 / kg fuel	41287
Bhandari et al. (2014)	H_2: MSR	13.0	kg CO_2 / kg fuel	44248
Altmann et al. (2004)	H_2: MSR	424.0	g CO_2/kWh fuel	47533
Cetinkaya et al. (2012)	H_2: MSR	9358.7	g CO_2 / kg fuel	40480
Hauck (2020)	H_2: MSR + CCS	1.8	kg CO_2 / kg fuel	6120
The Hydrogen Council (2021)	H_2: MSR + CCS	1.5	kg CO_2 / kg fuel	9190
The Hydrogen Council (2021)	H_2: MSR + CCS	2.7	kg CO_2 / kg fuel	13274
Dufour et al. (2012)	H_2: MSR + CCS	3.9	kg CO_2 / kg fuel	15332
Mehmeti et al. (2018)	H_2: MSR + CCS	3.4	kg CO_2 / kg fuel	11573
Mehmeti et al. (2018)	H_2: Electrolysis Grid	29.5	kg CO_2 / kg fuel	100545
Dufour et al. (2012)	H_2: Electrolysis Grid	2.5	kg CO_2 / Nm^3 fuel	95824
Gilbert et al. (2018)	H_2: Electrolysis Grid	28.9	kg CO_2 / kg fuel	98496
Bhandari et al. (2014)	H_2: Electrolysis Hydro	2.0	kg CO_2 / kg fuel	6807
Utgikar & Thiesen (2006)	H_2: Electrolysis Hydro	1.8	kg CO_2 / kg fuel	6127
Bhandari et al. (2014)	H_2: Electrolysis Nuclear	2.5	kg CO_2 / kg fuel	8509
Utgikar & Thiesen (2006)	H_2: Electrolysis Nuclear	2.0	kg CO_2 / kg fuel	6807
Cetinkaya et al. (2012)	H_2: Electrolysis Solar PV	2.21	kg CO_2 / kg fuel	8210
Dufour et al. (2012)	H_2: Electrolysis Solar PV	0.6	kg CO_2 / Nm^3 fuel	22998
Ozbilen et al. (2011)	H_2: Electrolysis Solar PV	2.0	kg CO_2 / kg fuel	6807
Utgikar & Thiesen (2006)	H_2: Electrolysis Solar PV	6.2	kg CO_2 / kg fuel	21103
Altmann et al. (2004)	H_2: Electrolysis Wind	25.0	g CO_2/ kWh fuel	2836
Bhandari et al. (2014)	H_2: Electrolysis Wind	0.95	kg CO_2 / kg fuel	3233
Cetinkaya et al. (2012)	H_2: Electrolysis Wind	0.97	kg CO_2 / kg fuel	3302
Gilbert et al. (2018)	H_2: Electrolysis Wind	2.01	kg CO_2 / kg fuel	6856
Mehmeti et al. (2018)	H_2: Electrolysis Wind	2.21	kg CO_2 / kg fuel	7522
Utgikar & Thiesen (2006)	H_2: Electrolysis Wind	1.1	kg CO_2 / kg fuel	3744
Ozbilen et al. (2011)	H_2: Electrolysis Wind	1.2	kg CO_2 / kg fuel	4084
Utgikar & Thiesen (2006)	H_2: Electrolysis Biomass	3.1	kg CO_2 / kg fuel	10551
Ozbilen et al. (2011)	H_2: Electrolysis Biomass	3.0	kg CO_2 / kg fuel	10211
Singh et al. (2018)	NH_3: MSR	3.032	kg CO_2 / kg fuel	76149
Bicer & Khalid (2020)	NH_3: MSR	0.87	kg CO_2 / kWhe	55225
Makhlouf et al. (2015)	NH_3: MSR	2.16	kg CO_2 / kg fuel	54244
Karaca (2019)	NH_3: MSR	1.8	kg CO_2 / kg fuel	45203
Smith et al. (2020)	NH_3: MSR	1.673	kg CO_2 / kg fuel	42014
Young & Quan-Haase (2013)	NH_3: MSR + CCS	N/A	N/A	24397
Smith et al. (2020)	NH_3: Electrolysis Grid	4.14	kg CO_2 / kg fuel	103926
Singh et al. (2018)	NH_3: Electrolysis Grid	3.66	kg CO_2 / kg fuel	91878
Singh et al. (2018)	NH_3: Electrolysis Solar	1.277	kg CO_2 / kg fuel	32081
Al-Breiki & Bicer (2021)	NH_3: Electrolysis Solar	0.9	kg CO_2 / kg fuel	22602
Bicer et al. (2016)	NH_3: Electrolysis Biomass	0.85	kg CO_2 / kg fuel	21346
Bicer et al. (2016)	NH_3: Electrolysis Nuclear	0.84	kg CO_2 / kg fuel	21095
Karaca (2019)	NH_3: Electrolysis Nuclear	0.224	kg CO_2 / kg fuel	5625
Al-Breiki & Bicer (2021)	NH_3: Electrolysis Wind	0.4	kg CO_2 / kg fuel	10045
Singh et al. (2018)	NH_3: Electrolysis Wind	0.496	kg CO_2 / kg fuel	12448
Bicer & Khalid (2020)	NH_3: Electrolysis Wind	0.16	kg CO_2 / kWhe	8867
Smith et al. (2020)	NH_3: Electrolysis Wind	0.325	kg CO_2 / kg fuel	8162
Smith et al. (2020)	NH_3: Electrolysis Hydro	0.455	kg CO_2 / kg fuel	11426
Bicer et al. (2016)	NH_3: Electrolysis Hydro	0.38	kg CO_2 / kg fuel	9543

F Literature & Data Detailing Review

This appendix presents the data used in the original calculations of the detailing review of the fuel cycle processes. The energy requirements for the hydrogen and ammonia requirements are presented in Tables 5 and 6 respectively.

Table 5: *Energy requirements of the different phases of the hydrogen production process.*

Hydrogen Production Inventories		
Source	*Fuel Production Phase*	*Energy Requirement (kWh / kg H_2)*
Lloyd's Register (2019)	Pretreatment	0.027
Hauck (2020)	Pretreatment	0.032
James et al. (2016)	Electrolyzer	54.6
Mehmeti et al. (2018)	Electrolyzer	54.6
Yates et al. (2020)	Electrolyzer	54
Bareiß et al. (2019)	Electrolyzer	55
Liu et al. (2020)	Electrolyzer	57
Lloyd's Register (2019)	Tank Compression	2.85
Patterson et al. (2014)	Tank Compression	3.73
DOE (2009)	Tank Compression	3
Makridis (2016)	Tank Compression	4.45
Hauck (2020)	Pipeline Compression	0.399168
Hauck (2020)	Pipeline Compression	0.737856
Wulf et al. (2018)	Pipeline Compression	0.344
Gilbert et al. (2018)	Liquification	10
Lloyd's Register (2019)	Liquification	10.18
Wulf & Zapp (2020)	Liquification	11.8
Wulf & Zapp (2020)	Fuel Delivery Pipeline	2.2
Wulf & Zapp (2020)	Fuel Delivery Compressed H_2	0.8
Wulf & Zapp (2020)	Fuel Delivery Liquid H_2	0.5

Table 6: *Energy requirements of the different phases of the ammonia production process.*

Hydrogen Production Inventories		
Source	*Fuel Production Phase*	*Energy Requirement (kWh / kg NH_3)*
Lloyd's Register (2019)	Pretreatment	0.00478
Hauck (2020)	Pretreatment	0.00566
Smith et al. (2020)	Electrolysis + Haber-Bosch	10.6
Bicer et al. (2016)	Electrolysis + Haber-Bosch	11.0
Bicer et al. (2016)	Electrolysis + Haber-Bosch	7.1
Bicer et al. (2016)	Electrolysis + Haber-Bosch	11.0
Makhlouf et al. (2015)	Electrolysis + Haber-Bosch	14.4
Lloyd's Register (2019)	Refrigiration + Storage	0.03789
Miura & Tezuka (2014)	Refrigiration + Storage	0.00556
T. Brown (2017)	Cracking	0.75
T. Brown (2017)	Cracking	0.3

Table 7 presents the fuel and trip parameters used to calculate the distribution emissions for different modes of transportation. For pipeline scenarios, data by Wulf & Zapp (2020) was used. For distribution via long-distance shipping, data by Lloyd's Register (2019) was used.

Table 7: *Fuel and trip parameters used to calculate the distribution emissions for different modes of transportation.*

Parameter	**Compressed H_2**	**Liquid H_2**	**Liquid NH_3**
Fuel Density (kg/L)	0.02	0.071	0.67
Fuel truck capacity (kg)	733	2596	24567
Number of trips in 30 years	4641	1311	1022
Distance in 30-years: 100 km trips (km)	464100	131100	102200
Distance in 30-years: 400 km trips (km)	1856400	524400	408800

Table 8 presents the emissions factors that have been used to translate the inventory data of Tables 5, 6 and 7 into CO_2 emissions data. The emissions factors of renewable energy sources are taken from the Annex II of the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (Moomaw et al., 2011). Emissions factors of the Dutch grid and average grid of the European Union countries are taken for the year 2019 (European Environment Agency, 2021). For truck driving scenarios, an emission factor of 1.943 kg CO_2 per km was used, assuming mid-sized truck with a tonnage between 10 and 20 (Otten et al., 2016).

Table 8: *Emission factors (g CO_2 per kWh of electric process energy) used in the original calculations of the detailing review, for different electricity sources.*

Energy Source	**Emission Factor (g CO_2 / kWh)**
Dutch Grid (2019)	390
EU Grid (2019)	253
Biomass Combustion	230
Solar PV Power	46
Hydro Power	24
Nuclear Power	16
Wind Power	11

G Grid Decarbonization Scenarios

Figure 7 presents the emission factors of different energy sources as a function of time. For the Dutch and European grid, annual data by the European Environment Agency (2021) has been used. The figure shows that grid emissions have decreased in the period from 1990 to 2019, to 390 g CO_2 per kWh in the Netherlands and an average of 253 g CO_2 per kWh in the European Union. The horizontal lines represent the emissions factor of electricity produced from renewable power sources. For this visual, it is assumed that the emissions factors remain constant. In reality, however, the emission factors will decrease slightly as a result of grid decarbonization. This is due to the use of grid electricity in upstream processes that are accounted for in the emissions factors.

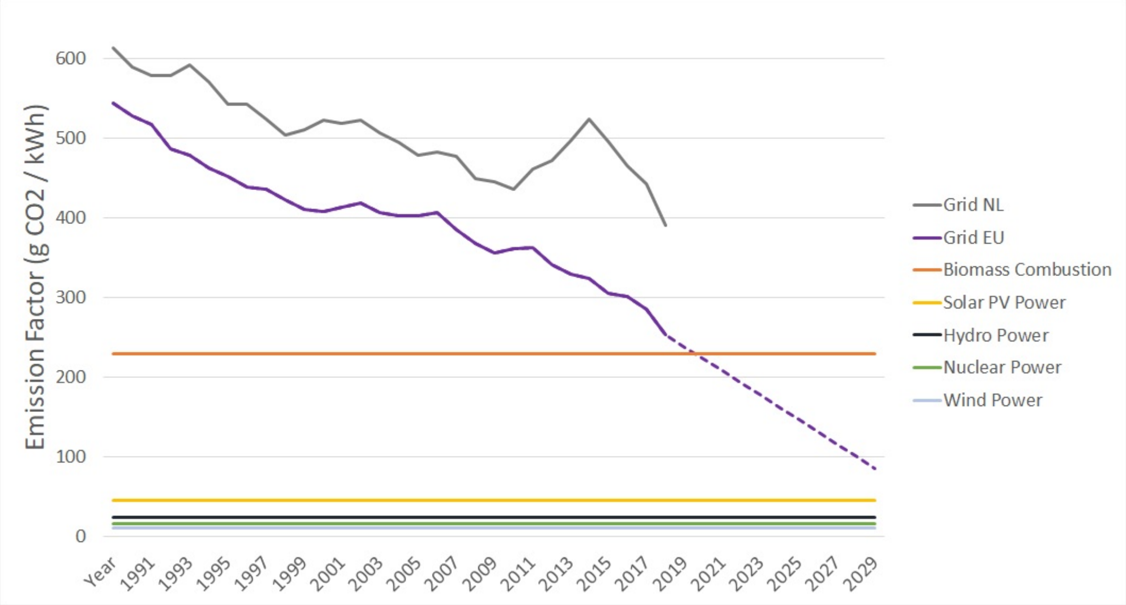

Figure 7: *An overview of the process flow involved in the fuel production cycle, from primary energy carrier to fuel cell operation of the electric motor.*

The dotted line in Figure 7 presents the decarbonization prediction for the EU grid by the European Environment Agency (2021). At this rate, the average EU grid outperforms biomass electricity by the year 2021. However, grid electricity is not expected to outperform solar PV or other renewable power sources, in terms of CO_2 emissions. As such, the use of grid electricity for electrolysis before the year 2030 is not advised, based on the currently available data.

H Fuel Cell Inventory Data

This appendix presents the inventory data that was used for the original calculations in the detailing review of the fuel cell manufacturing phase. Since detailed inventory data on 275 kW PEMFCs is not publicly available, an inventory of materials and processes was derived from the available inventory data of an 80 kW PEMFC reference system (Miotti et al., 2017a). The 80 kW reference system is scaled to the 275 kW research system, based on the active and passive fuel stack areas of the system. Fuel cell data by Battelle (2016) suggests that the active and passive fuel stack areas of the 275 kW are respectively 12.5 and 13.0 times larger, compared to the 80 kW system. Therefore the 275 kW inventory data is derived by multiplying the 80 kW inventory by a factor of 12.5 - 13.0.

Table 9 presents the data used to arrive at this multiplication factor. The first column is the data for the 80 kW system considered by Miotti et al. (2017a), while the second column presents the estimate for the 275 kW system. The results in the second column were validated by fuel cell manufacturer Nedstack. The results of this validation are presented in the third column. Based on the validation, it is suggested that the real multiplication factor is 10.3 rather than 12.5 - 13.0.

Table 9: *PEMFC design parameters based on a 80 kW reference system (column 1), scaled to the 275 kW research system (column 2), and validation of the 275 kW system by Nedstack.*

Design Parameter	**Reference System (Miotti et al., 2017a)**	**Research System (Battelle, 2016)**	**Nedstack Validation**
Installed Capacity (kW)	80	275	275
Installed Capacity per Stack (kW)	50	50	13.3
Fuel Cells per Stack	-	236	96
Stacks per System	2	6	32
Active Area per Fuel Cell (cm^2)	-	780	200
Active Area per System (m^2)	8.5	110.4	61.4
Total Area per Fuel Cell (cm^2)	-	1154	440
Total Area per System (m^2)	13.1	163.4	135.2
Inventory Scaling Factor	1.0	12.5 – 13.0	10.3

Table 10 now shows the inventory data of the fuel cell stack. The final three colums respectively represent the inventory for the 80 kW system by Miotti et al. (2017a), the estimated inventory data of the 275 kW system based on the 12.5 - 13.0 multiplication factor, and the validated inventory by Nedstack. Table 11 represents the same data for the BoP components. Data estimates of balance of plant components are particularly inaccurate, is as illustrated by the large differences compared to the validated inventory by Nedstack in Table 11. For reasons a confidentiality, a large number of BoP components cannot be validated. These are labeled ”unknown”.

Table 10: *PEMFC stack inventory: design parameters based on a 80 kW reference system (column 1). scaled to the 275 kW research system (column 2). and validation of the 275 kW system by Nedstack (column 3).*

Inventory Element	Material/ Process	Unit	80 kW Reference System	275 kW Research System	Nedstack Validation
1.1 Catalyst:					
Platinum	m	kg	0.034	0.442	0.350
Carbon Particles	m	kg	0.0102	0.133	0.105
Polytetrafluoroethylene (PTFE)	m	kg	0.001275	0.017	0.013
Solvent	m	kg	0.2975	3.87	3.064
Coating	p	m^2	8.5	110.4	87.6
Plant Electricity	p	kWh	42.5	552.2	437.8
1.2 Membrane:					
Tetrafluoroethylene (TFE)	m	kg	0.655	8.17	6.75
Sulfuric Trioxide	m	kg	0.0262	0.327	0.270
Expanded PTFE (ePTFE)	m	kg	0.0655	0.817	0.675
Polybenzimidazole (PBI)	m	kg	-	-	-
Production regular membrane	p	kg	0.6943	8.66	7.15
Production PBI membrane	p	kg	-	-	-
1.3 Gas Diffusion Layer (GDL):					
Macroporous Layer (MPL)	m	kg	2.38	30.9	24.5
PTFE (for MPL)	m	kg	0.1955	2.54	2.01
Microporous Layer (MiPL)	m	kg	0.459	5.96	4.73
PTFE (for MiPL)	m	kg	0.1445	1.88	1.49
Solvent	m	kg	0.0425	0.552	0.438
Weaving Cloth	p	kg	2.38	30.9	24.5
Production GDL	p	kg	2.805	36.4	28.9
Coating	p	m^2	8.5	110.4	87.6
1.4 MEA Production:					
MEA Assembly	p	kg	4.978	62.1	51.3
Gaskets	m	kg	3.406	42.5	35.1
Injection Molding of gaskets	p	kg	3.406	42.5	35.1
1.5 Bipolar Plates (BPP):					
Stainless Steel	m	kg	-	-	-
Titanium nitride (TiN)	m	kg	-	-	-
Graphite	m	kg	41.265	514.8	425.0
Thermoset Plastic	m	kg	17.685	220.6	182.2
Injection Moulded Gasket	m	kg	1.048	13.1	10.8
Screen Printed Gasket	m	kg	-	-	-
Injection Molding	p	kg	59.998	748.5	618.0
Stamping	p	kg	-	-	-
Coating	p	m^2	-	-	-
1.6 Other components & assembly:					
Glass Fiber (for end plate)	m	kg	0.786	9.8	8.1
Epoxy (for end plate)	m	kg	0.786	9.8	8.1
Copper (for current collector)	m	kg	1.441	18	15
Stainless Steel (compression band)	m	kg	0.917	11.4	9.4
Polypropylene (for casing)	m	kg	3.93	49	40
Production end plate	p	kg	1.572	19.6	16.2
Production collector	p	kg	1.441	18	15
Production casing	p	kg	3.93	49	40
Production end gaskets	p	m^2	13.1	163.4	134.9
Assembly and Conditioning	p	m^2	13.1	163.4	134.9
Transportation by Rail	p	tkm	51.09	637.4	526.2
Transportation by Truck	p	tkm	9.17	114.4	94.5

Table 11: *PEMFC Balance-of-Plnat: design parameters based on a 80 kW reference system (column 1). scaled to the 275 kW research system (column 2). and validation of the 275 kW system by Nedstack (column 3).*

Inventory Element	**Material/ Process**	**Unit**	**80 kW Reference System**	**275 kW Research System**	**Nedstack Validation**
2.1 Air Management:					
CEM	m	kg	17.5	52.5	310
Air filter	m	kg	1	3	Unknown
Air Ducting	m	kg	3	9	150
Mass Flow Sensor	m	kg	0.3	0.9	Unknown
2.2 Water Management:					
Humidifier (without Nafion tubes)	m	kg	2.7	8.1	250
TFE (for Nafion tubes in humidifier)	m	kg	0.52	1.56	Unknown
Sulfuric Trioxide (Nafion tubes)	m	kg	0.02	0.06	Unknown
ePTFE (for Nafion tubes in humidifier)	m	kg	0.05	0.15	Unknown
Production of Nafion tubes	p	kg	0.6	1.8	Unknown
Air Precoole	m	kg	2	6	Unknown
Demister	m	kg	2	6	Unknown
2.3 Heat Management:					
High temperature loop (HTL)	m	kg	10.9	32.7	50
Low temperature loop (LTL)	m	kg	2	6	230
Antifreeze liquid	m	kg	7	21	Unknown
2.4 Fuel Management:					
Ejectors	m	kg	0.1	0.3	250
Pipes	m	kg	5	15	150
Valves	m	kg	1.5	4.5	15
Inline Filter	m	kg	1	3	Unknown
Pressure Switch	m	kg	0.3	0.9	Unknown
2.5 Control:					
Hydrogen sensors	m	kg	0.3	0.9	Unknown
Other sensors	m	kg	0.4	1.2	Unknown
Control electronics	m	kg	2	6	250
2.6 Other & Assembly:					
Wiring	m	m	16	48	Unknown
Belly pan	m	kg	3	9	Unknown
Mounting frames	m	kg	5	15	600
Fasteners	m	kg	1	3	Unknown
Assembly of balance of plant	p	kg	70.6	211.8	500