Carbon footprint of hydrogen-powered inland shipping

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Carbon footprint of hydrogen-powered inland shipping: Impacts and hotspots

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ABSTRACT

The shipping sector is facing increasing pressure to implement clean fuels and drivetrains. Especially hydrogen-fuel cell drivetrains seem attractive. Although several studies have been conducted to assess the carbon footprint of hydrogen and its application in ships, their results remain hard to interpret and compare. Namely, it is necessary to include a variety of drivetrain solutions, and different studies are based on various assumptions and are expressed in other units. This paper addresses this problem by offering a three-step meta-review of life cycle assessment studies. First, a literature review was conducted. Second, results from the literature were harmonized to make the different analyses comparable, serving cross-examination. The entire life cycle of both the fuels and drivetrains were included. The results showed that the dominant impact was fuel use and related fuel production. And finally, life-cycle hot spots have been identified by looking at the effect of specific configurations in more detail. Hydrogen production by electrolysis powered by wind has the most negligible impact. For this ultra-low carbon pathway, the modes of hydrogen transport and the use of specific materials and components become relevant.

1. Introduction

The earth is increasingly facing the negative effect of environmental pressures caused by human activity [1,2]. Transport contributes significantly to global warming and air pollution [3,4]. The maritime sector is particularly crucial, as its transport represents 80–90% of international trade by volume [5–7]. Currently, this sector contributes 3% of anthropogenic greenhouse gas emissions [8,9]. But carbon dioxide emissions for the sector are projected to grow by a substantial 150–250% by 2050 [8], undermining the objectives of the Paris Climate Agreement. In addition, the shipping sector is responsible for 13–15% of SO_2 and 12–13% of NO_x emissions, which negatively impact the environment and human health [10]. Therefore, the sector faces increased attention, regulation, and emissions pricing, especially in the European Union [7,11,12].

Deep decarbonization of the shipping industry requires transitioning towards alternative fuels and conversion systems. Different options are being considered: liquefied natural gas or biogas, biofuels, methanol, ammonia, hydrogen, synthetic fuels, or battery-electric systems; in combination with electric or combustion engines or fuel cells [7,13–23]. While all these options are relevant, some applications have higher overall efficiencies, lower carbon footprint, or higher technological readiness and can be implemented in the short term – thereby creating a valuable learning experience and momentum for the transition towards sustainable systems. Especially inland shipping is an interesting niche in which early applications are being explored, as it combines standard routes, relatively small travel distances, and localized infrastructure.

Hydrogen-based propulsion in combination with fuel cells is promising due to high fuel conversion efficiencies resulting in suitability for mid-range shipping up to several hundreds of kilometers [16]. Moreover, it is inherently clean since it emits no carbon dioxide or other substances. A disadvantage is its low volumetric energy density, which can be overcome by using liquid hydrogen or converting hydrogen into liquid ammonia. Another option is the power-to-fuels route to produce hydrogen and subsequently create synthetic fuels like diesel or jet fuel. However, due to its lower overall energy efficiency and higher costs, this is mainly considered for ‘difficult’ applications like aviation or long-distance shipping [14,24–27]. Hydrogen is increasingly starting to find applications, and it receives strong support as an energy carrier for the future [15,28–30] – what is referred to as the hydrogen economy. Multiple ways of producing and converting hydrogen are being explored

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Abbreviations

CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
GE	Grid Electrolysis
H_2	Hydrogen
LCA	Life Cycle Assessment
MGO	Marine Gas Oil
MSR	Methane Steam Reforming
NH_3	Ammonia
PEMFC	Proton Exchange Membrane Fuel Cell
SOFC	Solid Oxide Fuel Cell

in this context.

However, hydrogen production is not free of impacts. It raises the question of what the impact is of different hydrogen-conversion pathways. This is a challenging question to answer, as most emissions shift upstream (mining, production) and occur out of sight. A carbon footprint study or life cycle assessment (LCA) can provide insight by assessing the emissions over the entire product life cycle: covering resource mining, production, use, and waste phase. In the shipping sector, several of these studies exist [18,31–33], including some covering the hydrogen option [34–37]. However, comparing their results is often challenging and confusing: different fuel-drivetrain configurations are considered under varying conditions, results are expressed in other units, assumptions are not always explicitly stated, and frequently different methodologies and datasets are used.

We argue in this context, on the one hand, for the need to harmonize results to support strategic decision-making by stakeholders in the maritime industry, and on the other hand, for a more nuanced and detailed assessment to better understand the cause of differences between studies. So, the research question is: '*What is the carbon footprint of hydrogen-based maritime propulsion systems, and what are the life-cycle hotspots causing these emissions.*' The total energy use of a ship depends on three factors: external circumstances (e.g. wind, current, waves); ship characteristics (e.g. shape, draft, speed); and the drivetrain and fuel applied. That latter holds our interest, as the first two will remain unchanged if alternative fuels are used. More specifically, the focus will be on low-carbon options that can support the sector to become climate neutral.

The relevance of reviewing and cross-examining LCA studies is widely recognized – see section 2. It holds clear benefits as it can help identify different system configurations, parameters, and assumptions and their consequences while increasing the accuracy and reliability of overall results [38]. However, thorough reviewing and harmonization of results is not a sinecure. Drawing a generalized conclusion from these LCA studies is complicated by the wide variety of methodological choices made in the studies that may have profound effects on the final results [39–44].

To overcome these challenges, a three-step approach will be used. First, a qualitative literature review will be conducted of existing LCA studies of hydrogen-based systems for shipping. Second, based on these studies and additional literature, results are harmonized to assess the carbon footprint of 8 different hydrogen pathways and 1 diesel reference case. Finally, data gaps and uncertainties in existing literature are addressed in the third step by collecting additional inventory and impact data from secondary sources for a more detailed assessment and contribution analysis of ultra-low carbon options.

The following paragraph will introduce the literature on LCA and the relevance of review articles in this field. Next, paragraph 3 will introduce the methodology, including options to compare, system boundaries, functional unit, and literature selection. Then, paragraph 4 will discuss the results, and paragraph 5 will present the conclusions and discussions.

2. Value of reviewing LCA literature

Life-Cycle Assessment is a widely used and mature methodology for assessing the environmental impacts of a product, process, or system over its entire life cycle [45,46]. The life cycle includes the sourcing and processing of raw materials, the manufacturing, and assembling of parts, the distribution of the final product, its usage, and its disposal.

The existing body of LCA literature provides valuable information and insight into the possible emissions of specific alternatives for shipping fuels and drivetrains. However, neither of these studies provides a complete and comprehensive picture of the total life-cycle emissions, the key impacts, and the most critical uncertainties. In contrast, LCA studies on hydrogen-fuel cell systems for road vehicles typically cover impacts across the entire life cycle [47–49].

Harmonization of results from different studies is complicated due to the variations mentioned above in methodological assumptions. Differences between studies may result in a perception of inconclusiveness concerning the "true" environmental impacts of alternative shipping systems. Strategies to deal with these differences have focused on increasing methodological transparency [42,43,50], statistical analysis of uncertainties [39,41,51], and qualitative assessments of assumptions [52,53]. In recent years, qualitative methods have received particular attention for creating situation-specific insights for decision-makers [43,52,54,55].

A meta-review of existing LCA literature combines qualitative and quantitative approaches [56]. Meta reviews can solidify or challenge assumptions and conclusions regarding different system configurations and their impact [57]. They can help understand critical uncertainties and system parameters better, thereby explaining discrepancies between various studies [38,58]. This approach has recently gained popularity. It has been employed in a variety of different industries, including the food sector [59], waste processing [60], building industry [61], solar PV manufacturing [62], and Carbon Capture and Storage [63]. This widespread application of the meta-analysis points to the prevalence of uncertainties in LCA studies and illustrates the need to make sense of conflicting results.

3. Methodology

The three-step approach will be described in the upcoming subsections: literature review, cross-examination of harmonized results, and a more detailed assessment of ultra-low carbon options. The research was conducted between September 2020 and July 2021. The first step, the literature review, has been updated to include studies until May 2022.

3.1. STEP 1: literature review

First, academic and grey literature was retrieved by using the search engines ScienceDirect, ResearchGate, Scopus, Google Scholar, and Google. The search queries typically included: marine or shipping; life cycle assessment, LCA, carbon footprint, or environmental impact assessment; and fuel, drivetrain, or propulsion. The most relevant articles were selected, initially by the title and abstract and subsequently by quick scanning of the full articles. The focus was on LCA studies that included hydrogen or ammonia for shipping, but studies on diesel were also included in support of a reference scenario. Used exclusion criteria were: an exclusive focus on alternative fossil fuel options; a focus on low-carbon options but not considering a hydrogen/ammonia option; or an exclusive focus on contextual factors (e.g. weather, current) or ship characteristics (e.g. draft, resistance) without considering the propulsion system and fuels applied. Literature on methanol fuel was included, as methanol is produced from hydrogen, and as such, this literature is relevant for reconstructing and assessing upstream processes. Also included is literature on battery systems, as batteries can be used in combination with hydrogen-fuel cells to come to an economically more optimal configuration – as was also done in this study; see the following sub-section. Subsequently, the selected literature was assessed to identify which fuels were studied and which scoping was applied (fuel production, drivetrain life cycle, shipping, or fuel transport), see Appendix A. Also, broader issues were identified to discuss the field, ongoing discussions, critical findings, and potential barriers for comparison, see section 4.1. The initial literature search was conducted at the beginning of the research in 2020, followed by a second search in 2022 to include recent results.

3.2. STEP 2: cross-examination of harmonized results

In the second step, the different studies are harmonized in three consecutive stages, each described in more detail below. First, clear system boundaries and a detailed functional unit are defined. Next, nine specific fuel-conversion pathways are identified and dimensioned accordingly. And finally, the results of different studies are recalculated to allow for cross-examination.

The scope of the study is defined to include the entire life cycle of the ship's propulsion system. It consists of the fuel and power system's complete life cycle, in line with the GREET approach for vehicle technology [64] – see Fig. 1.

As unit of analysis, the functional unit is defined as: *"Serving the power requirements of a standard inland container ship, with a maximum tonnage greater than 2000 tonnes, traveling 220 trips per year of* 200 km *each, for 30 years".* This type of ship relates to a standard-size inland container ship often used in the Netherlands (dimensions: size 110*11.5*3.5 m). Each ship has three power requirements: the stern propeller, which propels the ship; the bow propellers for sharp steering (e.g. in the harbor); and electrical power for hotel functions (lighting, communication, etc.) both during sailing and in port - in case the ship cannot plugin into the grid. In addition, refueling should be possible within hours to allow for 220 trips per year.

Next, the most relevant fuel-conversion pathways were identified. Nine different fuel-conversion pathways are selected, each relating to a specific primary energy source, fuel production of a particular energy carrier, and final energy conversion, see Fig. 2. The first pathway is the base-case scenario using Marine Gas Oil (MGO) driving an Internal Combustion Engine (ICE). In addition, four pathways are based on hydrogen and a Proton Exchange Membrane Fuel Cell (PEMFC). And another four pathways assume the conversion of hydrogen to ammonia to make it easier to store the fuel, followed by a final conversion by a Solid Oxide Fuel Cell (SOFC). All eight fuel-cell pathways use electromotors to drive the shafts and use lithium-ion batteries for extra peak power, fast response time, and powering the bow propellers. Initial production of hydrogen is either by Methane Steam Reforming (MSR) of natural gas (with or without Carbon Capture and Storage (CCS)) or by electrolysis based on either grid electricity or renewable power. The composition of the grid electricity mixes and selected renewable power sources vary depending on the underlying reviewed LCA literature.

To dimension the systems, the required power and energy have been determined based on the load-duration curve of a similar vessel [65]. Analysis of this curve showed that the energy use is dominated by propulsion by the stern propellers (~97%). The bow propellers are rarely used, so their energy use is negligible. The hotel functions makeup 2–3% of total energy use. Maximum power is determined by peak-load requirements: 1250 kW at the stern propeller (although typically the load stays below 750 kW for 99.5% of the trip), 375 kW for bow propellers, and 50 kW for hotelling functions. The total energy required per trip is 9000 kWh at the shaft, which determines the amount of fuel storage needed for the ship, taking an extra 10% safety margin into account. In addition, in this step, the conversion efficiency is assumed for combustion engines (33%), fuel cells (50%), electromotors (90%), and charge-discharge efficiency for batteries (95%). The batteries are charged with power from the fuel cells.

For pathway 1, the base case of marine gas oil, this results in a 1250 kW diesel engine for the stern thruster, 375 kW diesel engine for the bow thrusters, and a 50 kW diesel generator for hotel functions. All hydrogen/ammonia pathways are dimensioned at 825 kW power output by the fuel cells (resulting in 750 kW shaft power, considering the electromotors' efficiency) and 504 kW backup power by batteries. The provided power can be directed to either stern or bow propellers or can be used for hotelling functions. A type IV tank of 50 m^3 at 300 bar is used for hydrogen storage, dimensioned to contain enough fuel for a round trip. This type of tank holds the strategic advantage that it allows storage of hydrogen at higher pressures and, as such, would allow for even longer distances. For ammonia, a 25 m^3 type III storage tank is used. Components with lifetimes shorter than 30 years need a replacement one to four times, see Table 1.

The next step was harmonizing existing studies to the systems and dimensions as indicated above. All studies that were identified in the first reviewing step were assessed on whether these could be harmonized. This required 1) the inclusion of one or more of the fuel-conversion options identified above; and 2) being transparent in

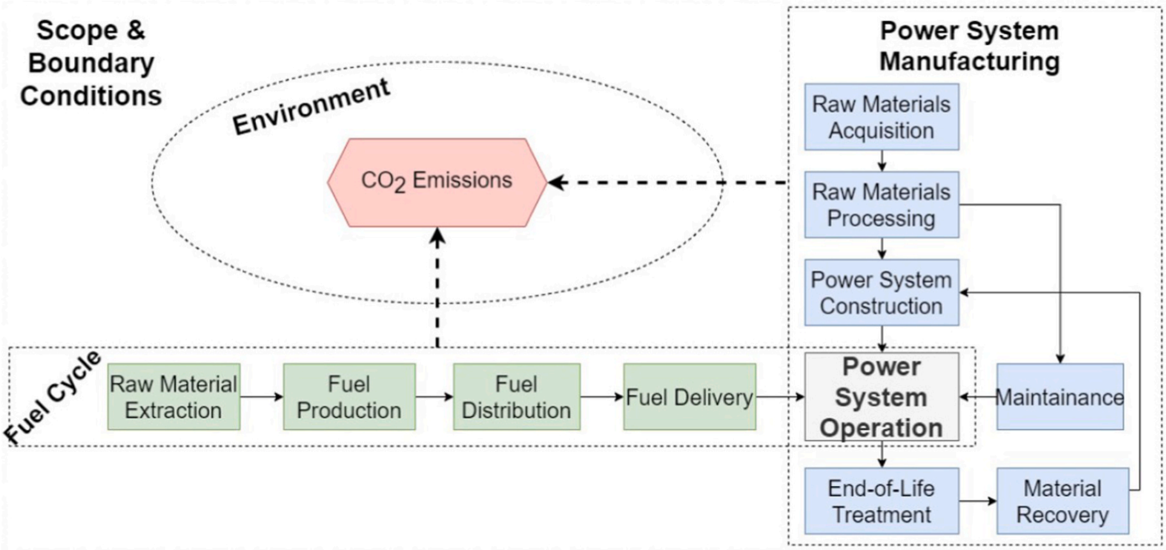

Fig. 1. System boundaries.

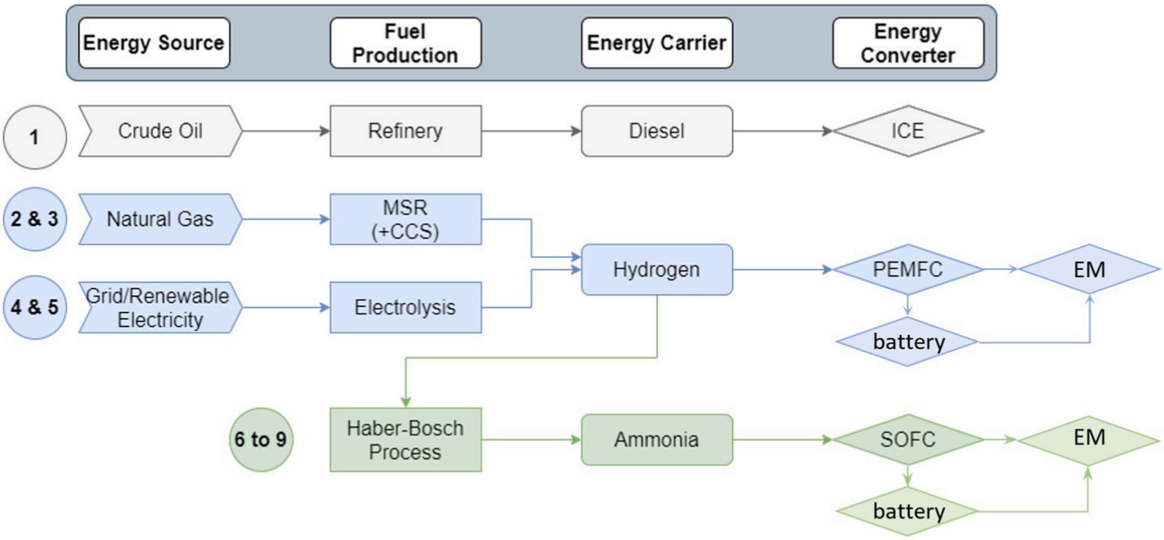

Fig. 2. The nine analyzed fuel-conversion pathways.

Table 1
The required number of components for a 30-year lifetime of the ship.

Component	Lifetime (years)	Number of components during 30-year lifetime
Diesel engine	30	1
Electromotor	15	2
Fuel cell – stack	7.5	4
Fuel cell – Balance-of-plant	30	1
Fuel storage tanks	20	2
Li-ion battery	10	3

scoping, assumptions, and disclosing data. Studies were considered either when they covered the full life cycle or when they covered one of the life cycle stages in enough detail. Only four studies met these criteria: Bengtson et al. (2011), Gilbert et al. (2018), Hydrogen Council (2021), and Lloyd's Register (2019) [31,36,66,67].

But the operationalization of the functional unit allowed us to renew the search and identify and include additional studies that focused on the fuel-conversion options but were not explicitly focused on the shipping sector. Search queries included (combinations of) diesel engine, fuel cell, hydrogen, ammonia, battery, and electrolysis. Studies were included that covered either the entire life cycle or specific life cycle stages. In total, 46 studies were considered, see appendix A. For harmonization, standardizing all studies in detail would be impossible. The focus was on standardizing power output, lifetime, and fuel-conversion pathway configurations. For the 46 studies, first, the results were split up per "component" of the different fuel-conversion pathways: fuel production, fuel storage and distribution, system operation, and fuel converter manufacturing. Next, per component conversion and scaling were applied: to *kg* of fuel output (fuel production), *liters* of transported fuel (fuel storage and distribution), *kW* of rated power (energy converters), and *kWh* of energy capacity (backup batteries). Linear scaling was assumed for all components. Finally, the individual components were recombined to represent the fuel-conversion pathways of Fig. 2, considering the replacement rate of components (Table 1). This resulted in 15.240 unique datapoints for the carbon footprint of fuel-conversion pathways. It can be considered a rich representation of the theoretical possibility space, representing carbon footprints under a wide diversity of assumptions, conditions, and choices. It allows drawing on the power of big data to conclude on averages and variation and thereby support robust conclusions.

3.3. STEP 3: detailed assessment

Next, in step 3, additional detailed assessments were conducted on specific topics that affect the carbon footprint. These more detailed studies help to understand the variation in outcomes between studies and the potential of ultra-low-carbon hydrogen options for the future. Specific topics studied included the influence of 1) specific renewable energy sources; 2) fuel transport; 3) fuel cell efficiency; and 4) manufacturing of fuel cells. Thirty-one of the studies of steps 1 and 2 provided enough detail to be relevant for this third step. To fill data gaps, additional queries were conducted on hydrogen and ammonia production, fuel cell manufacturing, and transport. This resulted in an addition of 19 studies, see appendix A. The methodological details of these four more detailed assessments have been included in the results section to improve overall readability.

4. Results

Section 4.1 presents the results of the review of existing LCA literature on alternative shipping fuel and drivetrains. Section 4.2 presents the harmonized results of the full life cycle impacts of the analyzed systems. And finally, section 4.3 shows the results of the more detailed assessments on electrolysis by renewable power, the hydrogen transportation phase, fuel cell efficiency, and the manufacturing of the drivetrain.

4.1. Step 1: reviewing LCA studies in the shipping sector

The initial literature search and selection provided 21 articles and reports from various academic journals and grey literature, see appendix A. The articles are typically published in journals related to (renewable) energy, impact assessment, or maritime engineering. There has been a substantial increase in literature after 2016 and especially since 2021, indicating the upcoming relevance of the topic. There are differences in scoping: some studies focus on a ship's life cycle [68–70]; others focus on the fuel cycle [13,34,66,71,72]. The considered impacts are only global warming [20,34,73] or multiple environmental impacts [35–37,68].

A wide variety of use cases are considered that hugely affect the outcomes of the studies. A crucial factor is the type of ship considered: ship size; inland ships or ocean steamers; and differences in the function of the ship, e.g., cargo ship, passenger ferry, dredger, tanker, wind farm support vessel [35,37,68,74–76]. The type and function of the ship directly relate to shipping characteristics (draft, resistance, amount of hotel functions) and the use cases (no movement, mainly maneuvering or steady cruising; shipping time and distance; wind and current that the ship will have to face; cargo load; speed). The geographic scoping can be relevant (e.g. Europe, China) as this might strongly influence fuel production data, especially by the electricity mix [36,76] and potentially as well by shipping standards and regulations. Mainly studies have been conducted for Europe. Most studies are of the past decade and assess the 'current' state, while some also consider a future state, typically using 2050 scenarios [36,73]. Several recent studies use GREET model for greenhouse gas emissions [33,37,76]; others use other LCA software or datasets (Ecoinvent, Simapro, GaBi, openLCA, TEAMS, LBST E3database, or literature).

Some studies focus only on fossil-fuel-based options, like diesel, Heavy Fuel Oil, Marine Diesel Oil, and Liquified Natural Gas [31,32,77]. These will be taken into account for reconstructing the diesel base scenario. Twelve studies consider the hydrogen option. Some of them are entirely focused on hydrogen [73,74,78]; others compare hydrogen options to alternative fuels [20,34,36,66,76]. Hydrogen is produced by SMR (either with or without CCS) or electrolysis. Electrolysis uses electricity from the grid or from renewables (wind, biomass, geothermal, waste incineration). For hydrogen conversion, typically, fuel cells are used, although not all studies clearly specify this. Only Fernández-Ríos [35] considers the use of internal combustion engines.

Three studies stand out for being more specific and detailed. First, Gilbert et al. [36] conduct a comparative LCA of twelve alternative shipping fuels in a Well-to-Propellor analysis. Results are differentiated between operational and upstream emissions and the contribution of different greenhouse gasses. According to this study, for hydrogen, only upstream emissions are relevant (during use, no greenhouse gas emissions are released), and CO_2 emissions contribute to over 90% of the global warming impact. The study contains an extensive sensitivity analysis of fuel cycle parameters and considers different grid emission factors for 2020 and 2050. While in the current situation, only hydrogen production by electrolysis based on renewables is advantageous, for 2050, SMR + CCS could also lead to a significant emission reduction. Second, Bicer and Dicer [68] compare hydrogen and ammonia, including dual fuel options for transoceanic transport by freight ships and tankers. The study includes the production of the ship and port facilities. Results show that operation (fuel use and fuel production) has a dominant impact (64–79%). However, for dual fuel use (ammonia--heavy fuel oil), the maintenance and operation of the port also have a significant contribution (31%). And finally, Perčić et al. [37] study the application of fuel cells in short-sea shipping. Its main contribution is the many alternative hydrogen configurations that are being compared: for three types of ships; grey (gas-based SMR), blue (with CCS), and green (based on renewables); and for SOFC and PEMFC conversion, both on the ship and land.

Different studies come to results in other units: tonne CO_2 equivalent over a ship's lifetime; or related to transport distance (kg CO_2 per kilometer, nautical mile, tonne-km, or passenger-km); or related to energy output (kg CO_2 per MJ fuel or kWh shaft power). This variety in data and units, combined with the variety of scoping (ships, life cycle, geography, time) and the usage of specific assumptions or data sets, makes it hard to compare the different studies. And even when studies are comparable, the results might show a wide range and therefore be inconclusive. For example, Fernández-Rios et al. [35] compared five studies on the same technology, PEMFC based on SMR of natural gas, indicating a range of 0.51–1.06 kg CO_2 eq./kWh. Still, there are some general trends. Typically, natural-gas-based hydrogen production by Steam Methane Reforming shows an increase in global warming emissions compared to the diesel base case. Hydrogen production by SMR + CCS can significantly reduce emissions by up to 50–75% [37]. If hydrogen is produced by electrolysis using renewable power, the carbon footprint is reduced further to 84–89% compared to diesel [37,78], and a reduction with a factor of 10–50 compared to hydrogen SMR [34,36,66].

Most of these studies show several shortcomings: disregarding the impact of manufacturing the drivetrain and related components; not specifying well the electricity mix used for electrolysis or considering only a few (renewable) power sources; the differences in scoping and functional units, which makes it hard to compare studies; and lacking detailed data and conclusions on hot spots (e.g. most relevant life cycle stages, processes, materials).

4.2. Step 2: harmonized results

The studies have been standardized by relating them to the predefined systems configurations and functional units, see section 3.2. For this purpose, four studies from step 1 have been used that disclosed enough detail and data. In addition, 41 additional studies have been identified that provide information about hydrogen production, batteries, or fuel cells, without a specific focus on maritime applications. For all nine fuel-conversion pathways, the total carbon footprint has been calculated over the ship's lifetime, see Fig. 3.

On average, the base-case diesel pathway produces 57 ktonnes of CO_2 over the vessel's entire life cycle. Hydrogen production via electrolysis by using grid electricity (GE) results in a significant increase in emissions compared to the base case, up to 100 ktonnes for both PEMFC and SOFC. This is due to the relatively low efficiency of traditional power plants and the relatively high carbon intensity of coal, often used as fuel for power production. In contrast, electrolysis using renewable electricity (RE) and the application of carbon capture and storage (CCS) both significantly reduce the carbon footprint, with total emissions in the range of 10–27 ktonnes of CO_2. While looking in more detail, the renewable energy options consistently outperform the Methane Steam Reforming with carbon capture and storage options. The pathways based on Methane Steam Reforming without carbon capture and storage – currently frequently used for hydrogen production - score in a similar range as the diesel base case (44–57 ktonnes of CO_2).

Results suggest that routes based on hydrogen-PEMFC fuel cells score better than the hydrogen-ammonia-SOFC routes. This difference might result from the extra process step, the Haber-Bosch process that produces ammonia from hydrogen, which might reduce the overall efficiency, or the higher temperatures at which SOFC operates. These explanations would hold for all SOFC options. However, in the figure, scores from PEMFC and SOFC based on grid electricity are similar. Also, for the other pathways, the relative differences are not consistent. The ratio between the carbon footprint of SOFC versus PEMFC differs from 1.3 to 2 for the Methane Steam Reforming pathways, respectively, without and with CCS. The results and analysis do not offer a clear explanation for these differences.

Most fuel-conversion pathways show significant variation between minimum and maximum scores, resulting from differences in the underlying studies. One of the contributing factors is the difference in background electricity mixes used in the different studies. The variation is more prominent for SOFC pathways. A potential explanation can be found in the extra Haber-Bosch process step. Also, in the SOFC pathway, heat integration between MSR and Haber-Bosch might play a role. Due to differences in allocation in the underlying studies of heat integration and the followed approach (component level split up followed by recombining into pathways), this might have resulted in under- or overestimation of the total carbon footprint.

Especially for low-carbon options, the relative uncertainty is high. For example, for hydrogen production by electrolysis based on renewable power, the impact ranges from 3.3 to 26.0 ktonnes for PEMFC and 6.7–36.5 ktonnes for SOFC. As these might be preferred transition pathways for low-carbon shipping, these differences in results are interesting to study in more detail – as is done in the next step.

Next, for each pathway (average case), the relative contribution of the different life cycle phases and components is analyzed, see Fig. 4. The fuel production stage strongly dominates the overall impact in each

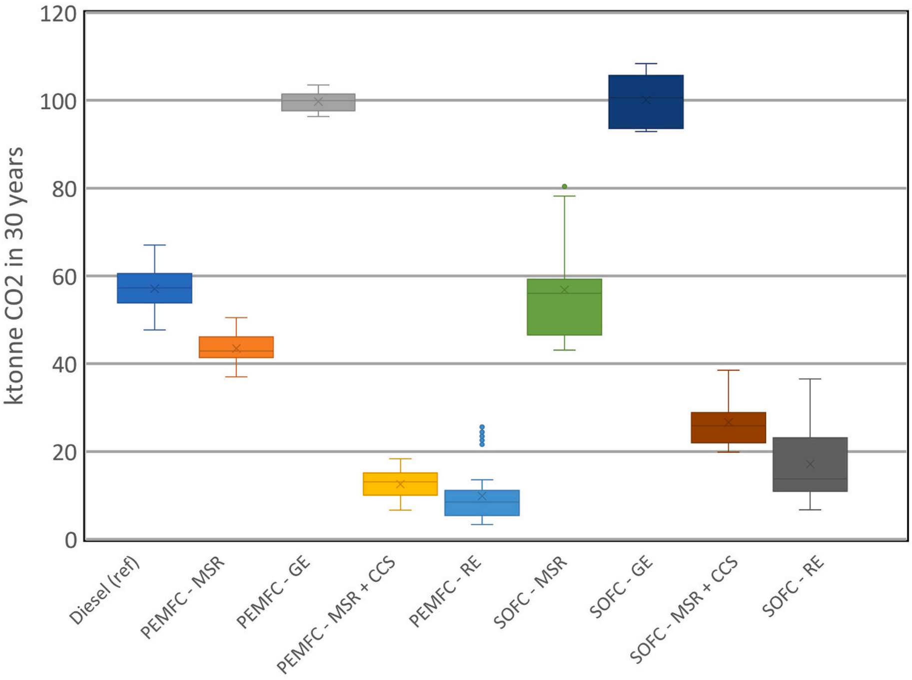

Fig. 3. The total carbon footprint of the nine fuel-conversion pathways, based on 15.240 unique datapoints. The Box and Whisker plots indicate the distribution of results by representing the median and the four quartiles. In addition, the average value is represented by 'X'.

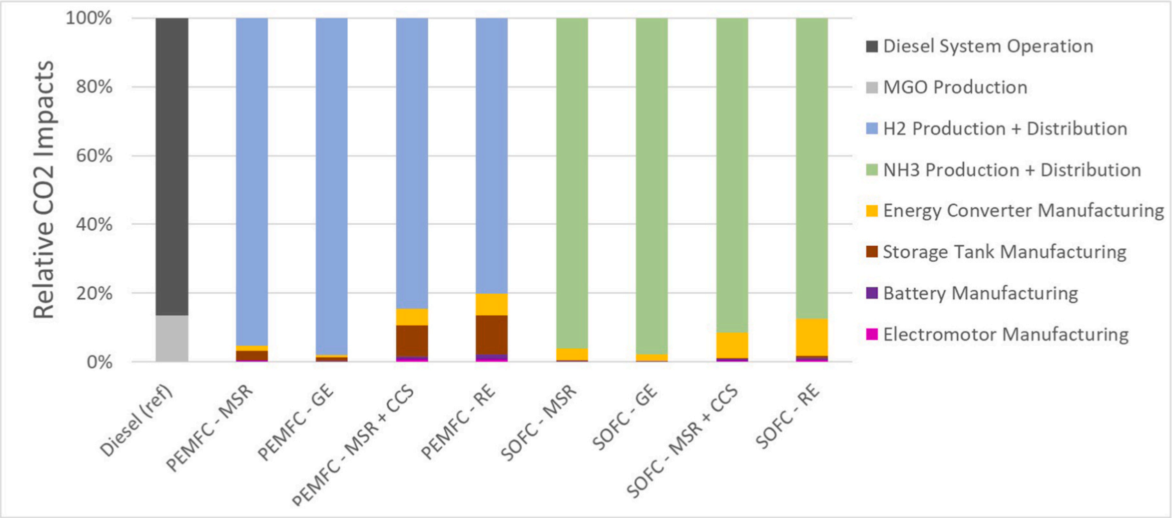

Fig. 4. The relative contribution of the different life cycle phases and components to the overall carbon footprint of the nine fuel-conversion pathways.

pathway, as that stage is responsible for 80–98% of life cycle emissions. For low-carbon options, the effect of manufacturing the energy converter and the storage tanks (for PEMFC) becomes relevant. Although their combined impact remains still very modest, contributing 8–20% to the overall carbon footprint.

4.3. *Step 3: detailed assessment and analysis*

The previous section highlighted the potential of low-carbon pathways based on electrolysis using renewable power sources, but there are significant differences between the underlying studies. Therefore, a more detailed assessment was conducted on crucial assumptions and parameters to explore these differences. The focus was mainly on the fuel production and delivery stage, as it had a dominant impact: what is the effect of using different renewables, varying fuel transport modes, and fuel cell efficiency? In addition, also the manufacturing of the drivetrain was assessed, as in ultra-low-carbon pathways, its impact gains in importance.

4.3.1. *Fuel production: electrolysis by different renewables*

As shown in the previous section, hydrogen's electrolysis and transport dominate the overall carbon footprint. In case renewable power is used for electrolysis, no CO_2 emissions occur during power production, but they occur upstream during material mining and the production of the energy devices. The previous section showed that the low-carbon pathways based on electrolysis by renewable power had an impact of 8 ktonnes for PEMFC to 18 ktonnes for SOFC. There is a large diversity in renewable power technologies, so the actual carbon footprint might be sensitive to which renewable energy source is applied. This diversity might explain some of the differences in outcomes found in the previous section: 3–14 ktonnes for PEMFC and 5–38 ktonnes for SOFC, of which 77–80% is the result of fuel production and distribution. Therefore, the analysis is split up into specific renewable technologies, specifically for the case of PEMFC.

Of the included studies on shipping fuels and hydrogen production, two studies discuss hydro, nuclear, and wind; four studies the PV option; and seven studies the wind option, see Fig. 5. These studies were published between 2004 and 2018 - the older studies have been included as they provided rich and detailed data. However, the development and application of renewables have gone fast. This might have resulted in economies of scale, optimization, and learning effects that might also have resulted in a decreased carbon footprint of renewables over time. Therefore two recent overview studies on the carbon footprints of renewables were added, one by NREL and one by Scarlat et al. [79,80]. By combining their data on carbon intensity with the electricity requirement as determined in this study, the carbon footprint over the ship's lifetime is calculated.

According to the shipping fuel and hydrogen production studies, hydrogen production based on solar power results in the most emissions, almost 15 ktonnes of CO_2, while wind power results in the least emissions, resulting in 4.5 ktonnes of CO_2. There are significant relative uncertainties, especially for solar PV and wind. Basic assumptions influence this. Cetinkaya, Dincer and Naterer [81], for instance, assumed a lifetime of thirty years for PV panels, whereas Dufour et al., in 2012 [82] considered a lifetime of just over ten years under a conservative technical lifetime and high solar irradiation. These differences in assumptions likely reflects that the technology at the time was not fully mature and that experience with the technology was limited, which would be reflected in more conservative estimations and more variations in assessments. More recently, Frishknecht et al. (2020) [83] provided guidelines for assessing solar panels, coming to a lifetime of 30 years for mature module technologies under normal conditions.

The added review studies on the carbon footprint of renewables confirm the right order of magnitude of total footprint scores and bring some specific nuances. Compared to the other studies, solar and nuclear score a bit lower, respectively 11 and 6 ktonnes, while biomass scores significantly higher (13–18 ktonnes). Scarlat et al. [80] add a critical warning and explanation regarding the uncertainties and variation, which likely also explains a significant part of the variation between studies included in this research. Especially the carbon footprint of biomass-to-power is very dependent on circumstances (e.g. type of biomass, biofuel, climate, practices), resulting in substantial uncertainties. Also, the carbon footprint of solar power shows high uncertainty due to differences in plant location (e.g. solar irradiance), solar cell technology, technological performance, and various modeling assumptions made in LCA. The uncertainty is much smaller for wind, especially for offshore wind. Differences depend on local wind speeds, system design, capacity factors, etc.

4.3.2. *Fuel transportation*

So far, the considered studies reported on fuel production, often without specifying whether the transport was included and what its contribution was. Especially for low-carbon pathways, fuel transport might have a significant impact if based on fossil fuels. Therefore, a more detailed analysis was conducted to study the influence of transport for the low carbon case of hydrogen production by wind electrolysis and subsequent conversion by a PEMFC – in line with the previous subsection. Several transport scenarios are considered (pipeline and truck) over different distances. As, in general, liquid fuels are more energy efficient to transport by a truck than gaseous fuels, both liquid hydrogen (under pressure) and liquid ammonia were considered. For the latter, hydrogen is converted to liquid ammonia for the sake of transport. Still, after delivery, the ammonia is cracked to hydrogen again and to be used in a PEMFC. For the analysis, the fuel cycle was split up into five phases: pre-treatment, fuel production (only in the case of hydrogen conversion to ammonia), fuel distribution (the driving of trucks or the pumping through pipelines), delivery to the ship (including bringing under pressure and in the case of ammonia the cracking and cleaning), and fuel storage (including pressurization prior to distribution).

To assess all different transport scenarios, several sources were used and assumptions were made. The fuel truck capacity is set at 733 kg for compressed hydrogen (volume limited), 2596 kg for liquid hydrogen, and 24567 kg for liquid ammonia (weight limited). The number of roundtrips is calculated based on these numbers and the required total energy. An emission factor of 1.943 kg CO_2 per tonne-km was used for trucks, assuming a mid-sized truck of 10–20 tonnes [84]. Data from Ref. [85] was used for the pipeline scenario and for distribution via long-distance shipping data by Ref. [66]. Bringing the hydrogen under pressure requires electricity. For short-distance scenarios, the emission factor of the Dutch grid in 2019 was used (390 g CO_2 eq per kWh); and for longer distances, the average emission factor for the European Union was used (253 g CO_2 eq/kWh) – both derived from the European Environment Agency [85]. Results are depicted in Fig. 6.

The previous section showed that the total carbon footprint of production and transport of hydrogen by wind-powered electrolysis and conversion by PEMFC resulted in approximately 4.5 ktonnes CO_2. The

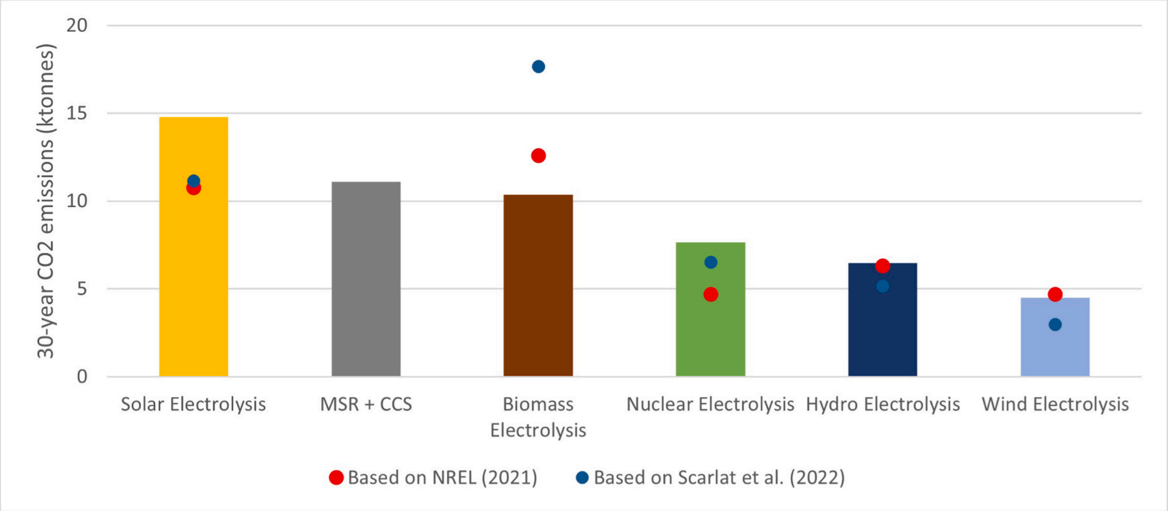

Fig. 5. The carbon footprint of electrolysis by different renewable power sources for the case of electrolysis-PEMFC. Bar charts represent the average values of the shipping fuel and hydrogen production studies. Colored dots represent data from recent carbon footprint studies on renewables applied to this case.

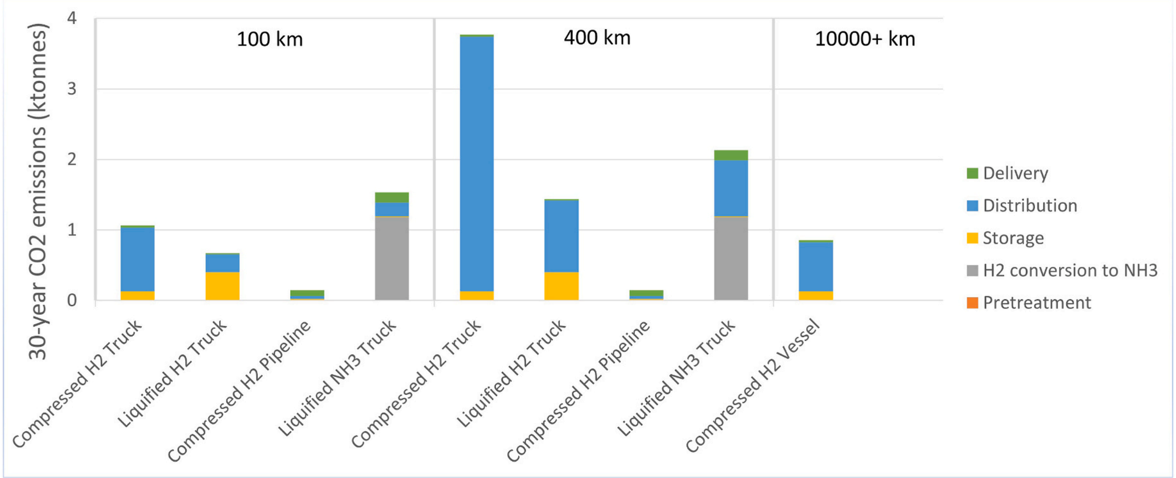

Fig. 6. The carbon footprint of fuel transport for different transportation modes and distances.

transport analysis shows that transport typically only contributes 0.2–1.6 ktonnes to this for the most realistic cases. So, the transport of hydrogen is not dominant in the overall carbon footprint of low-carbon pathways, but it is relevant and cannot be neglected.

Transportation by pipeline is highly efficient and only contributes 0.2 ktonnes of carbon - although pipelines typically only reach specific locations like major harbors or chemical industry clusters, so that additional truck transport might be required. Local truck transport and international long-distance transport by vessels add 0.7–0.9 ktonnes of carbon. So, as long as transportation is optimized, it is feasible to produce hydrogen globally in places with abundant renewables without a significant carbon penalty. Only in the case that longer distances need to be traveled by trucks or that transport by vessel or pipeline is followed by truck transport to distribute the hydrogen to different harbors, the carbon footprint is in the range of ~1–2 ktonnes and thereby making up 20–40% of the total footprint of production and distribution. Hydrogen transport (either in gaseous or liquid form) is preferred over liquified ammonia for all distances, as the latter comes with higher emissions due to the extra conversions.

However, the assumed trailer capacity is rather low compared to the state-of-the-art: 1 ton for gaseous hydrogen and 4 tons for liquid hydrogen are proven technology for specialized trucks [86,87]. As a result, the findings for the carbon footprint of hydrogen trucking might be overestimated, making the liquified ammonia option even less preferable.

Emissions from truck driving increase linearly with distribution distance, making it unsuitable for longer distances. Under the stated assumptions, the analysis shows that liquified fuels are more optimal for transport by truck. However, other studies come to much higher carbon footprints for compression, pre-cooling, and liquefaction [86,87]. As a result, only at larger distances would transporting liquid hydrogen by truck be beneficial over the trucking of gaseous hydrogen, and the contribution of transport to the total carbon footprint would increase.

And finally, the emissions of transport by pipelines are nearly independent of distribution distance and depend instead on the flow rate of the distribution grid, in line with [88]. However, Frank et al. [87] assume that the carbon footprint of transport by pipeline is a combination of a fixed footprint at the refueling station and a distance-dependent footprint for the pipeline. They come to significantly higher carbon footprints for pipeline transport but confirm it is a better option than hydrogen trucking.

4.3.3. *Fuel cell efficiency*

This study assumed a 50% conversion efficiency for both the PEMFC and the SOFC fuel cells. It is questionable how reliable this assumption is and how sensitive results are to this assumption. Surprisingly, many literature sources are not explicit regarding what efficiency they assume. The few explicit sources consider values from 40 to 60% [16] up to 50–65% [34,37]. The achieved efficiency depends on power output/partial load, aging, and operation temperature [89]. More detailed data on the net effect over a fuel cell's lifetime in ships are missing, making it impossible to develop more nuanced approaches.

The efficiency is inversely proportional to fuel use: if efficiency goes up from 50 to 60%, the fuel use will be reduced to 83%. As the total carbon footprint is strongly dominated by fuel production, a change in efficiency will strongly influence the overall carbon footprint. Changes in required fuel quantities also affect the sizing of the fuel storage tanks and the fuel converters, although not necessarily proportional due to scaling effects.

So, differences in assumptions on fuel efficiency typically strongly affect the overall carbon footprint. But current data and sources do not allow for a more accurate approach. This issue is similar to general LCA studies on diesel drivetrains. More specific models require detailed input parameters regarding technologies used and use-cases. However, such an approach will lose the more generic insight that we aim for in this study.

4.3.4. *Manufacturing of drivetrains*

The drivetrain components include hydrogen storage, fuel cell, battery, and electromotor. The impact of manufacturing these components has been accounted for in the harmonized results in section 4.2. Fig. 4 shows that manufacturing these components accounts for 20% of the total carbon footprint for PEMFC in the renewable power pathway, which is equal to 2.0 ktonne CO_2 over the ship's lifetime (e.g., by combining the findings of Figs. 3 and 4, or the related data from Tables 3 and 4 in Appendix B). The most significant impacts originate from manufacturing the type IV storage tank (57%) and the PEMFC (32%). For the SOFC with renewable power pathway, manufacturing drivetrain components contribute 13% to the total carbon footprint or 2.2 ktonne CO_2. The main contributor is the SOFC (86%).

However, in an ultra-low carbon pathway (e.g., combining wind-based electrolysis, optimized transport, and high fuel cell efficiency), the relative contribution of manufacturing the drivetrain will increase. Therefore, for drivetrains, a hotspot analysis was conducted, but only for the most impactful components, as identified above. Original literature was used in case it provided enough detail, combined with additional literature – see references below and appendix A. The carbon footprint of the manufacturing of the type IV storage tank is dominated by carbon fiber [90–92]. For the PEMFC fuel cells, especially platinum has a substantial contribution [90,93,94]. And for SOFC fuel cells, especially the significant amounts of steel and other metals are relevant [90,95,96].

In addition, the potential contribution was assessed of different strategies to reduce the carbon footprint of the manufacturing stage. For PEMFC, a type III storage tank can be applied instead of a type IV tank, similar to the one used for SOFC. It would reduce the carbon footprint by 1 ktonnes. This tank works well under stipulated conditions (300 bar) but would reduce the strategic potential to raise the pressure in the future to store more hydrogen and increase transport distance.

Another strategy is focussing on recycling, in line with current interest in the circular economy. Recycling platinum and steel can reduce CO_2 emissions in the manufacturing phase by 8–16% [93–95,97]. For Lithium-ion batteries, recycling can reduce process energy by 50% [98]. However, all these options would require improvements in end-of-life infrastructure and recycling practices, except for steel recycling which is already an established and mature practice. Also, not all materials can be recycled (e.g. carbon fiber).

Data on the impact of drivetrains show to be highly uncertain. For example, while the average impact of the PEMFC drivetrain was 2.0 ktonnes CO_2 according to our assessment, the actual values covered a range from 0.7 to 4.5 ktonnes CO_2. Limited reliable manufacturing data is available, and systems' inventories and impacts depend strongly on learning and scaling. Also, linear upscaling of material and energy requirements can result in overestimations. For example, in our analysis, the upscaled small-scale systems of the PEMFC based on Stropnik et al. (2019) [99] and Lotric et al. (2020) [94] result in a significantly higher carbon footprint compared to the largest system included in the analysis based on Miotti et al. (2017b) [90]. Especially large upscaling of casings and storage tanks is problematic, as the surface/volume ratio decreases during upscaling.

Some LCA studies or inventories exist for larger-scale fuel cell systems: e.g. Miotti, Hofer & Bauer consider an 80 kW PEMFC [90]; Mehmeti et al. (2018) [100] and Al-Khori et al. (2021) [101] consider SOFC at respectively 60 kW and 10 MW scale. But to use these data and come to a state-of-the-art, properly scaled system designed explicitly for inland shipping requires a different approach that goes beyond the scope of this paper.

5. Conclusion & discussion

The shipping sector faces increased pressure to reduce emissions by implementing other fuels and pathways. As a result, there is an increased interest in applying hydrogen-fuel cell drivetrains. LCA studies have studied their carbon footprint, but the results are hard to compare and interpret. Therefore, the research question was, 'What is the carbon footprint of hydrogen-based maritime propulsion systems, and what are the life-cycle hotspots causing these emissions?'. The focus has been on inland cargo shipping as a relevant and feasible case. To answer this question, a three-step approach was followed: a general literature review of LCA studies appropriate for this context; a harmonization of these studies by recalculating outcomes to standard conditions and configurations to make results comparable; and an in-depth assessment to understand better specific aspects that are relevant for ultra-low carbon pathways.

The literature review confirms the increased interest in hydrogen-propelled shipping and impact studies. Several factors make it hard to compare these studies, including differences in ships, use practices, geographic and time scope, system boundaries, assumptions and data sets – and disclosure of these, and the use of different functional units. Also, comparisons between studies on the same fuel-drivetrain show significant differences. The impact mainly comes from fuel production. Especially hydrogen production based on renewables seems advantageous.

The harmonized results strongly confirm these findings. They show that only fuel-drivetrains that use renewable energy-based electrolysis for hydrogen production or CCS to reduce emissions result in a substantial carbon footprint reduction, resulting in a carbon footprint of ~10–30 ktonnes CO_2 over a ship's lifetime. Hydrogen production based on electrolysis with the grid electricity mix results in a substantial increase in emission compared to the diesel case and should be avoided. 80% or more of the emissions originate from fuel production in all options. PEMFC seems to score slightly better than SOFC, requiring one process step less – although results are inconsistent. But general trends are similar for both technologies, so the choice for a specific technology might depend more on techno-economic considerations than the carbon footprint.

To further explore where the differences between studies are coming from and the consequences of different configurations on low-carbon pathways of hydrogen production using renewable power, four more in-depth analyses were conducted. First, the impact of using various renewable energy sources was assessed. Hydrogen produced by electrolysis powered by solar PV has a 2–3 higher carbon footprint compared to wind at sea. The wind-PEMFC drivetrain has the least impact, 4.5 ktonnes CO_2. Of this, between 0.2 and 2 ktonnes of CO_2 are attributed to fuel transport, depending on the specific transport mode and distance – although results are highly dependent on assumptions. The carbon footprint also relies on fuel cell efficiency, which is kept constant in this study. Different values for efficiencies are mentioned in the literature, and values strongly depend on other influencing factors like temperature, age, and current/load. For ultra-low carbon pathways, also the manufacturing of the drivetrain has a significant impact. It adds ~2ktonnes to the total life cycle emissions, mainly due to platinum use in PEMFC, carbon fiber in its storage tanks, and stainless steel for SOFC. The use of a type III storage tank for PEMFC can avoid the use of carbon fibers. Also, increased recycling of batteries and platinum might help reduce some of these impacts in the future.

By using a three-step review process, the research question was answered. This approach made different studies comparable, and crucial differences between studies could be identified and explained. However, not all differences were addressed, e.g., using specific LCA datasets, software, and modeling decisions. Here we highlight two of the issues that were not harmonized. First, the underlying studies made different assumptions regarding the grid electricity mix, which has added to the variation in outcomes for the scenarios based on grey electricity. The grid mix has not been addressed in more detail, as our main interest was in the (ultra) low-carbon options. Second, the underlying studies are not always explicit in what greenhouse gasses they consider: only carbon dioxide or all greenhouse gasses. This also added to the variation in outcomes but did not affect the overall conclusions.

Also, one of the goals of this paper was to disclose and overcome differences in assumptions in the existing literature. However, in this process, assumptions were made, and a specific approach was followed that might have resulted in a bias – a catch-22 situation. To address this, we tried to be as transparent as possible.

Finally, we draw attention to the implication of these findings for transition pathways. As shown by this research, low-carbon pathways require large-scale availability of renewable power or CCS. Currently, neither of these technologies is available for large-scale hydrogen production. Recent developments show a substantial increase in renewable electricity production, but this is only a fraction of total power production for now. Also, power demands in the future will likely show a substantial increase due to the electrification of transport, heating, and industry. Still, hydrogen is expected to play a crucial role in the energy transition [14,15,25]. It can help match supply and demand in the power sector when power production becomes increasingly variable due to wind and solar power applications. It can provide coupling between the power, industry, and transport sectors. And hydrogen or hydrogen-based fuels can be used for the international trade of renewables, coupling regions with high potential of renewables to areas of high demand.

The current status of hydrogen is one of lock-in Ref. [25]. Becoming successful requires large-scale investment and application. To do so, companies and investors are looking for large-scale availability of low-cost renewables, replacing or reusing (gas) infrastructures, and increasing hydrogen demand. While on the other hand, cost reduction and demand increases depend on learning and scaling of hydrogen production. A chicken and egg problem that can only be overcome by strong policy support, strategic investment, and starting applications in the most promising niche markets and demo projects.

Ports might offer good opportunities to initiate developments [14, 25]. Much of the chemical production and oil refining already takes place in coastal zones, including hydrogen production. These potential sources of hydrogen can fuel inland shipping. Methane Steam Reforming can be applied in the short term without a severe carbon penalty compared to current practices to kick-start hydrogen production and application. For the long term, hydrogen production should be based on renewables or MSR with carbon capture and storage to make the sector carbon neutral. Power-to-fuels are unlikely to become applied in the sector, as they come at lower overall efficiency, higher carbon footprint, and high costs. As such, they are more likely to become applied in hard-to-decarbonize sectors like aviation. For inland shipping, hydrogen-based fuel cell solutions offer better feasibility for the longer term. It also provides additional benefits, like eliminating other polluting emissions in harbors and avoiding installation costs for electrical connections in ports.

Author contributions

Vince Evers: Conceptualization; Methodology; Software; Formal analysis; Validation; Investigation; Resources; Data curation; Writing – original draft; Writing – review & editing; Visualization; Arjan Kirkels: Conceptualization; Validation; Formal analysis; Investigation; Resources and Data curation (literature study); Writing – review & editing; Visualization; Supervision; Milinko Godjevac: Conceptualization; Formal analysis; Writing – review & editing; Supervision. All authors have read and agreed to the published version of the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data come from articles, which have been fully disclosed in the article and appendix. All data from figures are disclosed in appendix B.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.113629.

References

[1] Rockström J, Steffen W, Noone K, Persson Å, Chapin FS, Lambin E, et al. Planetary boundaries: exploring the safe operating space for humanity. Ecol Soc 2009;14. https://doi.org/10.5751/ES-03180-140232.

[2] IPCC. Climate change 2022: impacts, adaptation, and vulnerability. Cambridge: Cambridge University Press; 2022.

[3] European Environment Agency. Transport: increasing oil consumption and greenhouse gas emissions hamper EU progress towards environment and climate objectives. European Environment Agency; 2019. https://doi.org/10.2800/375771.

[4] International Energy Agency. Key world energy statistics 2021. Paris: IEA; 2021.

[5] Walker TR, Adebambo O, Del Aguila Feijoo MC, Elhaimer E, Hossain T, Edwards SJ, et al. Environmental effects of marine transportation. World Seas An Environ Eval Vol III Ecol Issues Environ Impacts 2018:505–30. https://doi.org/10.1016/B978-0-12-805052-1.00030-9.

[6] Hansson J, Månsson S, Brynolf S, Grahn M. Alternative marine fuels: prospects based on multi-criteria decision analysis involving Swedish stakeholders. Biomass Bioenergy 2019;126:159–73. https://doi.org/10.1016/j.biombioe.2019.05.008.

[7] IRENA. A pathway to decarbonise the shipping sector by 2050. Abu Dhabi: International Renewable Energy Agency; 2021.

[8] International Maritime Organization. Fourth IMO greenhouse gas study 2020. London: IMO; 2021.

[9] Lindstad H, Eskeland GS. Low carbon maritime transport: how speed, size and slenderness amounts to substantial capital energy substitution. Transport Res Transport Environ 2015;41:244–56. https://doi.org/10.1016/j.trd.2015.10.006.

[10] International Maritime Organization. Third IMO greenhouse gas study 2014. London: IMO; 2015.

[11] Kuciaba E. Emission from inland waterway transport in the context of energy, climate and transport policy of the European union. Zesz Nauk Uniw Szczecińskiego Probl Transp i Logistyki 2018;43:61–71. https://doi.org/10.18276/ptl.2018.43-06.

[12] European Commission. Reducing emissions from the shipping sector n.d. https://ec.europa.eu/clima/eu-action/transport-emissions/reducing-emissions-shipping-sector_en (accessed December 23, 2021).

[13] Brynolf S, Fridell E, Andersson K. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J Clean Prod 2014;74:86–95. https://doi.org/10.1016/j.jclepro.2014.03.052.

[14] IRENA. Hydrogen from renewable power. Technology outlook for the energy transition. 2018. Abu Dhabi.

[15] International Energy Agency. Global hydrogen review 2021. Paris: IEA; 2021.

[16] van Biert L, Godjevac M, Visser K, Aravind PV. A review of fuel cell systems for maritime applications. J Power Sources 2016;327:345–64. https://doi.org/10.1016/j.jpowsour.2016.07.007.

[17] Xing H, Stuart C, Spence S, Chen H. Alternative fuel options for low carbon maritime transportation: pathways to 2050. J Clean Prod 2021;297:126651. https://doi.org/10.1016/j.jclepro.2021.126651.

[18] Al-Enazi A, Okonkwo EC, Bicer Y, Al-Ansari T. A review of cleaner alternative fuels for maritime transportation. Energy Rep 2021;7:1962–85. https://doi.org/10.1016/j.egyr.2021.03.036.

[19] Korberg AD, Brynolf S, Grahn M, Skov IR. Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Renew Sustain Energy Rev 2021;142:110861. https://doi.org/10.1016/j.rser.2021.110861.

[20] Bilgili L. Comparative assessment of alternative marine fuels in life cycle perspective. Renew Sustain Energy Rev 2021;144:110985. https://doi.org/10.1016/J.RSER.2021.110985.

[21] Tan ECD, Hawkins TR, Lee U, Tao L, Meyer PA, Wang M, et al. Biofuel options for marine applications: technoeconomic and life-cycle analyses. Environ Sci Technol 2021;55:7561–70. https://doi.org/10.1021/acs.est.0c06141.

[22] Fernández-Dacosta C, Shen L, Schakel W, Ramirez A, Kramer GJ. Potential and challenges of low-carbon energy options: comparative assessment of alternative fuels for the transport sector. Appl Energy 2019;236:590–606. https://doi.org/10.1016/J.APENERGY.2018.11.055.

[23] DNV GL. Comparison of Alternative Marine Fuels 2019;1–65.

[24] International Energy Agency I. Global hydrogen review 2021 n.d.

[25] IEA. The future of hydrogen. Seizing today's opportunities; 2019. https://doi.org/10.1787/1e0514c4-en.

[26] Schmidt P, Batteiger V, Roth A, Weindorf W, Raksha T. Power-to-Liquids as renewable fuel option for aviation: a review. Chem-Ing-Tech 2018;90:127–40. https://doi.org/10.1002/CITE.201700129.

[27] European Federation for Transport and Environment AISBL. Roadmap to decarbonising European cars. 2018.

[28] Fuel Cells and Hydrogen 2 Joint Undertaking (FCH). Hydrogen Roadmap Europe. A sustainable pathway for the European energy transtion. Luxembourg. 2019. https://doi.org/10.2843/249013.

[29] Hydrogen Council. Path to hydrogen competitiveness: a cost perspective. 2020.

[30] European Commission. A hydrogen strategy for a climate-neutral Europe. 2020. p. 24.

[31] Bengtson S, Andersson K, Fridell E, Bengtsson S, Andersson K, Fridell E. Life cycle assessment of marine fuels - a comparative study of four fossil fuels for marine propulsion. Gothenburg: Chalmers University of Technology; 2011.

[32] Corbett JJ, Winebrake JJ. Emissions tradeoffs among alternative marine fuels: total fuel cycle analysis of residual oil, marine gas oil, and marine diesel oil. J Air Waste Manag Assoc 2008;58:538–42. https://doi.org/10.3155/1047-3289.58.4.538.

[33] Fan A, Wang J, He Y, Perčić M, Vladimir N, Yang L. Decarbonising inland ship power system: alternative solution and assessment method. Energy 2021;226:120266. https://doi.org/10.1016/J.ENERGY.2021.120266.

[34] DNV GL. Assessment of selected alternative fuels and technologies, vol. 391; 2019.

[35] Fernández-Ríos A, Santos G, Pinedo J, Santos E, Ruiz-Salmón I, Laso J, et al. Environmental sustainability of alternative marine propulsion technologies powered by hydrogen - a life cycle assessment approach. Sci Total Environ 2022;820:153189. https://doi.org/10.1016/j.scitotenv.2022.153189.

[36] Gilbert P, Walsh C, Traut M, Kesieme U, Pazouki K, Murphy A. Assessment of full life-cycle air emissions of alternative shipping fuels. J Clean Prod 2018;172:855–66. https://doi.org/10.1016/j.jclepro.2017.10.165.

[37] Perčić M, Vladimir N, Jovanović I, Koričan M. Application of fuel cells with zero-carbon fuels in short-sea shipping. Appl Energy 2022;309. https://doi.org/10.1016/j.apenergy.2021.118463.

[38] Post C, Sarala R, Gatrell C, Prescott JE. Advancing theory with review articles. J Manag Stud 2020;57:351–76. https://doi.org/10.1111/joms.12549.

[39] Cherubini E, Franco D, Zanghelini GM, Soares SR. Uncertainty in LCA case study due to allocation approaches and life cycle impact assessment methods. Int J Life Cycle Assess 2018;23:2055–70. https://doi.org/10.1007/s11367-017-1432-6.

[40] Finnveden G. On the limitations of life cycle assessment and environmental systems analysis tools in general. Int J Life Cycle Assess 2000;5:229–38. https://doi.org/10.1007/BF02979365.

[41] Heijungs R, Huijbregts M a J. A review of approaches to treat uncertainty in LCA. IEMSs 2004 Int Congr 2004;8.

[42] Ross S, Evans D, Webber M. How LCA studies deal with uncertainty. Int J Life Cycle Assess 2002;7:47–52. https://doi.org/10.1007/BF02978909.

[43] van der Giesen C, Cucurachi S, Guinée J, Kramer GJ, Tukker A. A critical view on the current application of LCA for new technologies and recommendations for improved practice. J Clean Prod 2020;259:120904. https://doi.org/10.1016/j.jclepro.2020.120904.

[44] Valente A, Iribarren D, Dufour J. Life cycle assessment of hydrogen energy systems: a review of methodological choices. Int J Life Cycle Assess 2017;22:346–63. https://doi.org/10.1007/s11367-016-1156-z.

[45] Guinée JB, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, et al. Life cycle assessment: past, present, and future. Environ Sci Technol 2011;45:90–6. https://doi.org/10.1021/es101316v.

[46] Bjørn A, Owsianiak M, Molin C, Hauschild MZ. LCA history. Life Cycle Assess Theory Pract 2017;17–30. https://doi.org/10.1007/978-3-319-56475-3_3/FIGURES/3.

[47] Evangelisti S, Tagliaferri C, Brett DJL, Lettieri P. Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles. J Clean Prod 2017;142:4339–55. https://doi.org/10.1016/j.jclepro.2016.11.159.

[48] Lombardi L, Tribioli L, Cozzolino R, Bella G. Comparative environmental assessment of conventional, electric, hybrid, and fuel cell powertrains based on LCA. Int J Life Cycle Assess 2017;22:1989–2006. https://doi.org/10.1007/s11367-017-1294-y.

[49] Bauer C, Hofer J, Althaus HJ, Del Duce A, Simons A. The environmental performance of current and future passenger vehicles: life Cycle Assessment based on a novel scenario analysis framework. Appl Energy 2015;157:871–83. https://doi.org/10.1016/j.apenergy.2015.01.019.

[50] Hetherington AC, Borrion AL, Griffiths OG, McManus MC. Use of LCA as a development tool within early research: challenges and issues across different sectors. Int J Life Cycle Assess 2014;19:130–43. https://doi.org/10.1007/s11367-013-0627-8.

[51] Guo M, Murphy RJ. LCA data quality: sensitivity and uncertainty analysis. Sci Total Environ 2012;435–436:230–43. https://doi.org/10.1016/j.scitotenv.2012.07.006.

[52] Igos E, Benetto E, Meyer R, Baustert P, Othoniel B. How to treat uncertainties in life cycle assessment studies? Int J Life Cycle Assess 2019;24:794–807. https://doi.org/10.1007/s11367-018-1477-1.

[53] Leroy Y, Froelich D. Qualitative and quantitative approaches dealing with uncertainty in life cycle assessment (LCA) of complex systems: towards a selective integration of uncertainty according to LCA objectives. Int J Des Eng 2010;3:151. https://doi.org/10.1504/ijde.2010.034862.

[54] Bałdowska-Witos P, Piotrowska K, Kruszelnicka W, Błaszczak M, Tomporowski A, Opielak M, et al. Managing the uncertainty and accuracy of life cycle assessment results for the process of beverage bottle moulding. Polymers 2020;12. https://doi.org/10.3390/polym12061320.

[55] Alyaseri I, Zhou J. Handling uncertainties inherited in life cycle inventory and life cycle impact assessment method for improved life cycle assessment of wastewater sludge treatment. Heliyon 2019;5. https://doi.org/10.1016/j.heliyon.2019.e02793.

[56] Lifset R. Toward meta-analysis in life cycle assessment. J Ind Ecol 2012;16:1–2. https://doi.org/10.1111/j.1530-9290.2012.00473.x.

[57] Zamagni A, Masoni P, Buttol P, Raggi A, Buonamici R. Finding life cycle assessment research direction with the aid of meta-analysis. J Ind Ecol 2012;16:39–52. https://doi.org/10.1111/j.1530-9290.2012.00467.x.

[58] Brandão M, Burkhardt J. What can MetaAnalyses tell us about the reliability of life cycle assessment for decision support? Related papers life cycle greenhouse gas emissions of trough and tower concent rat ing solar power elect ri…. J Ind Ecol 2012;16. https://doi.org/10.1111/j.1530-9290.2012.00477.x. S3–7.

[59] Henriksson PJG, Cucurachi S, Guinée JB, Heijungs R, Troell M, Ziegler F. A rapid review of meta-analyses and systematic reviews of environmental footprints of food commodities and diets. Global Food Secur 2021;28. https://doi.org/10.1016/j.gfs.2021.100508.

[60] Gentil EC, Damgaard A, Hauschild M, Finnveden G, Eriksson O, Thorneloe S, et al. Models for waste life cycle assessment: review of technical assumptions. Waste Manag 2010;30:2636–48. https://doi.org/10.1016/j.wasman.2010.06.004.

[61] Abd Rashid AF, Yusoff S. A review of life cycle assessment method for building industry. Renew Sustain Energy Rev 2015;45:244–8. https://doi.org/10.1016/j.rser.2015.01.043.

[62] Muteri V, Cellura M, Curto D, Franzitta V, Longo S, Mistretta M, et al. Review on life cycle assessment of solar photovoltaic panels. Energies 2020;13:252. https://doi.org/10.3390/en13010252.

[63] Corsten M, Ramírez A, Shen L, Koornneef J, Faaij A. Environmental impact assessment of CCS chains - lessons learned and limitations from LCA literature. Int J Greenh Gas Control 2013;13:59–71. https://doi.org/10.1016/j.ijggc.2012.12.003.

[64] Elgowainy A, Wang M, Joseck F, Ward J. Life-cycle analysis of fuels and vehicle technologies, vol. 1. Elsevier; 2017. https://doi.org/10.1016/B978-0-12-409548-9.10078-8.

[65] Godjevac M, Van Der Veen F. White Paper: operational Performance of MV Maas. Operational profile measurements of an inland container vessel and sizing of fuel cells and hydrogen storage. Future Proof Shipping; 2021.

[66] Register Lloyd's. Fuel production cost estimates and assumptions. 2019. p. 44.

[67] Hydrogen Council. Hydrogen decarbonization pathways. 2021.

[68] Bicer Y, Dincer I. Clean fuel options with hydrogen for sea transportation: a life cycle approach. Int J Hydrogen Energy 2018;43:1179–93. https://doi.org/10.1016/j.ijhydene.2017.10.157.

[69] Perčić M, Vladimir N, Fan A. Techno-economic assessment of alternative marine fuels for inland shipping in Croatia. Renew Sustain Energy Rev 2021;148:111363. https://doi.org/10.1016/J.RSER.2021.111363.

[70] Jeong B, Wang H, Oguz E, Zhou P. An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems. J Clean Prod 2018;187:111–30. https://doi.org/10.1016/j.jclepro.2018.03.184.

[71] Deniz C, Zincir B. Environmental and economical assessment of alternative marine fuels. J Clean Prod 2016;113:438–49. https://doi.org/10.1016/j.jclepro.2015.11.089.

[72] Register UMAS Lloyd's. Techno-economic assessment of zero-carbon fuels. Lloyds Regist 2020.

[73] Hydrogen Council. Hydrogen decarbonization pathways A life-cycle assessment. 2021.

[74] Bicer Y, Dincer I. Environmental impact categories of hydrogen and ammonia driven transoceanic maritime vehicles: a comparative evaluation. Int J Hydrogen Energy 2018;43:4583–96. https://doi.org/10.1016/j.ijhydene.2017.07.110.

[75] Winebrake JJ, Corbett JJ, Meyer PE. Energy use and emissions from marine vessels: a total fuel life cycle approach. J Air Waste Manag Assoc 2007;57:102–10. https://doi.org/10.1080/10473289.2007.10465301.

[76] Perčić M, Ančić I, Vladimir N, Fan A, He Y. Comparative life cycle assessment of battery- and diesel engine-powered river cruise ship. Dev Marit Technol Eng 2021:415–21. https://doi.org/10.1201/9781003216582-47.

[77] El-Houjeiri H, Monfort JC, Bouchard J, Przesmitzki S. Life cycle assessment of greenhouse gas emissions from marine fuels: a case study of Saudi crude oil versus natural gas in different global regions. J Ind Ecol 2019;23:374–88. https://doi.org/10.1111/jiec.12751.

[78] Trillos JCG, Wilken D, Brand U, Vogt T, G Trillos JC, Brand U, et al. Life cycle assessment of a hydrogen and fuel cell RoPax ferry prototype. In: Albrecht S, Fischer M, Leistner P, Schebek L, editors. Prog. Life cycle assess. 2019. Sustain. Prod. Life cycle eng. Manag. Cham: Springer; 2021. p. 5–23. https://doi.org/10.1007/978-3-030-50519-6_2.

[79] Nicholson S, Heath G. Life cycle emissions factors for electricity generation technologies. Natl Renew Energy Lab 2021:1–4.

[80] Scarlat N, Prussi M, Padella M. Quantification of the carbon intensity of electricity produced and used in Europe. Appl Energy 2022;305:117901. https://doi.org/10.1016/j.apenergy.2021.117901.

[81] Cetinkaya E, Dincer I, Naterer GF. Life cycle assessment of various hydrogen production methods. Int J Hydrogen Energy 2012;37:2071–80. https://doi.org/10.1016/j.ijhydene.2011.10.064.

[82] Dufour J, Serrano DP, Gálvez JL, González A, Soria E, Fierro JLG. Life cycle assessment of alternatives for hydrogen production from renewable and fossil sources. Int J Hydrogen Energy 2012;37:1173–83. https://doi.org/10.1016/j.ijhydene.2011.09.135.

[83] Frischknecht R, Heath G, Raugei M, Sinha P, de Wild-Scholten M. Methodology guidelines on life cycle assessment of photovoltaic electricity. fourth ed. 2020.

[84] Otten M, 't Hoen M, Den Boer E. STREAM Goederenvervoer - emissies van modaliteiten in het goederenvervoer - versie 2. CE Delft; 2017.

[85] European Environment Agency. Greenhouse gas emission intensity of electricity generation. 2021.

[86] Liu X, Reddi K, Elgowainy A, Lohse-Busch H, Wang M, Rustagi N. Comparison of well-to-wheels energy use and emissions of a hydrogen fuel cell electric vehicle relative to a conventional gasoline-powered internal combustion engine vehicle. Int J Hydrogen Energy 2020;45:972–83. https://doi.org/10.1016/J.IJHYDENE.2019.10.192.

[87] Frank ED, Elgowainy A, Reddi K, Bafana A. Life-cycle analysis of greenhouse gas emissions from hydrogen delivery: a cost-guided analysis. Int J Hydrogen Energy 2021;46:22670–83. https://doi.org/10.1016/J.IJHYDENE.2021.04.078.

[88] Wulf C, Reuß M, Grube T, Zapp P, Robinius M, Hake JF, et al. Life Cycle Assessment of hydrogen transport and distribution options. J Clean Prod 2018;199:431–43. https://doi.org/10.1016/j.jclepro.2018.07.180.

[89] Pell J, Schörghuber C, Pretsch S, Schreier H. Optimized operating strategies for fuel cell trucks. ATZheavy Duty Worldw 2022 151 2022;15:26–31. https://doi.org/10.1007/S41321-021-0464-9.

[90] Miotti M, Hofer J, Bauer C. Integrated environmental and economic assessment of current and future fuel cell vehicles - Supplementary. Material. Int J Life Cycle Assess 2017;22:94–110. https://doi.org/10.1007/s11367-015-0986-4.

[91] Agostini A, Belmonte N, Masala A, Hu J, Rizzi P, Fichtner M, et al. Role of hydrogen tanks in the life cycle assessment of fuel cell-based auxiliary power units. Appl Energy 2018;215:1–12. https://doi.org/10.1016/j.apenergy.2018.01.095.

[92] Benitez A, Wulf C, de Palmenaer A, Lengersdorf M, Röding T, Grube T, et al. Ecological assessment of fuel cell electric vehicles with special focus on type IV

carbon fiber hydrogen tank. J Clean Prod 2021;278. https://doi.org/10.1016/j.jclepro.2020.123277.

[93] Stropnik R, Lotrič A, Bernad Montenegro A, Sekavčnik M, Mori M. Critical materials in PEMFC systems and a LCA analysis for the potential reduction of environmental impacts with EoL strategies. Energy Sci Eng 2019;7:2519–39. https://doi.org/10.1002/ese3.441.

[94] Lotrič A, Sekavčnik M, Kuštrin I, Mori M. Life-cycle assessment of hydrogen technologies with the focus on EU critical raw materials and end-of-life strategies. Int J Hydrogen Energy 2020. https://doi.org/10.1016/j.ijhydene.2020.06.190.

[95] Staffell I, Ingram A, Kendall K. Energy and carbon payback times for solid oxide fuel cell based domestic CHP. Int J Hydrogen Energy 2012;37:2509–23. https://doi.org/10.1016/j.ijhydene.2011.10.060.

[96] Bicer Y, Khalid F. Life cycle environmental impact comparison of solid oxide fuel cells fueled by natural gas, hydrogen, ammonia and methanol for combined heat and power generation. Int J Hydrogen Energy 2020;45:3670–85. https://doi.org/10.1016/j.ijhydene.2018.11.122.

[97] Stropnik R, Sekavčnik M, Ferriz AM, Mori M. Reducing environmental impacts of the ups system based on PEM fuel cell with circular economy. Energy 2018;165:824–35. https://doi.org/10.1016/j.energy.2018.09.201.

[98] Gaines L, Sullivan J, Burnham A, Bel. Life-cycle analysis for lithium-ion battery production and recycling. Washington, D.C.: Transp. Res. Board 90th Annu. Meet.; 2011. p. 23–7.

[99] Stropnik R, Sekavcnik M, Lorric A, Mori M. Life Cycle Assessment of 1kW PEMFC system with the focus on critical materials. In: 7th int youth conf energy, IYCE; 2019. https://doi.org/10.1109/IYCE45807.2019.8991589. 2019.

[100] Mehmeti A, McPhail SJ, Ulgiati S. Life cycle inventory data and metrics for high-temperature fuel cells: a streamlined decision-support tool and case study application. Energy 2018;159:1195–205. https://doi.org/10.1016/j.energy.2018.06.139.

[101] Al-Khori K, Al-Ghamdi SG, Boulfrad S, Koç M. Life cycle assessment for integration of solid oxide fuel cells into gas processing operations. Energies 2021;14. https://doi.org/10.3390/en14154668.