Future environmental impacts of hydrogen production and its use in container shipping

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1 General introduction

1.1 Background

Since the Industrial Revolution, greenhouse gas (GHG) emissions from human activities have steadily increased, driving climate change. The resulting rise in global temperatures is leading to severe adverse impacts on both the natural environment and human health and wellbeing, including sea-level rise, extreme weather events, and increased mortality and morbidity.[1] To mitigate these effects, it is crucial to limit global temperature rise to 1.5 degrees Celsius (°C) above pre-industrial levels by the end of this century and to achieve carbon neutrality by 2050 or earlier.[2] This requires the widespread decarbonization of all economic sectors.

The growing emphasis on reducing GHG emissions to near zero by mid-century has highlighted the challenge of addressing hard-to-abate emission sources.[3] These emissions arise from sectors where electricity is not currently used as the primary energy carrier, and where direct electrification is either technically challenging or economically unviable.[4] As one of the hard-to-abate sectors, maritime shipping facilitates more than 80% of global merchandise trade by volume and accounted for 2% of annual global greenhouse gas (GHG) emissions in 2022, amounting to 1.01 Gt of carbon dioxide equivalent (CO_2-eq), primarily due to its reliance on fossil fuels such as heavy fuel oil (HFO) and marine gas oil (MGO).[5, 6] If left unregulated, these emissions could rise to as much as 1.5 Gt CO_2-eq by 2050.[7] The maritime shipping sector faces an urgent need for decarbonization, but the transition pathway remains highly uncertain.[8, 9]

Among the wide range of technologies and fuel options under consideration, low-carbon H_2-based fuels such as H_2, ammonia (NH_3), and methanol (MeOH) show strong potential to reduce greenhouse gas (GHG) emissions from ships, due to their relatively high technology readiness levels and the availability of feedstocks.[10-13] According to the International Energy Agency's (IEA) Net Zero Emissions (NZE) scenario for 2050, 57 million tonnes (Mt) of H_2 are projected to be used in the shipping sector in the form of H_2-based fuels by that year.[13] The uptake of these alternative fuels is further promoted by regional policies, including the Fuel EU Maritime Regulation under the European Union's Fit for 55 package.[14]

1.2 Challenges and opportunities related to the H_2 production and H_2-based use in container shipping

Low-carbon H_2-based fuels are expected to play a key role in decarbonizing the maritime shipping sector.[13] Alongside the supply of these fuels and their use in ships, the long-term environmental impacts of these emerging technologies need to be clarified. This will enable the development of an effective roadmap to minimize environmental impacts while decarbonizing maritime shipping with H_2-based fuels. Two main aspects should be the focus:

H_2 production: As the fundamental feedstock for H_2-based fuels, the production of H_2 is not by definition GHG-free and can be produced through various pathways.[15] Given H_2's critical role in the energy transition beyond just the shipping sector, its global production volume is projected to increase six-fold by 2050 compared to 2020.[13] Production pathways will expand from conventional methods like coal gasification and natural gas steam reforming to include carbon capture and storage (CCS), biomass gasification, and water electrolysis.[13] Emerging technologies such as fossil-based production with CCS, biomass gasification, and electrolysis can significantly reduce GHG emissions compared to traditional production methods. However, they are not free from environmental burdens.[16-19] Moreover, the environmental impacts of each production pathway vary across regions and evolve over time due to technological advancements.[20-23] This can result in different GHG reduction potentials for emerging H_2-production technologies depending on the region and time frame. Understanding these differences can offer valuable insights for selecting technologies that minimize environmental impacts in the long term, tailored to regional contexts.

H_2-based fuels use in maritime shipping: Low-carbon H_2-based fuels are expected to replace fossil fuels such as heavy fuel oil and marine gas oil to reduce GHG emissions in the maritime sector. According to the IEA's Net NZE scenario, 63% of transport demand in shipping could be powered by H_2-based fuels by 2050.[13] Switching from fossil fuels to low-carbon H_2-based alternatives can significantly reduce GHG emissions, but also introduces environmental trade-offs.[24, 25] The adoption of hydrogen-based fuels requires either retrofitting existing propulsion systems or deploying new ones. Dual-fuel ICEs, which use fuel oil as a pilot fuel alongside H_2-based fuels, are relatively low-cost and scalable but operate at lower efficiency.[26] In contrast, fuel cells offer higher efficiency but come with higher costs.[26] The substitution of propulsion systems affects both cargo capacity and energy consumption. More importantly, the low energy density of H_2-based fuels poses technical and economic challenges, as ships may need to sacrifice cargo space or payload capacity to carry enough fuel for a given voyage compared to conventional fuel oil.[10] This, in turn, affects energy consumption per unit of transport work and leads to changes in the associated environmental impacts. Establishing a comprehensive assessment framework that considers these factors is essential for informing policymakers in the development of effective roadmaps to decarbonize the maritime sector using H_2-based fuels.

1.3 Analytical methods to address challenges and opportunities

To quantify the environmental impacts, life cycle assessment (LCA) offers a scientific approach. By modeling the unit processes of the target technologies and the background processes in their supply chains, their direct and indirect emissions can be evaluated across various environmental impact categories.[27-29]

Prospective life cycle assessment: A life cycle perspective is essential to fully understand the environmental impacts of emerging technologies. LCA is a suitable method for evaluating the environmental performance of products and services throughout their entire life cycle at a current stage. To assess the environmental impacts of emerging technologies at an early stage of development—particularly those that may be widely deployed in the future—prospective LCA has been proposed and applied.[29, 30] A key aspect of prospective LCA is modeling both the foreground and background systems for emerging technologies at a future time.[29] The performance of technologies in the foreground system may change due to scaling effects and technological improvements, while the background system evolves in response to broader socio-economic developments.[31, 32] A common approach to implementing prospective LCA is to combine dynamic foreground technology scenarios (e.g., changes in energy and material inputs and associated emissions) with broader background energy scenarios (e.g., future electricity mixes derived from integrated assessment models), in order to avoid temporal mismatches between the two systems.[29] The results can provide long-term guidance for minimizing the environmental impacts of emerging technologies. In conducting prospective LCA for H_2 production technologies, energy efficiency improvements in biomass gasification and water electrolysis, as well as extended lifespan and enhanced material efficiency of electrolyzer stacks, are anticipated in the future and should be fully considered in the foreground system modeling alongside the background scnearios.

H_2 production technology modelling: Different H_2 production technologies vary in terms of feedstocks, processing methods, energy efficiency, and emissions. Technologies such as coal gasification, natural gas steam reforming, and biomass gasification primarily react feedstocks with steam at high temperatures and pressures to produce syngas rich in H_2, followed by separation processes to obtain high-purity gaseous H_2.[33-35] These thermochemical pathways can be coupled with CCS technologies, which capture CO_2 from flue gas and store it underground for long-term mitigation of climate change.[36] However, the suitability and energy demand of capture technologies differ across H_2 production routes.[37-39] Water electrolysis, in contrast, splits water into H_2 and oxygen using electricity. Three leading electrolyzer technologies—alkaline electrolyzers (AE), proton exchange membrane electrolyzers (PEM), and solid oxide electrolysis cells (SOEC)—exhibit varying energy efficiencies and require different manufacturing materials and operating conditions.[40] Electrolyzers consist of two main components: the stack and the balance of plant. In stack manufacturing, while steel is used in all types, PEM systems also require rare earth metals such as iridium and platinum.[40, 41] SOECs offer the highest energy efficiency but operate at high temperatures and thus require external heat sources.[40]

Ship alternative-fuel powered transportation modelling: To quantify the cradle-to-gate environmental impacts of ship transportation, multiple processes must be considered, including fuel supply, ship construction, propulsion system installation, on-board fuel storage, and ship operation. H_2-based fuels are primarily utilized in the forms of H_2, NH_3, and MeOH, where NH_3 and MeOH are synthesized via the Haber-Bosch and MeOH synthesis processes using gaseous H_2 as a feedstock.[13] The use of H_2-based fuels requires alternative propulsion systems, such as dual-fuel ICEs and fuel cells, which differ in component configurations and sizes to achieve the same output power.[42] Due to differences in energy efficiency, the energy demand of each propulsion system for completing an identical voyage also varies. Moreover, operational factors such as sailing speed (average or reduced) and route design (e.g., with or without interim port calls) significantly affect total energy consumption.[43, 44] To store H_2 and NH_3 on board, cryogenic tanks are typically needed to maintain these fuels in liquid form, thereby reducing storage volume.[45] The tanks for H_2-based fuels also require different materials, depending on the type of fuel and storage conditions.[46] However, additional energy is required to manage boil-off gases.[47] The lower volumetric and gravimetric energy densities of H_2-based fuels, coupled with the substitution of conventional propulsion systems, can negatively impact cargo capacity.[10] As a result, the energy consumption per unit of transport work differs between propulsion systems. Finally, emissions also vary across different systems, influenced by fuel type, combustion mode, and the presence of exhaust gas treatment technologies.[26]

1.4 Research gaps

Given the uncertainty surrounding the development of the H_2 economy and the potential role of H_2-based fuels in decarbonizing maritime shipping, several research gaps still exist. These concern the future environmental impacts of global H_2 production and the future impacts of H_2 derived fuels in shipping. To keep this PhD thesis manageable, not all types of shipping could be covered. Currently, container shipping accounts for the largest share of energy consumption and CO_2 emissions among all ship types in international shipping, at approximately 27%.[11, 48] Therefore, we decided to focus the analysis of impacts of use of H_2 derived fuels in shipping to container ships. We elaborate the gaps in more detail below.

Future environmental impacts of global H_2 production: Emerging H_2 technologies currently occupy only a small share of the market and may involve environmental trade-offs that are not yet well understood. Several LCA studies have demonstrated that H_2 produced via water electrolysis powered by renewable electricity, as well as from biomass and fossil fuels coupled with CCS, can substantially reduce GHG emissions.[16-19] Taking into account improvements in process efficiency, changes in electrolyzer characteristics (e.g., lifespan and material requirements), and the potential decarbonization of the electricity mix, prospective LCA has been applied to evaluate the environmental impacts of these emerging technologies in specific countries or regions—such as Spain, the Netherlands, and the USA—at different future time points.[20-22] However, existing studies often focus on a limited set of H_2 production pathways in isolated regional contexts, which restricts our understanding of how environmental impacts may vary across different technologies, regions, and time horizons. In particular, it remains unclear when and where advances in H_2 technologies and electricity decarbonization will most significantly affect environmental outcomes. A more comprehensive assessment covering key H_2 production pathways across multiple global regions is therefore essential.

Future environmental impacts of H_2-based fuels use in internal combustion engines of container ships per tonne-nautical mile (t-nm): At present, the shipping sector has limited practical experience with H_2-based fuels, and the associated environmental trade-offs remain insufficiently analyzed. While several LCA studies have evaluated the environmental impacts of using H_2-based fuels in international shipping, the comparison with HFO are based on equivalent energy use per transport work (e.g., ton-kilometers),[24] without taking into account the impact of fuel and propulsion system changes on cargo capacity. Although a recent study has quantified the changes in volume and mass of H_2-based propulsion systems relative to conventional ones through technical feasibility analysis,[26] the environmental implications of associated cargo capacity changes have yet to be comprehensively assessed. Furthermore, existing research frequently assumes that H_2-based fuels are derived from renewable or low-carbon electricity sources, often overlooking the constraints of the global H_2 market. Such assumptions risk overestimating the decarbonization potential of H_2 in shipping. A more holistic assessment that incorporates cargo capacity impacts and broader energy supply scenarios is therefore needed.

Future environmental impacts of fuel cells use in container shipping per t-nm: H_2 and NH_3 used with fuel cells offer promising pathways to reduce hard-to-abate emissions from the maritime shipping sector.[4, 49] However, their environmental performance should be assessed from a life cycle perspective. Several life cycle assessment studies have investigated the application of fuel cell technologies in ships. Examples include proton exchange membrane fuel cells (PEMFC) using compressed hydrogen on nearshore ferries,[50] PEMFC systems using liquid H_2 on coastal ferries,[51] and passenger ships powered by combinations of PEMFC and solid oxide fuel cells (SOFC) fueled by liquid H_2 and NH_3.[52] Other research has explored the deployment of liquid H_2–PEMFC and liquid NH_3–SOFC systems on RoPax ferries, tankers, and service vessels projected for 2030.[25, 26] However, these studies largely focus on short-sea shipping, leaving significant gaps in understanding the environmental implications for deep-sea shipping, where direct electrification is less feasible. In addition, the impacts of cargo capacity changes and altered energy consumption due to different propulsion systems remain underexplored. Other important aspects—such as technology efficiency gains, regional variability, and the evolving dynamics of H_2 production—are often overlooked. Broader socio-economic factors also play a role in shaping the life cycle impacts of emerging marine fuel technologies.

Decarbonization potential of the global container shipping fleet with H_2-based fuels: Low-carbon H_2-based fuels (e.g., H_2, NH_3, MeOH) have the potential to reduce GHG emissions from ships, supported by their relatively high technology readiness and feedstock availability.[10-13] However, due to the complexity of fuel supply chains, propulsion technologies, and fleet structures, their full life-cycle decarbonization potential remains unclear. GHG emissions from H_2-based fuels vary by feedstock (e.g., fossil fuels, biomass, electricity) and differ regionally and over time.[15, 53-55] These fuels can be used in cost-effective ICEs or in more efficient fuel cells (e.g., PEMFC, SOFC),[25] and may also complement other low-carbon alternatives such as liquefied natural gas (LNG), biofuels, and batteries.[56] However, their lower energy density can impact cargo capacity.[10, 57] Additionally, future transport demand and fleet size composition—which affects GHG emissions through economies of scale—will further influence the decarbonization potential of H_2-based fuels.[7] While prior studies have assessed life-cycle GHG reductions at the individual ship level using LCA,[26, 42, 52, 58] most focus on single fuel types within specific countries or regions, limiting a comprehensive understanding of the global decarbonization potential of H_2-based fuels in maritime shipping.

1.5 Overall research question and sub-questions

To address the research gaps identified above, this thesis develops prospective life cycle models for global H_2 production, H_2-based fuel use in internal combustion engines and fuel cells at the individual ship level, and container shipping at the global fleet level. It aims to answer the overarching research question (RQ): **What are the future environmental impacts of H_2 production and its use in container shipping?**

This overall RQ is further addressed through four key sub-RQs:

RQ1: What are the future environmental impacts of the global H_2 production?

RQ2: What are the future environmental impacts of H_2-based fuels use in internal combustion engines of container ships per t-nm?

RQ3: What are the future environmental impacts of fuel cells use in container shipping per t-nm?

RQ4: What is the decarbonization potential of the global container shipping fleet with H_2-based fuels?

1.6 Thesis outline

This thesis consists of six chapters. Chapter 1 provides a general introduction. Chapters 2 to 5 address the sub-research questions individually. Chapter 6 presents an overall discussion of the thesis.

Chapter 2 quantifies the life cycle environmental impacts of H_2 production at both regional and global levels through 2050. The assessment considers nine leading H_2 production technologies across 15 global regions, as outlooked by the IEA. Key drivers of environmental impacts—such as electricity decarbonization, efficiency improvements, advancements in electrolyzer technologies, the application of CCS, and shifts in the H_2 production mix—are included in the analysis. Future H_2 market impacts are examined under three IEA scenarios: the Stated Policies Scenario, which reflects current policy settings; the Announced Pledges Scenario, which includes all climate commitments beyond implemented policies; and the Net Zero Emissions by 2050 Scenario, which aims to achieve carbon neutrality by mid-century. The prospective global H_2 production LCA databases developed in this chapter form the foundation for analyses in the subsequent chapters.

Chapter 3 assesses the life cycle environmental impacts of using H_2-based fuels in ICEs of container ships through 2050 per t-nm. In this chapter, a framework is established that integrates ship design for H_2-based dual-fuel ICE propulsion systems with LCA of container ship transportation. The analysis comprehensively accounts for the impacts of cargo capacity changes resulting from the replacement of propulsion systems, the evolution of H_2 production technologies and markets, and the decarbonization of electricity. It identifies the environmental trade-offs associated with the use of H_2-based fuels in ICE propulsion systems.

Chapter 4 analyzes the life cycle environmental impacts of fuel cell use in container shipping through 2050 per t-nm. In this analysis, a methodology is developed to quantify the effects of fuel cell integration on cargo capacity and energy consumption. By building on the H_2-based fuel supply models presented in Chapter 3, this chapter explores how ship operating modes and regional variations influence GHG emissions. The environmental trade-offs associated with the use of fuel cells are also examined.

Chapter 5 explores the life cycle decarbonization potential of global container shipping fleet using H_2-based fuels between 2020 and 2050. Building on the databases introduced in Chapter 1 and the assessment frameworks for alternative propulsion systems developed in Chapters 2 and 3, this chapter investigates the long-term climate change impacts of the global container shipping sector. Key drivers such as hydrogen-based fuel supply, deployment of propulsion systems, fleet composition, and future demand for containerized transport are taken into account. The opportunities and challenges of using H_2-based fuels to decarbonize container shipping are identified.

Chapter 6 answers the research questions, discusses the limitations of the thesis, offers recommendations for future research, and outlines the policy implications of this work.