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

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6 General discussion

H_2-based fuels are considered promising candidates for decarbonizing the maritime shipping sector. However, the uncertainty surrounding the development of the H_2 economy, along with the complexity of using H_2-based fuels in maritime shipping, calls for a life cycle perspective to fully understand their role in decarbonization and the potential environmental trade-offs. Accordingly, this thesis aims to address the overarching question: **What are the future environmental impacts of H_2 production and its use in container shipping?** Table 6.1 summarizes the research questions introduced in the first chapter, along with the methods applied and the corresponding answers.

Table 6.1. Summary of the research questions (RQs), applied methods, and corresponding answers.

Research questions	Methods	Results
What are the future environmental impacts of the global H_2 production?	• Prospective LCA • H_2 production technology modelling	• The global average GHG emissions per kg of H_2 can decrease over time primarily driven by water electrolysis. • H_2 production related GHG emissions need to be further minimized and avoid the carbon lock-in risk from CCS. • Environmental trade-offs of H_2 production should be further examined and minimized.
What are the future environmental impacts of H_2-based fuels use in internal combustion engines of container ships per t-nm?	• Prospective LCA • H_2 production technology modelling. • Ship alternative-fuel powered transportation modelling	• The impact of using H_2-based fuels by ICEs on ship cargo capacity varies with ship range and fuel choice. • H_2-based fuels may lower GHG emissions from container ships by 48-65% per tonne nautical mile by 2050. • H_2-based fuels come with other environmental trade-offs compared to HFO.
What are the future environmental impacts of fuel cells use in container shipping per t-nm?	• Prospective LCA • H_2 production technology modelling. • Ship alternative-fuel powered transportation modelling	• The liquid H_2-PEMFC system consistently results in less cargo weight loss than the liquid NH_3-SOFC system. • Fuel cells can reduce GHG emissions by 65-75% per tonne nautical mile compared to traditional ships by 2050. • The use of fuel cells involves environmental trade-offs.
What is the decarbonizing potential of the global container shipping fleet with H_2-based fuels?	• Prospective LCA • H_2 production technology modelling • Ship alternative-fuel powered transportation modelling	• H_2-based fuels can substantially decarbonize maritime shipping. • Replacing HFO with H_2-based fuels can reduce 3-5 Gt cumulative GHG between 2020 and 2050. • Fleet renovation, NH_3 production and electrolyzer capacity expansion, and renewable electricity supply can be major bottlenecks.

6.1 Answers to research questions

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

Results

The global average GHG emissions per kg of H_2 can decrease over time primarily driven by water electrolysis. The global average GHG emissions per kg of H_2 decrease from 14 kg CO_2-eq today to 9–14 kg CO_2-eq in 2030 and 2–12 kg CO_2-eq in 2050 under the NZE and STEPS scenarios. Even with CCS, fossil fuel-based technologies still exhibit considerably higher GHG emissions and show limited improvement over time. In contrast, water electrolysis becomes progressively less carbon-intensive with the low-carbon energy transition and can approach near carbon neutrality by 2050, despite regional variations and differences among electrolyzer types.

H_2 production related GHG emissions need to be further minimized and avoid the carbon lock-in risk from CCS. Cumulative GHG emissions from H_2 production between 2020 and 2050 could reach 39 Gt CO_2-eq under the APS scenario and 47 Gt CO_2-eq under NZE. The latter accounts for nearly 12% of the remaining carbon budget compatible with the 1.5°C target, largely due to natural gas steam reforming (NG SMR) with CCS. CCS is expected to achieve an overall capture efficiency of only 64% for NG SMR, making this pathway nearly fully responsible for 1 Gt CO_2-eq of annual emissions from H_2 production by 2050. These emissions could persist for several decades due to the long remaining lifespan of newly built infrastructure.

Environmental trade-offs of H_2 production should be further examined and minimized. As CCS and water electrolysis increasingly rely on low-carbon electricity, co-benefits are likely to arise for other environmental indicators such as particulate matter formation, ozone depletion, and fossil fuel depletion. At the same time, some indicators may worsen, including water use, land use, metals and minerals extraction, and human toxicity. However, water consumption for electrolysis remains small compared to global agricultural irrigation.

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

Results

The impact of using H_2-based fuels on ship cargo capacity depends on the ship's range and fuel choice. For voyages without interim refueling stops, the use of H_2-based fuels in container ships invariably requires a trade-off in cargo space and weight, regardless of the specific fuel type. This can lead to reductions of up to 10% in available cargo space and 12% in cargo weight for a typical one-way non-stop trip. When interim refueling is available, liquid NH_3 and MeOH-fueled ships can free up about 1-2% of their cargo space.

H_2-based fuels may lower GHG emissions from container ships by 48-65% per t-nm by 2050. As H_2 production increasingly shifts toward water electrolysis powered by low-carbon electricity in the NZE scenario, H_2-based ships can substantially reduce GHG emissions compared to HFO-powered counterparts. Among the evaluated options, liquid H_2-ICE demonstrates the highest potential, with up to a 65% reduction in GHG emissions per t-nm by 2050. Liquid NH_3-ICE and MeOH-ICE follow closely, achieving reductions of up to 64% and 57%, respectively.

H_2-based fuels come with other environmental trade-offs compared to HFO. Replacing HFO with liquid H_2 can significantly reduce environmental impacts such as photochemical ozone formation, fossil fuel depletion, acidification, ecotoxicity, and ozone depletion. In contrast, liquid NH_3 and MeOH provide fewer environmental benefits. Overall, H_2-based fuels tend to increase environmental burdens in most assessed categories, with metal and mineral resource use being particularly significant due to their dependence on renewable energy and water electrolysis technologies.

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

Results

The liquid H_2-PEMFC system consistently results in less cargo weight loss than the liquid NH_3-SOFC system. Across various operational modes, the liquid H_2-PEMFC system can either increase cargo space by up to 1% or decrease it by as much as 19%. In contrast, the liquid NH_3-SOFC system consistently reduces cargo space, with reductions ranging from 1% to 9%. When an interim port is available, the impact of the liquid H_2-PEMFC system on cargo space is less severe compared to that of the liquid NH_3-SOFC system. Regarding cargo weight, the liquid H_2-PEMFC system can increase it by up to 2% or decrease it by up to 10%, whereas the liquid NH_3-SOFC system typically leads to decreases between 4% and 22%.

Fuel cells can reduce GHG emissions by 65-75% per tonne nautical mile compared to traditional ships by 2050. Fuel cell ships currently cannot drive the decarbonization of deep-sea shipping due to the dominance of fossil fuels in the energy supply. However, under the NZE scenario—where H_2 production transitions to water electrolysis powered by low-carbon grid electricity—liquid H_2-PEMFC and liquid NH_3-SOFC ships can reduce GHG emissions by 69%–75% and 65%–71%, respectively, by 2050 compared to conventional HFO-ICE ships.

The use of fuel cells involves environmental trade-offs. Compared to conventional ships, fuel cell-powered ships can provide co-benefits by reducing impacts such as marine and terrestrial eutrophication, photochemical ozone formation, ozone depletion, acidification, freshwater ecotoxicity, and fossil fuel depletion. However, their adoption also brings new environmental burdens, including increased use of minerals and metals, water use, land use, freshwater eutrophication, human toxicity, ionizing radiation, and particulate matter formation.

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

Results

H_2-based fuels can substantially decarbonize maritime shipping. GHG emissions from container shipping, measured per t-nm, could decline from 22 g CO_2-eq in 2020 to 21 g, 9 g, and 3 g CO_2-eq by 2050 under the Less Ambitious, Ambitious, and Very Ambitious scenarios, respectively. The largest reduction is achieved when H_2-based fuels are produced entirely from renewable electricity. However, this pathway requires substantial additional renewable electricity capacity. In contrast, H_2-based fuels derived from fossil sources with CCS offer, at most, a 50% reduction in emissions compared to HFO.

Replacing HFO with H_2-based fuels does not always result in reduced GHG emissions but could reduce emissions by up to 3–5 Gt CO_2-eq. Between 2020 and 2050, cumulative emissions from global container shipping could reach 9–12 Gt, 7–10 Gt, and 4–5 Gt CO_2-eq under the Less Ambitious, Ambitious, and Very Ambitious scenarios, respectively—accounting for 1–3% of the global carbon budget aligned with the net-zero target. In the Less Ambitious scenario, the slow decarbonization of H_2 production leads to an increase of 0.4–0.6 Gt CO_2-eq in cumulative emissions. In contrast, the Ambitious and Very Ambitious scenarios see reductions of 1–2 Gt and 3–5 Gt CO_2-eq, respectively.

Fleet renovation, NH_3 production and electrolyzer capacity expansion, and renewable electricity supply can be major bottlenecks. The current fleet still mainly relies on HFO-ICE systems. Decarbonizing with H_2-based fuels will require major retrofitting or new ship builds. By 2050, container shipping's NH_3 demand could exceed half of today's global production under the Ambitious and Very Ambitious scenarios. In the Ambitious scenario, the electrolyzer capacity needed by 2030 would consume 50% of the realistically projected deployment; in the Very Ambitious scenario, nearly triple that amount. The additional renewable electricity required for H_2-based fuel production could account for around 6% of global low-emissions electricity growth between 2023 and 2050 under current policies.

6.1.5 Answer on overall RQ

Overall RQ: What are the future environmental impacts of H_2 production and its use in container shipping?

By developing comprehensive databases of long-term global H_2 production and a framework that accounts for the impacts of H_2-based fuel use on ship operations, life cycle environmental impacts from 2020 to 2050 can be quantified in a systematic and globally consistent manner. This can provide valuable guidance for policymakers from a long-term perspective.

Decarbonizing container shipping by H_2-based fuels requires a rapid transition to renewable H_2 production. The extent to which H_2 production is decarbonized is the key determinant of whether container shipping can achieve meaningful emissions reductions. Under current policy settings, large-scale use of H_2-based fuels in shipping may result in higher GHG emissions than conventional HFO. Significant GHG reductions are only possible if H_2 production shifts towards CCS and water electrolysis powered by low-carbon electricity, as modeled in the NZE scenario. However, even in the NZE scenario, residual emissions from H_2 production and container ship operations still consume part of the remaining carbon budget compatible with the 1.5 °C target—an impact that must not be overlooked.

Achieving the net-zero target for container shipping requires carbon removal technologies even if H_2-based fuels are fully renewable. If H_2-based fuels are produced entirely from renewable electricity, they can substantially reduce GHG emissions from container shipping. However, this requires a rapid expansion of additional renewable electricity capacity, which is a highly competitive resource across sectors beyond maritime shipping. Even with substantial availability of renewables electricity, container shipping would still fall short of the net-zero target. This underscores the need for bioenergy with CCS or direct air capture to offset the remaining emissions, although their potential is constrained by limited availability and scalability.

H_2-based fuels use in container shipping comes with environmental trade-offs. When H_2-based fuels are used to decarbonize container shipping by replacing HFO, co-benefits may arise from both H_2 production and its use in shipping, such as reductions in ozone depletion and ecotoxicity. At the same time, the expansion of water electrolysis powered by low-carbon electricity may exacerbate other environmental burdens, including human toxicity, ionizing radiation, minerals and metals use, and land use.

6.2 Limitations and suggestions for further research

This thesis has certain modeling and methodological limitations that could be addressed in future research, as summarized below:

Model consistency and environmental impact coverage in prospective life cycle assessment. For the future scenarios of H_2 production, the STEPS, APS, and NZE scenarios from the IEA are used due to their more timely and comprehensive modeling of H_2 production compared to the REMIND model.[53] To avoid mismatches between foreground and background data over time and to account for developments in other key sectors, we integrated the ecoinvent database with electricity mix outputs modeled by REMIND using *premise*.[65] Although the IEA and REMIND scenarios are aligned based on projected global average temperature increases by 2100, differences in electricity mix projections between the two models mean that mismatches between foreground and background data remain unresolved. Moreover, the regional classification differs in granularity between the IEA and REMIND models at the global scale. REMIND includes 12 regions,[66] whereas the IEA H_2 scenarios cover 15 regions by splitting Latin America into Brazil and the Rest of Central and South America, Other Asian countries into Southeast Asia and the Rest of Asia Pacific, and the reforming economies into Russia and the Rest of Eurasia.[103] In the future, different models should be better coordinated to ensure greater consistency between foreground and background data.

Moreover, most of the primary data collected in this thesis are focused on climate change. This may lead to an overestimation or underestimation of other environmental impacts that are not directly related to the climate change impact. Technological improvement and waste management for other environmental impacts can be considered and modelled in the future to ensure a more comprehensive and accurate assessment for the future environmental impacts for emerging technologies.

H_2 production technology modelling. For the unit process data of each H_2 production technology in different regions, background data such as energy, feedstocks, and materials that can be sourced locally are differentiated. However, values in foreground data remain the same across regions due to data limitations. Unit process data may also vary regionally based on current technology development levels and local environmental regulations regarding waste treatment and emissions. Furthermore, technological improvements for various processes assume uniform energy and material efficiency gains based on the IEA's report or existing literature. Research and development funding can be allocated differently across technologies and efficiencies according to regional conditions and development roadmaps, meaning that efficiency improvements for the same technology could differ across regions in the future. If more detailed regional data were obtained and modeled, the results would be more accurate and meaningful for regional policymaking.

Ship alternative-fuel powered transportation modelling. To assess the climate change impacts of global container shipping at the fleet level and to account for variations across ship size categories, nine representative ships are selected—based on average deadweight tonnage and installed main engine power from the IMO's Fourth Greenhouse Gas Report[7]—as prototypes for nine ship size categories ranging from 0–999 TEU to 20,000+ TEU. However, it is difficult to find actual ships that exactly match the average deadweight tonnage and engine power values for each category. In addition, the energy demand for ship operation is estimated using average ship speed and draught for typical voyages, which may introduce some deviation from real-world conditions. If detailed information on individual container ships worldwide, along with their hour-level operational conditions, were available, a ship-by-ship global analysis could be performed, allowing for a more accurate and granular assessment. This would enable quantification of GHG emission reductions for each ship using alternative fuels and provide guidance on the environmentally optimal alternative fuel choice for each vessel.

6.3 Policy implications

This thesis systematically assesses the future environmental impacts of H_2 production and its use in container shipping from the bottom up. Technological details and socio-economic developments are integrated to support effective policy decisions. The specific recommendations are outlined below:

The transition to renewables-based water electrolysis should be prioritized over fossil-based H_2 with CCS. Whether in H_2 production or its use in container shipping, electrolytic H_2 powered offers greater long-term GHG reduction potential than fossil-based H_2 with CCS. If additional renewable electricity capacity becomes available for the production of H_2-based fuels, substantial emissions reductions can be achieved immediately across both H_2 supply and its use in shipping. In contrast, if fossil-based H_2 with CCS accounts for a substantial share of future production, its relatively unchanged emission intensity over time may result in considerable residual emissions and risk long-term fossil fuel and carbon lock-in, posing a challenge to achieving net-zero targets. Moreover, without full electricity decarbonization, fossil-based H_2 with CCS fails to reduce GHG emissions from container shipping compared to HFO. Therefore, a transition toward water electrolysis and renewable energy represents a safer, more climate-friendly, and future-proof pathway.

Coordinated framework across multiple sectors is required to decarbonize maritime shipping by H_2-based fuels. Reducing GHG emissions from maritime shipping using H_2-based fuels involves multiple sectors and may encounter bottlenecks, including fleet retrofitting, ammonia and electrolyzer capacity expansion, and renewable electricity supply. In the early stages, container ships below 8,000 TEU can be prioritized for adopting H_2-based fuels, as they contribute disproportionately high GHG emissions relative to their transport work, offering greater emissions reduction potential. As H_2-based fuels are scaled up, timely development and deployment of NH_3 production and electrolyzer capacity are essential to ensure a stable fuel supply and support a smooth fleet transition. Most importantly, sufficient renewable electricity is fundamental to realizing the full decarbonization potential of H_2-based fuels in maritime shipping. A coordinated roadmap encompassing these elements is crucial to facilitate the achievement of maritime shipping's decarbonization targets.

The environmental trade-offs associated with the use of H_2-based fuels in maritime shipping should be given careful attention. Using electrolytic H_2 from low-carbon electricity to decarbonize the maritime shipping sector still involves environmental trade-offs, such as increased minerals and metals use, land use, and human toxicity. These potential environmental burdens should be further assessed and minimized. On the one hand, country- and local-level assessments of absolute impacts across society are needed prior to the deployment of low-carbon H_2-based fuels to identify environmentally optimal technologies. On the other hand, where necessary, targeted technological improvements and waste management measures should be developed to mitigate specific environmental impacts.