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

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Summary

H_2-based fuels are regarded as potential solutions for decarbonizing the maritime shipping sector. Nevertheless, the uncertain trajectory of the H_2 economy and the technical and operational challenges associated with their use in shipping highlight the need for a life cycle perspective to clarify their decarbonization potential and associated environmental trade-offs. This will support the development of an effective roadmap to reduce other environmental impacts while decarbonizing maritime shipping with H_2-based fuels. 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?

To answer this question systematically, this thesis investigates four sub-questions in Chapters 2–5, respectively:

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

Chapter 2 evaluates the life cycle environmental impacts of H_2 production at regional and global scales up to 2050, using three scenarios from the International Energy Agency (IEA): the Stated Policies Scenario (STEPS), the Announced Pledges Scenario (APS), which extends beyond existing policies to include aspirational targets, and the Net Zero Emissions by 2050 Scenario (NZE). The analysis shows that global average greenhouse gas (GHG) emissions per kilogram of H_2 decline from about 14 kg CO_2-eq at present to 9–14 kg CO_2-eq by 2030, and further to 2–12 kg CO_2-eq by 2050 under the NZE and STEPS scenarios. Without carbon capture and storage, fossil fuel-based production routes offer only limited emission reductions, whereas H_2 produced via water electrolysis becomes progressively less carbon intensive as electricity decarbonizes and may approach near zero emissions by mid-century. Although global H_2 production volumes are expected to grow four to eight times by 2050, GHG emissions could already peak between 2025 and 2035. Cumulative GHG emissions from H_2 production over the period 2020–2050 are estimated at 39 Gt CO_2-eq in APS and up to 47 Gt CO_2-eq in NZE, with the latter accounting for nearly 12% of the remaining carbon budget consistent with the 1.5 °C target. These results highlight the need for more rapid and deeper decarbonization of H_2 supply, which would require accelerated deployment of electrolytic H_2 together with substantial expansion of renewable electricity. In contrast, the IEA projected investments in natural gas steam methane reforming with carbon capture and storage pose considerable risks, as they may become a major future source of emissions unless very high capture rates are achieved, while also reinforcing fossil fuel and carbon lock in. Overall, limiting climate and broader environmental impacts from H_2 production calls for a swift transition away from fossil fuels toward electrolysis and renewable energy, supported by continued technological and material innovation.

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

Chapter 3 examines the life cycle environmental impacts of liquid H_2, liquid ammonia (NH_3), and methanol used in internal combustion engines (ICEs) on a Post Panamax container ship over the period 2020 to 2050. The chapter develops an integrated framework that combines ship design for H_2-based dual fuel ICE propulsion systems with life cycle assessment of container ship transport. The framework accounts for changes in cargo capacity, electricity system decarbonization, and transitions in H_2 production under two IEA scenarios, namely STEPS and NZE. The results indicate that, relative to a conventional heavy fuel oil (HFO) powered ship, H_2-based propulsion systems can reduce cargo weight capacity by approximately 0.3% to 25%. Under the NZE scenario, H_2-based fuels achieve reductions of 48% to 65% in GHG emissions per t-nm by 2050 compared with HFO. However, even when H_2-based fuels are fully renewable, 18% to 31% of GHG emissions persist. There is also a need for careful implementation of H_2-based fuels in ICE applications to avoid unintended environmental trade-offs.

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

Chapter 4 evaluates the life cycle environmental impacts over the period 2020 to 2050 of two prominent fuel cell systems applied to a Post Panamax container ship: liquid H_2 with proton exchange membrane fuel cells (liquid-H_2 PEMFC) and liquid NH_3 with solid oxide fuel cells (liquid-NH_3 SOFC). The chapter develops a methodology to quantify how fuel cell integration affects cargo capacity and onboard energy demand. Building on the H_2-based fuel supply modeling introduced in Chapter 3, it further investigates the influence of ship operating conditions and regional differences on GHG emissions, while also assessing the environmental trade-offs associated with fuel cell deployment. The results show that, depending on sailing range and speed, liquid-H_2 PEMFC systems lead to cargo weight changes ranging from a 2% increase to a 10% decrease, whereas liquid-NH_3 SOFC systems result in reductions of approximately 4% to 23%. Under the NZE scenario in 2050, liquid-H_2 PEMFC and liquid-NH_3 SOFC reduce GHG emissions per t-nm by about 69% to 75% and 65% to 71%, respectively, relative to conventional ships. At the same time, the adoption of fuel cells can introduce additional environmental trade-offs.

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

Building on the global H_2 production life cycle inventory database presented in Chapter 2 and the life cycle assessment frameworks for alternative propulsion systems developed in Chapters 3 and 4, Chapter 5 investigates the life cycle decarbonization potential of the global container shipping fleet through the adoption of H_2-based fuels over the period 2020 to 2050. The analysis considers three scenarios reflecting different levels of ambition in H_2 production pathways, deployment of H_2-based fuels, and associated transport demand. The results suggest that GHG emissions from container shipping 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. Over the 2020–2050 timeframe, cumulative emissions from global container shipping are estimated at 9–12 Gt, 7–10 Gt, and 4–5 Gt CO_2-eq across the three scenarios, corresponding to approximately 1–3% of the global carbon budget consistent with achieving net zero emissions. Importantly, replacing HFO with H_2-based fuels does not necessarily guarantee emission reductions. In the Less Ambitious scenario, cumulative emissions increase by about 0.4–0.6 Gt CO_2-eq due to the slow decarbonization of H_2 production. In contrast, cumulative emissions decline by roughly 1–2 Gt and 3–5 Gt CO_2-eq in the Ambitious and Very Ambitious scenarios, respectively. Achieving deep decarbonization in maritime shipping depends on addressing critical constraints related to fleet renewal, expansion of ammonia production and electrolyzer capacity, and the availability of low carbon electricity.

Several overcharging observations emerge from this thesis. Decarbonizing container shipping with 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. 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. If H_2-based fuels are produced entirely from renewable electricity, they can substantially reduce GHG emissions from container shipping. Even with substantial availability of renewable electricity, container shipping would still fall short of the net-zero target. Negative emissions technologies like bioenergy with CCS or direct air capture could be used to offset the remaining emissions. Decarbonizing container shipping comes with environmental trade-offs. It can deliver co-benefits such as reduced ozone depletion and ecotoxicity, but may also exacerbate other environmental burdens, including human toxicity, ionizing radiation, mineral and metal use, and land use, driven by the expansion of water electrolysis powered by low-carbon electricity.

To effectively decarbonize container shipping via H_2-based fuels while minimizing other environmental impacts, this thesis provides several policy recommendations: The transition to renewables-based water electrolysis should be prioritized over fossil-based H_2 with CCS, as water electrolysis is a safer, more climate-friendly, and future-proof pathway and can avoid the risk of carbon lock-in. Coherent policies to foster multi-sectoral coordination among maritime shipping, H_2-based fuel production, and power generation are necessary to maximize the decarbonization potential of container shipping with H_2-based fuels. The environmental trade-offs associated with the use of H_2-based fuels in maritime shipping should be given careful attention; country- and local-level assessments of absolute impacts across society should be further conducted, and targeted technological improvements and waste management measures should be developed to mitigate specific environmental impacts.