Evaluating overall performance of hydrogen fuel for marine transportation

Abstract

Hydrogen fuel cell-based ship propulsion is one of the approaches to reduce greenhouse gases emissions from maritime transportation. For such propulsion to be feasible, production and transportation modes of hydrogen need to be sustainable in addition to efficient operation of fuel cells. Although life cycle assessments and well-to-wake approaches have been used to evaluate the performance of hydrogen fuel cells, there is a need for holistic performance framework that also incorporates safety in addition to technical, economic and environmental considerations. In order to address this, a framework to holistically assess the overall performance of hydrogen fuel cell-based ship propulsion is proposed here. The approach proposed in this paper can aid in evaluating the performance of hydrogen based marine transportation in addition to identifying optimal implementation options.

Keywords: Marine transportation; Hydrogen fuel cell; Composite performance index

1. Introduction

The International Maritime Organisation (IMO) has a target of reducing maritime related greenhouse gases (GHG) emissions by 50% of the 2008 level by 2050 (MEPC, 2018). Hydrogen fuel cell-based ship propulsion is one option to achieve the IMO reduction target since this type of propulsion reduces GHG emissions as well as local air pollutions like SOx and NOx emissions. Furthermore, fuel cell systems have the potential to produce electricity more efficiently for propulsion and a significant cost reduction may be possible even with current technology (Biert et al., 2016). Sustainability of hydrogen based marine transportation is affected by various factors such as availability of clean hydrogen, modes of hydrogen transportation and storage, and efficiency of hydrogen fuel cells for ship propulsion.

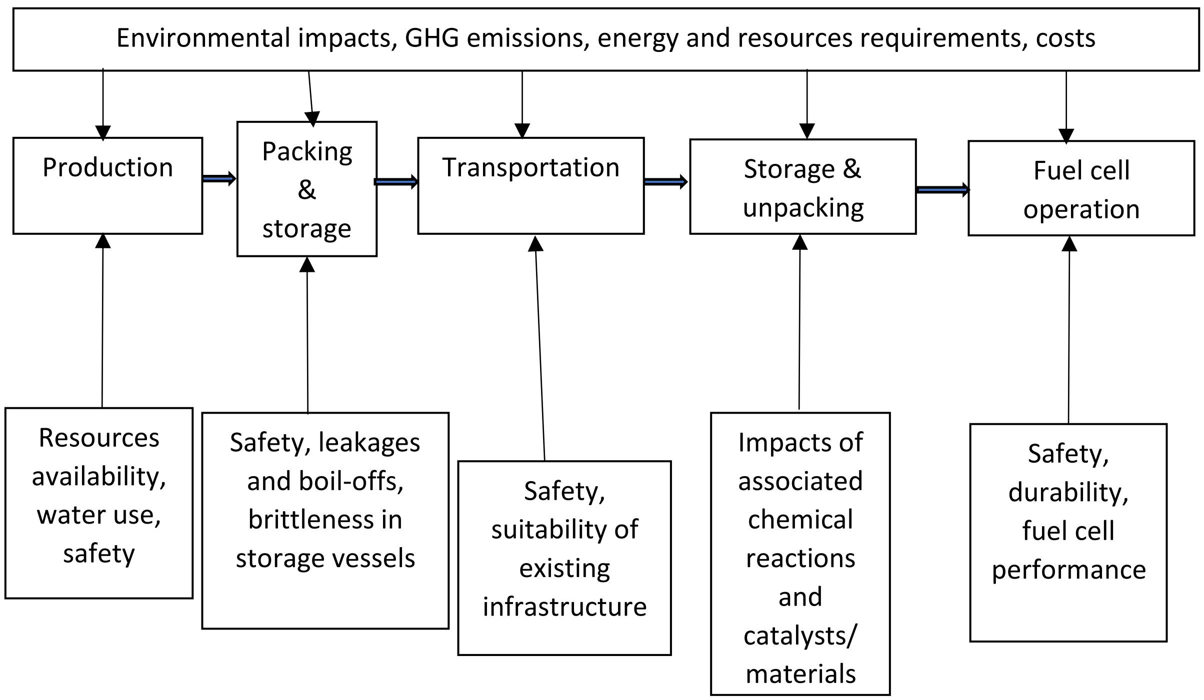
Although several studies (Atilhan et al., 2021; Wulf et al., 2018; Inal et al., 2022; Xing et al., 2021) have evaluated alternative fuels including hydrogen for maritime transportation, a holistic approach that takes safety, costs, environment and technical considerations into account is needed. Atilhan et al. (2021) have carried out a thorough study on the prospect of hydrogen for ship propulsion by considering both environmental and economic aspects, but they have not included the factors such as fuel cell efficiency and impacts of carrier chemicals like methanol that could be used as a medium to transport hydrogen long distances.

This short paper proposes a framework to evaluate the performance and thereby sustainability of hydrogen fuel cell-based ship propulsion. The framework proposed here can enable a holistic evaluation that takes into account the processes from hydrogen production to fuel cell operation by considering safety, technical, economic and environmental factors.

2. Evaluation framework

The proposed evaluation framework takes into account environmental, economic, safety and technical considerations of five processes comprising hydrogen production, packing and storage, transportation, storage and unpacking, and fuel cell operation. The term ‘packing’ here is adopted from JRC (2021) and refers to the process of storing hydrogen in a chemical medium or a carrier. For instance, instead of storing and transporting in its pure form, it may be more feasible to store and transport hydrogen as methanol (Schorn et al., 2021) or Liquid Organic Hydrogen Carriers (LOHC) (Lahnaoui et al., 2021) in some cases. Likewise, the term ‘unpacking’ here refers to the process of extracting hydrogen (dehydrogenation) from its chemical carrier. The figure below is the graphical representation of the proposed framework.

Figure 1 Evaluation framework for hydrogen fuel cell-based ship propulsion



As shown in the figure, environmental impacts, GHG emissions, energy and resources requirements, and costs are common elements considered for the evaluation of all the five processes characterizing hydrogen fuel cell-based ship propulsion, i.e., production, packing and storage, transportation, storage and unpacking, and fuel cell operation. Environmental impacts here refer to local level pollutions excluding GHG emissions. Evaluation approach for different processes is described below.

2.1 Production

The boundary of performance evaluation begins with hydrogen production process (Figure 1). Presently, sustainability of hydrogen production process is typically evaluated in terms of its GHG emissions by classifying hydrogen as green, blue, brown and grey (Howarth & Jacobson, 2021). However, other factors such as local pollutions, safety issues during mining and resources availability should also be taken into account. Majority of hydrogen is currently produced from fossil fuels and labelled as blue, brown or grey hydrogen. Therefore, availability of fossil fuels such as natural gas required to produce hydrogen has to be taken into account. This availability may be quantified in terms of reserve-to-production ratios for quantitative analyses. Green hydrogen produced from electrolysers powered by renewable energy also have environmental implications such as huge demand for highly pure freshwater (EPRI, 2020) and needs to be considered in the evaluation. It is also noteworthy that green hydrogen generally costs more than blue, brown or grey hydrogen (Howarth & Jacobson, 2021).

2.2 Packing and storage

Hydrogen could be packed and stored in order to transport it to refuelling stations in seaports. If hydrogen is stored in its pure form, there are no impacts associated with packing since these exist only if hydrogen is embedded (hydrogenated) in a carrier fuel like methanol or LOHC. In such case, comparison should be made between storing hydrogen in liquid form versus storing it in compressed gas form. The comparison could be in terms of material footprint, durability, energy and resources requirements, and costs. Other important evaluation parameters are the potential of hydrogen to cause brittleness in the storage vessel (Elberry et al., 2021), leakages, and boil-off associated with hydrogen storage.

On the other hand, if hydrogen is packed and stored in a chemical medium such as methane and LOHC, relevant environmental impacts should be considered in addition to evaluation parameters such as GHG emissions, energy and resources requirements, and costs. For instance, LOHC can be toxic and have low biodegradability (Rao & Yoon, 2020). Likewise, hydrogenation of CO_2 to store hydrogen as methanol may require precious metal-based catalysts such as Platinum and Palladium (Jiang et al., 2020), raising concerns of resources availability which has to be considered in the evaluation.

2.3 Transportation

Hydrogen may be transported to the refuelling stations in seaports in its pure form or in a chemical media such as methanol or LOHC. Due to the differences in gravimetric and volumetric densities of different forms, the form in which hydrogen is transported can impact evaluation parameters such as local pollutions, GHG emissions, energy and resources requirements, and costs.

The use of existing piping infrastructure can improve the feasibility of hydrogen fuel transportation and should be considered. For instance, the use of existing natural gas pipelines to transport hydrogen can decrease costs (Yoon et al., 2022) as well as environmental impacts. However, safety issues associated with using existing transportation infrastructure need to be properly investigated. Evaluation of trade-offs of different transportation modes, e.g., development of new piping infrastructure versus using trucks or other transportation modes, should also be carried out.

2.4 Storage and unpacking

Hydrogen may have to be stored and unpacked (if embedded in carrier chemicals) once it is transported to refuelling stations. The evaluation approach for storage has already been discussed above and the approach for unpacking is similar to that of packing (Section 2.2). It may be noted here that unpacking of hydrogen is typically done through catalytic dehydrogenation which is an endothermic reaction (Rao & Yoon, 2020). Consequently, energy requirement of unpacking can be relatively high.

2.5 Fuel cell operation

The boundary of sustainability evaluation ends with the operation of hydrogen fuel cells to propel ships. Evaluation should consider power capacity, reliability, safety, durability, operability (Xing et al., 2021) and fuel economy in addition to environmental impacts, resources requirements, and costs. Potential of capturing and utilizing waste heat from fuel cells may also be considered for evaluation where applicable.

2.6 Quantitative approach

Quantitative evaluation is preferred to reduce subjectivity and improve precision as far as practicable and when data are available. The composite performance index for hydrogen fuel cell-based ship propulsion may be expressed as a weighted sum of indices for all the considered processes as:

$$I = w_p I_p + w_s I_s + w_t I_t + w_u I_u + w_f I_f \quad (1),$$

where I_p, I_s, I_t, I_u, and I_f are process indices for production, packing & storage, transportation, storage & unpacking, and fuel cell operation respectively, and w_p, w_s, w_t, w_u, and w_f are the corresponding weighing factors.

Numerical values could be estimated to the process indices based on parameters shown in Figure 1. For instance, index for production (I_p) can be quantified based on availability of relevant resources, safety issues and water use in addition to GHG emissions, energy and resources requirements, and costs. These indices may be normalized by finding suitable reference values for standardization. Likewise, suitable weighing factors also need to be assigned and at a simplistic level, an equal value of one can be assigned to all of them.

It may be noteworthy that estimations of process indices and weighing factors can differ in a case-by-case basis. Hence, the purpose of this paper is to provide a generic approach that can be adapted to different cases without targeting any particular case. As seen, the composite performance index (I) calculated from Equation 1 can capture trade-offs from environmental impacts, costs, safety, and efficiency of fuel cells holistically. This composite index can be utilized to standardize the evaluation procedure of fuel cell-based ship propulsion, compare performance of different options, and provide inputs to policies intended to support deployment of hydrogen fuel cell-based marine transportation.

3. Discussion

Existing performance evaluation of hydrogen based marine propulsion are very valuable but not holistic. For example, life cycle assessments of hydrogen fuel cell based marine propulsion have been carried out (Fernández-Ríos et al., 2022; Hwang et al., 2020) but they do not consider several key performance factors such as costs, fuel cell efficiency and safety. Therefore, a holistic approach is developed here to complement the existing analysis methods. Further studies are needed to estimate reference values to normalize the indices (Equation 1) and to quantify safety issues. One approach to quantify safety issues could be to take these into account in weighing factors (Equation 1) based on expert judgement. However, in cases where quantitative evaluation is not practical due to complexity or lack of data, qualitative evaluation may be used in conjunction with quantitative approach. This Short Communications paper is an attempt to engage wider research community to develop a robust and holistic mathematical tool for performance evaluation of hydrogen based marine transportation by extending the framework proposed here. One limitation of the proposed framework is that it does not consider end of life processes and could be added in future studies for completeness.

4. Conclusions

A holistic approach to evaluate the performance of hydrogen fuel cell-based ship propulsion by considering environmental impacts, GHG emissions, safety, energy and resources requirements, and costs is proposed in this short paper. The approach takes into account the processes such as hydrogen production, packing and storage of hydrogen, fuel transportation, storage and unpacking, and fuel cell operation. A metric termed composite performance index is proposed for quantitative evaluation where practical. The approach presented here can support sustainable design and planning of hydrogen fuel cell-based marine transportation.

Acknowledgement

The author would like to thank anonymous reviewers for their valuable feedback to improve the paper.

References

Atilhan, S., Park, S., & El-Halwagi, M. M., et al. (2021). Green hydrogen as an alternative fuel for the shipping industry. *Current Opinion in Chemical Engineering*, *31*, 100668. DOI: 10.1016/j.coche.2020.100668.

Biert, L. van, Godjevac, M., Visser, K., & Aravind, P. V. (2016). A review of fuel cell systems for maritime applications. *Journal of Power Sources, 327,* 345-364.

Elberry, A. M., Thakur, J., Santasalo-Aarnio, A., & Larmi, M. (2021). Large-scale compressed hydrogen storage as part of renewable electricity storage systems. *International Journal of Hydrogen Energy*, *46(29)*, 15671-15690.

EPRI. (2020). Summary of environmental impacts from green hydrogen projects. *Electric Power Research Institute*. Available at: https://4echile-datastore.s3.eu-central-1.amazonaws.com/wp-content/uploads/2020/10/31004817/GIZ_Memo-Energy-Power-Research-Institute-EPRI.pdf.

Fernández-Ríos, A., Santos, G., Pinedo, G., & et al. (2022). Environmental sustainability of alternative marine propulsion technologies powered by hydrogen - a life cycle assessment approach. *Science of The Total Environment, 820*, 153189.

Hwang, S. S., Gil, S. J., Lee, G. N., & et al. (2020). Life Cycle Assessment of Alternative Ship Fuels for Coastal Ferry Operating in Republic of Korea. *Journal of Marine Science and Engineering, 8(660)*.

Howarth, R. W., & Jacobson, M. Z. (2021). How green is blue hydrogen? *Energy Science & Engineering, 9(10)*, 1676-1687.

Inal, O. B., Zincir, B., & Deniz, C. (2022). Investigation on the decarbonization of shipping: An approach to hydrogen and ammonia. International *Journal of Hydrogen Energy*. DOI: 10.1016/j.ijhydene.2022.01.189.

Jiang, X., Nie, X., Guo, X., Song, C., & Chen, J. G. (2020). Recent Advances in Carbon Dioxide Hydrogenation to Methanol via Heterogeneous Catalysis. *Chemical Reviews*, *120 (15)*, 7984–8034.

JRC. (2021). Assessment of Hydrogen Delivery Options. *Joint Research Centre, European Union*. Available at: https://joint-research-centre.ec.europa.eu/system/files/2021-06/jrc124206_assessment_of_hydrogen_delivery_options.pdf.

Lahnaoui, A., Wulf, C., & Dalmazzone, D. (2021). Optimization of Hydrogen Cost and Transport Technology in France and Germany for Various Production and Demand Scenarios. *Energies, 14*, 744. DOI: 10.3390/en14030744.

MEPC. (2018). Annex 11 Resolution MEPC.304(72): Initial IMO Strategy on Reduction of GHG Emissions from Ships. *International Maritime Organization*. Available at: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/ResolutionMEPC.304(72)_E.pdf.

Rao, P. C., & Yoon, M. (2020). Potential Liquid-Organic Hydrogen Carrier (LOHC) Systems: A Review on Recent Progress. *Energies, 13,* 6040.

Schorn, F., Breuer, J. L., Samsun, R. C., & et al. (2021). Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations. *Advances in Applied Energy, 3*. DOI: 10.1016/j.adapen.2021.100050.

Wulf, C., Reuß, M., Grube, T., & et al. (2018). Life Cycle Assessment of hydrogen transport and distribution options. *Journal of Cleaner Production, 199*, 431-443.

Yoon, H. J., Seo, S. K., & Lee, C. J. (2022). Multi-period optimization of hydrogen supply chain utilizing natural gas pipelines and byproduct hydrogen. *Renewable and Sustainable Energy Reviews, 157,* 112083.

Xing, H., Stuart, C., Spence, S., & Chen, H. (2021). Fuel Cell Power Systems for Maritime Applications: Progress and Perspectives. *Sustainability,13,* 1213.