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RENEWABLE ELECTRICITY ALLOCATION BETWEEN GRID DECARBONISATION AND MARITIME HYDROGEN PRODUCTION: A THRESHOLD-BASED SYSTEM-LEVEL ASSESSMENT

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ABSTRACT

Hydrogen is increasingly considered a promising zero-carbon fuel option for maritime transport under emerging regulatory frameworks such as the International Maritime Organization lifecycle assessment guidelines and the EU FuelEU Maritime regulation. However, hydrogen production via electrolysis requires significant amounts of renewable electricity, raising questions about the optimal allocation of renewable energy across sectors. This study evaluates the system-level greenhouse gas abatement implications of allocating renewable electricity either to direct grid decarbonisation or to maritime hydrogen production. A threshold-based framework is developed to identify the grid carbon intensity conditions under which hydrogen production yields higher system-level emission reductions than direct renewable electricity integration into the grid. The analysis combines regulatory lifecycle emission factors for conventional marine fuels with electrolyzer efficiencies ranging from 60% to 85%. Results indicate that the hydrogen abatement threshold lies between 195 and 287 $kgCO_2eq/MWh$, depending on regulatory assumptions and marine fuel baselines. Comparison with electricity carbon intensities of selected hydrogen bunkering candidate countries suggests that most analysed regions currently remain above this threshold, while some lower-carbon electricity systems may benefit more from allocating renewable electricity to hydrogen production for maritime use. These findings highlight the importance of renewable electricity allocation efficiency when evaluating hydrogen-based maritime decarbonisation strategies.

Keywords: Hydrogen fuel, Lifecycle emissions, Maritime decarbonization, Renewable energy allocation, System-level GHG abatement

INTRODUCTION

The maritime sector faces increasing pressure to reduce greenhouse gas (GHG) emissions in line with global climate targets. International regulatory initiatives, including the International Maritime Organization's lifecycle assessment (IMO LCA) guidelines [1] and the European Union's FuelEU Maritime regulation [2], aim to accelerate the transition toward low-carbon and zero-carbon marine fuels. Among the proposed alternatives, hydrogen has attracted significant attention due to its potential to eliminate direct carbon emissions when used as a marine fuel.

However, hydrogen production via electrolysis requires significant amounts of electricity, raising important questions regarding the allocation of renewable energy across sectors. As several countries pursue hydrogen bunkering projects and hydrogen export strategies for maritime transport, renewable electricity may be increasingly diverted toward hydrogen production. At the same time, fossil fuels continue to dominate global electricity generation. In 2024, coal and natural gas together accounted for more than half of global electricity production (Table 1), indicating that electricity carbon intensities remain highly variable across regions.

Table 1. Global electricity generation mix in 2024 [5].

Energy Source	Share (%)
Coal	34.4%
Natural gas	22.0%
Other fossil	2.8%
Nuclear	9.0%
Bioenergy	2.3%
Hydro	14.3%
Wind	8.1%
Solar	6.9%

Previous studies on maritime decarbonisation have primarily focused on lifecycle greenhouse gas emissions of alternative fuels such as hydrogen, ammonia, and other electrofuels [3,4]. While these studies provide important insights into fuel pathway emissions, relatively little attention has been given to the system-level implications of renewable electricity allocation between maritime hydrogen production and grid decarbonisation.

In electricity systems with high carbon intensity, renewable electricity may achieve greater climate benefits when used to displace fossil-based power generation rather than producing hydrogen. Conversely, in already low-carbon electricity systems, allocating renewable electricity to hydrogen production may provide greater marginal emission reductions when hydrogen replaces fossil marine fuels.

This study addresses this gap by introducing a threshold-based framework to evaluate when renewable electricity allocation to maritime hydrogen production becomes system-optimal compared to direct grid decarbonisation. By combining regulatory lifecycle emission values with electricity carbon intensity data from selected hydrogen bunkering candidate countries, the analysis provides a system-level perspective on the climate effectiveness of hydrogen deployment in maritime transport.

METHODS

This study evaluates the system-level GHG abatement efficiency of allocating renewable electricity either to (i) direct grid decarbonisation or (ii) maritime hydrogen production. The functional unit is defined as 1 MWh of additional renewable electricity.

A well-to-wake (WtW) perspective is adopted, consistent with lifecycle accounting principles applied in maritime regulations. Baseline marine fuel carbon intensities are taken from regulatory default values under the IMO LCA Guidelines [1] and FuelEU Maritime [2], as summarised in Table 2.

During CO_2-equivalent calculations, 100-year global warming potential (GWP100) factors are used, with values of 28 for CH_4 and 265 for N_2O. The tank-to-wake (TtW) carbon intensity of marine fuels is determined as:

$$CI_{TtW} = \frac{gCO_2 + 28 \times gCH_4 + 265 \times gN_2O}{LCV} \quad (1)$$

Table 2. Lifecycle carbon intensity values used for maritime fuel baselines under IMO LCA and FuelEU Maritime frameworks.

	IMO LCA		FuelEU Maritime	
Fuel	HFO	MDO/MGO	HFO	MDO/MGO
LCV (MJ/g)	0.0402[a]	0.0427[a]	0.405[b]	0.0427[b]
WtT gCO_2eq/MJ	14.1[a]	17.7[a]	13.5[b]	14.4[b]
TtW $gCFCO_2/gfuel$	3.114[a]	3.206[a]	3.114[b]	3.206[b]
TtW $gCFCH_4/gfuel$	0.00005[a]	0.00005[a]	0.00005[b]	0.00005[b]
TtW $gCFN_2O/gfuel$	0.00018[a]	0.00018[a]	0.00018[b]	0.00018[b]
TtW gCO_2eq/MJ	78.68[c]	76.23[c]	78.10[c]	76.23[c]
WtW gCO_2eq/MJ	92.78[c]	93.93[c]	91.60[c]	90.63[c]
WtW $kgCO_2eq/MWh$	334.0[c]	338.2[c]	329.8[c]	326.3[c]

[a]IMO LCA Guidelines values [1]
[b]FuelEU Maritime values [2]
[c]Author's own calculations

The objective is to determine under which grid carbon intensity conditions hydrogen allocation yields higher system-level GHG abatement than direct grid decarbonisation. When renewable electricity is integrated into the grid, it is assumed to displace fossil-based electricity generation. The avoided emissions are therefore proportional to the carbon intensity of grid electricity. Representative country-level electricity carbon intensity values are adopted from international datasets [6,7] and used as indicative proxies for prevailing grid conditions. The analysed countries, Australia, Brunei, Germany, Japan, Malaysia, the Netherlands, Oman, and Singapore, were selected due to their current or emerging roles in maritime hydrogen development [8]. Several of these countries are either actively developing hydrogen bunkering infrastructure or have announced hydrogen export and maritime fuel initiatives, making them relevant case studies for evaluating the system-level implications of renewable electricity allocation.

Alternatively, renewable electricity may be converted into hydrogen via electrolysis. The system-level abatement from maritime hydrogen allocation is calculated as in Equation 2.

$$A_{H_2} = \eta_{el} \times CI_{marine} \quad (2)$$

A_{H_2} is the avoided emissions from maritime hydrogen allocation, while η_{el} is electrolyzer efficiency, and CI_{marine} is WtW carbon intensity of baseline marine fuel (WtW $kgCO_2eq/MWh$). Electrolyzer efficiency is varied within a representative range of 60–85%, reflecting current and near-term electrolysis technologies [9,10].

A threshold grid carbon intensity is then defined as the value at which the abatement from hydrogen production equals that from direct grid integration. If actual grid carbon intensity exceeds this threshold, grid decarbonisation yields higher system-level GHG abatement. If it falls below the threshold, renewable allocation to maritime hydrogen becomes system-optimal.

RESULTS AND DISCUSSION

Figure 1 presents the calculated hydrogen abatement thresholds and the corresponding electricity carbon intensities of selected countries with emerging hydrogen bunkering potential. The threshold represents the grid carbon intensity below which allocating renewable electricity to maritime hydrogen production yields higher system-level GHG abatement than direct grid decarbonisation.

As shown in Figure 1(a), the threshold grid carbon intensity increases with electrolyzer efficiency. For the efficiency range considered (60–85%), the threshold varies between 195 and 287 $kgCO_2eq/MWh$ depending on the regulatory lifecycle framework and the marine fuel baseline. Slightly higher threshold values are observed under the IMO LCA framework compared to FuelEU Maritime due to differences in default lifecycle emission assumptions. These results indicate that hydrogen allocation becomes more favourable as electrolyzer efficiency improves. However, even at higher efficiency levels, the threshold remains significantly below the electricity carbon intensities observed in many regions.

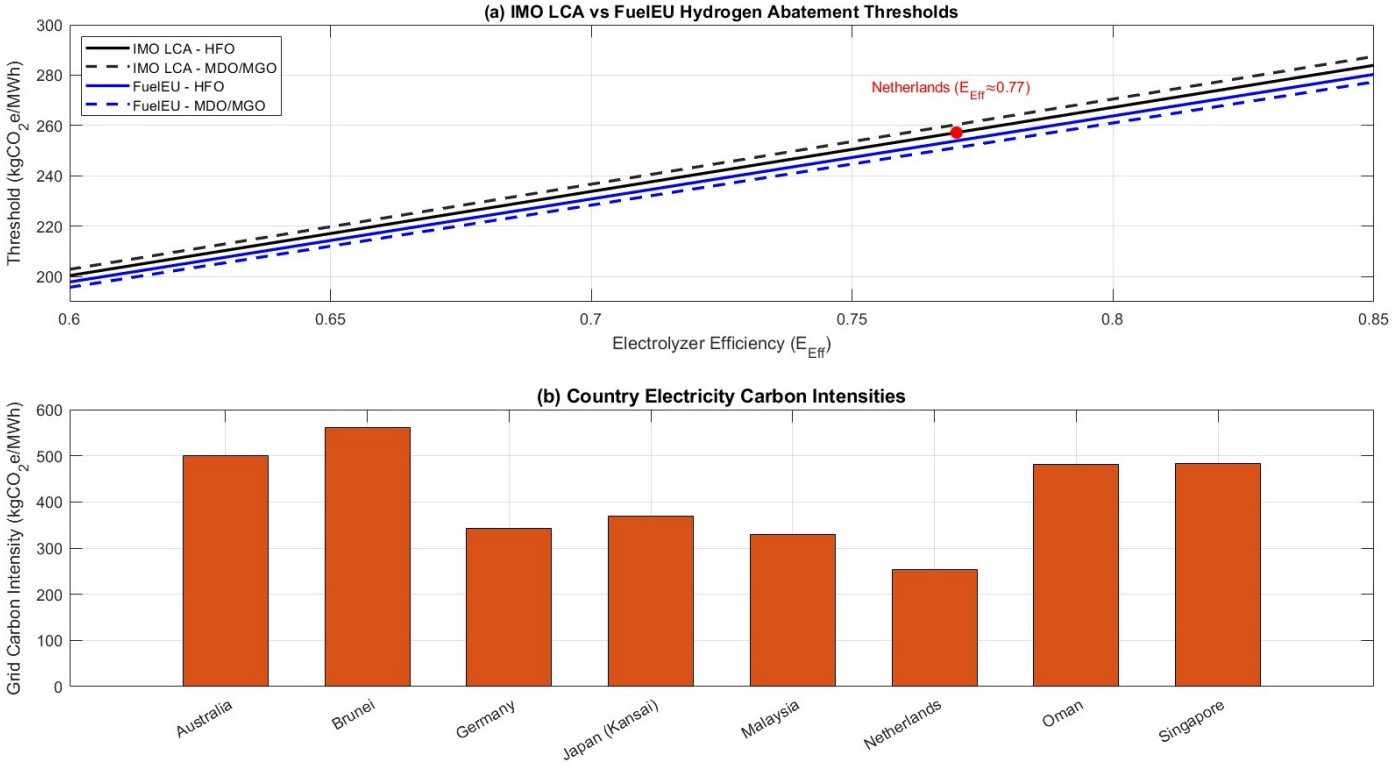


Fig. 1. System-level hydrogen abatement thresholds and regional grid carbon intensities. (a) Threshold grid carbon intensity ($kgCO_2eq/MWh$) as a function of electrolyzer efficiency under IMO LCA and FuelEU Maritime lifecycle assumptions for HFO and MDO/MGO baselines. The threshold represents the grid carbon intensity below which renewable electricity allocation to maritime hydrogen production yields higher system-level GHG abatement than direct grid decarbonisation. (b) Representative country-level average electricity carbon intensities used for comparative assessment [6,7].

Figure 1(b) compares these threshold values with representative country-level electricity carbon intensities for selected hydrogen bunkering candidate countries. The results show that most of the analysed countries, including Australia, Brunei, Japan, Oman, and Singapore, have grid carbon intensities well above the calculated threshold values. Under such conditions, allocating renewable electricity directly to grid decarbonisation yields greater system-level GHG abatement than producing hydrogen for maritime use.

Countries with intermediate carbon intensities, such as Germany and Malaysia, remain above the threshold under most efficiency scenarios, indicating that grid decarbonisation continues to provide higher marginal emission reductions. Among the analysed countries, the Netherlands appears closest to the threshold boundary, suggesting that hydrogen allocation may become competitive under higher electrolyzer efficiency conditions.

These findings highlight that the climate effectiveness of maritime hydrogen deployment is highly sensitive to regional electricity system characteristics. While hydrogen bunkering initiatives are expanding in several countries with relatively carbon-intensive electricity systems, the system-level GHG benefits of hydrogen production are significantly higher in regions where electricity generation is already largely decarbonised.

From a policy perspective, current maritime decarbonisation frameworks primarily focus on reducing sectoral lifecycle emission intensities. However, the results suggest that cross-sector renewable electricity allocation efficiency may play an important role in determining the overall climate effectiveness of hydrogen-based maritime fuels. Strategic

consideration of electricity system conditions may therefore enhance the global mitigation impact of hydrogen deployment in maritime transport.

CONCLUSIONS

This study assessed the system-level GHG abatement implications of allocating renewable electricity either to grid decarbonisation or to maritime hydrogen production. The analysis shows that the hydrogen abatement threshold ranges between 195 and 287 $kgCO_2eq/MWh$ depending on electrolyzer efficiency and regulatory lifecycle assumptions. Comparison with electricity carbon intensities of selected hydrogen bunkering candidate countries indicates that most regions remain above this threshold, meaning that direct grid decarbonisation currently delivers higher marginal emission reductions. These results highlight that the climate effectiveness of maritime hydrogen deployment depends strongly on regional electricity system characteristics and that renewable electricity allocation efficiency should be considered in future maritime decarbonisation strategies.
Future work could extend this framework by incorporating additional hydrogen-derived fuels such as ammonia, country-specific electricity system characteristics and marginal carbon intensities, and dynamic electricity scenarios reflecting future grid decarbonisation pathways. Such extensions would allow a more detailed assessment of the geographical and policy implications of hydrogen deployment in maritime transport.

NOMENCLATURE

CI	Carbon intensity
EU	European Union
HFO	Heavy fuel oil
GHG	Greenhouse gas
GWP	Global warming potential
IMO	International Maritime Organization
LCA	Lifecycle assessment
LCV	Lower calorific value
MDO	Marine diesel oil
MGO	Marine gas oil
TtW	Tank-to-wake
WtT	Well-to-tank
WtW	Well-to-wake

Greek Letters

η_{el}	Electrolyzer efficiency

Subscripts

CF	*Coefficient factor*
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Nitrous oxide

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