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A systematic review of technologies, measures, and CO_2 emission reduction potential for maritime transport decarbonisation

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ABSTRACT

The maritime shipping sector is a significant contributor to global carbon dioxide (CO_2) emissions, accounting for approximately 2.7%-3% of global emissions. In response, the International Maritime Organization (IMO) has set ambitious targets: a 30% reduction in emissions by 2030, 80% by 2040, and net-zero by 2050, relative to 2008 levels. Meeting these goals requires a comprehensive understanding of the full range of viable decarbonisation measures. Therefore, this study conducts a systematic review of maritime decarbonisation measures, applying the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. Unlike previous studies, this paper not only provides an updated overview of CO_2 reduction measures but also maps them to specific vessel types based on data reported in the literature. Furthermore, the findings are compared with literature to highlight shifts in mitigation potential. A case study is also included to schematically demonstrate how these measures can be applied in practice. Following a rigorous analysis: (i) thirty-two individual CO_2 mitigation measures were identified and classified into six categories, (ii) alternative fuels shown the highest long-term potential (5–100 % CO_2 emission reduction), whereas hull design improvements show the lowest (1–20 %), (iii) the wide disparity in reported abatement values is attributed to inconsistent system boundaries, variability in fuel origin, partial-blend scenarios, and differing assumptions across studies, (iv) combinations of measures provide the most practical and realistic pathway to phased emissions reduction. These findings are expected to assist decision-makers in selecting effective, context-appropriate strategies to support global maritime decarbonisation and ensure long-term sectoral sustainability.

Introduction

The ongoing rise in global temperatures has largely been attributed to increasing concentrations of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere, mainly driven by human activities [1,2]. Transportation is the second-largest contributor to global CO_2 emissions, generating over eight billion metric tonnes of carbon dioxide ($GtCO_2$) globally [3] (see Fig. 1). Within this sector, shipping is the second-largest source after road transport, with international and domestic maritime emissions together accounting for 12 % of the total (7.5 % from international shipping and 4.5 % from domestic shipping) [3]. In recent years, maritime shipping has emitted approximately 1.0 gigatonne of CO_2 annually, accounting for around 2.7–3 % of global CO_2 emissions [2,4], making it crucial to take appropriate action to decarbonise the sector [5].

If current trends continue under a business-as-usual (BAU) scenario with global trade projected to triple between 2012 and 2050, and no additional mitigation efforts implemented, emissions are anticipated to increase by between 150 % and 250 % by 2050 [1,2,6–8]. In response to the increasing trend in CO_2 emissions, the International Maritime Organization (IMO) introduced a strategy focused on enhancing energy efficiency and reducing emissions. The updated 2025 IMO strategy outlines ambitious greenhouse gas reduction targets for the shipping sector, relative to 2008 levels: a 30 % reduction by 2030, an 80 % cut by 2040, and the achievement of net-zero emissions by 2050, as illustrated in Fig. 2.

To meet the targets set out in the IMO strategy, timely identification of effective CO_2 reduction measures is essential. Equally important is assessing each option's mitigation potential. Numerous studies have been undertaken to evaluate a wide spectrum of approaches focused on potential marine alternative fuels [7–13], while others only concentrated on the potential of specific fuels such as ammonia [14,15],

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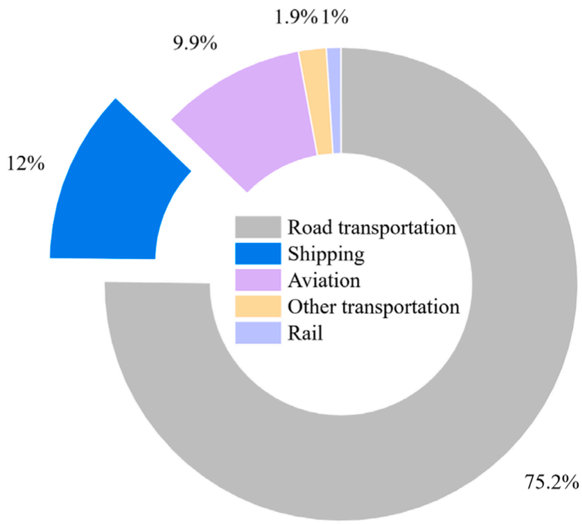


Fig. 1. Distribution of CO2 emissions in the global transport sector by subsector in 2023 (data extracted from www.statista.com) [3].

methanol [16,17], hydrogen [18–22], or LNG [23,24]. Some studies focused on a comparative assessment of such fuels across maritime, aviation, and haulage sectors, evaluating their energy density, and scalability. Their analysis supports the relevance of hydrogen and ammonia as particularly promising candidates for long-range maritime operations due to their high mitigation potential and alignment with broader decarbonisation goals [12]. Furthermore, some studies have been conducted on blending alternative fuels for decarbonisation purpose [25]. Some studies explored decarbonisation strategies within the shipping industry [26,27], whereas others examined the potential of technologies and operational measures [2,28–31]. Additionally, several papers reviewed the potential of market-based policy measures [32–36]. Although multiple studies explore mitigation measures, technologies, and scenarios in the shipping sector, they tend to be either narrowly topical or already outdated, and none offers a comprehensive and updated review of all available decarbonisation options. A systematic and wide-ranging review is therefore lacking in the scientific literature. Therefore, there is an urgent need for a clear and impartial assessment of the current state of the art, one that evaluates the mitigation potential of each measure and helps to guide future research priorities

The purpose of this study is to deliver a comprehensive and systematic review of potential measures for decarbonising the maritime sector. It also evaluates the reported capacity of each measure to reduce CO_2 emissions, based on evidence from the literature. The objective is not only to identify the promising measures and technologies but also to quantify their CO_2 mitigation potential. It should be noted that, although other pollutants such as nitrogen oxides (NO_X), sulphur oxides (SO_X), and particulate matter (PM) are also important components of maritime emissions, this study focuses specifically on CO_2 due to its extensive coverage in the literature and its established use as a proxy for overall greenhouse gas (GHG) reductions [1,2,5]. CO_2 emission reduction potential is adopted as the primary metric for quantifying the environmental benefits of proposed technologies in the context of clean maritime initiatives, in alignment with the International Maritime Organization's decarbonisation strategy [1,6,7,37]. It is noted, however, that not all reviewed studies explicitly quantify CO_2 reductions, some present data in terms of energy and fuel savings. In such instances, a direct correlation is assumed, whereby a percentage reduction in fuel consumption equates to an equivalent percentage reduction in CO_2 emissions [38]. Unlike previous studies, this paper not only provides an updated and comprehensive overview of CO_2 reduction measures but also maps these measures to specific vessel types based on data reported in the literature. In addition, the findings are compared with an earlier study [1], to identify shifts in mitigation potential over time. A case study is also included to schematically illustrate the practical application of the proposed measures.

The remainder of this paper is structured as follows. Section 2 outlines the methodology employed in this study, which includes bibliometric and network analysis alongside a systematic literature review, forming the foundation for the subsequent analysis. Section 3 presents the results of the systematic review of potential measures for maritime decarbonisation. Building on these findings, Section 4 offers a discussion that explores the variation in reported CO_2 reduction values and proposes a classification of the measures according to their implementation timeframe. To demonstrate the practical relevance of the review, Section 5 presents a case study illustrating how the identified measures and insights can be applied in real-world scenarios. Section 6 summarises the novel findings of the paper and highlights directions for future research.

Methodology

This section outlines the framework of the approaches employed to systematically review the literature relevant to maritime transport decarbonisation. The main subsections cover the systematic literature review, as well as the bibliometric and network analysis conducted using VOSviewer.

Systematic literature review

To ensure a rigorous and transparent process, this study applied the

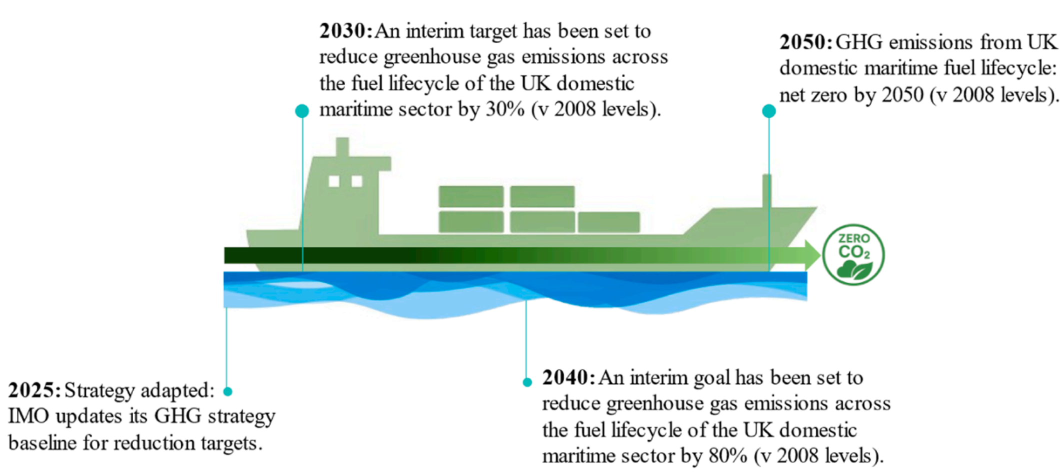


Fig. 2. Decarbonisation targets adapted by IMO for maritime sector relative to 2008 levels.

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to structure and guide the systematic literature review [39]. PRISMA provides a standardised framework for conducting and reporting systematic reviews, allowing for a comprehensive and unbiased selection and synthesis of relevant literature. By following this widely recognised guideline, the review process is made explicit and replicable, enhancing the reliability and credibility of the findings [39]. Moreover, appropriate search terms and Boolean operators were developed through preliminary scoping research. This approach ensured comprehensive coverage of key publications in the field while keeping the number of results manageable and relevant. The search terms used were: ((green OR clean OR sustainable OR eco-friendly OR low-carbon) AND (ship OR shipping)) OR ((maritime OR Marine OR shipping) AND decarbonisation). These terms were applied within the Web of Science (WoS) database. An initial total of 13,119 records were identified. To refine the search results and ensure both relevance and currency, especially in comparison with the timeframes covered by previous publications, a set of inclusion criteria was applied. These included the following filters. Studies that did not meet the inclusion criteria detailed in the next paragraph were excluded from the review (the number of excluded records is indicated in parentheses).

Documents published prior to 2018 were excluded ($n = 4219$), as the review focused on literature published between 2018 and 25 February 2025. This time frame was selected to ensure that the analysis reflects the most recent developments and emerging trends in the field since 2018, following the research conducted by Bouman et al. (2017). By focusing on a defined and recent period, the study aims to provide a timely and relevant synthesis of the current research landscape.

Only peer-reviewed journal articles were retained ($n = 1651$), and further exclusions were made for non-open access documents ($n = 3412$) and non-English language publications ($n = 62$). Additionally, records were limited to specific Web of Science categories and only articles published in the following journals were included: Environmental Sciences, Green Sustainable Science Technology, Energy Fuels, Environmental Studies, Engineering Marine, Engineering Ocean, Material Science Multidisciplinary, Transportation, Engineering Environmental, Engineering Civil, Transportation Science Technology, Engineering Multidisciplinary, Chemistry Multidisciplinary, Multidisciplinary Sciences, and Chemical Engineering ($n = 925$).

Following this initial filtering process, 2850 studies remained. Title

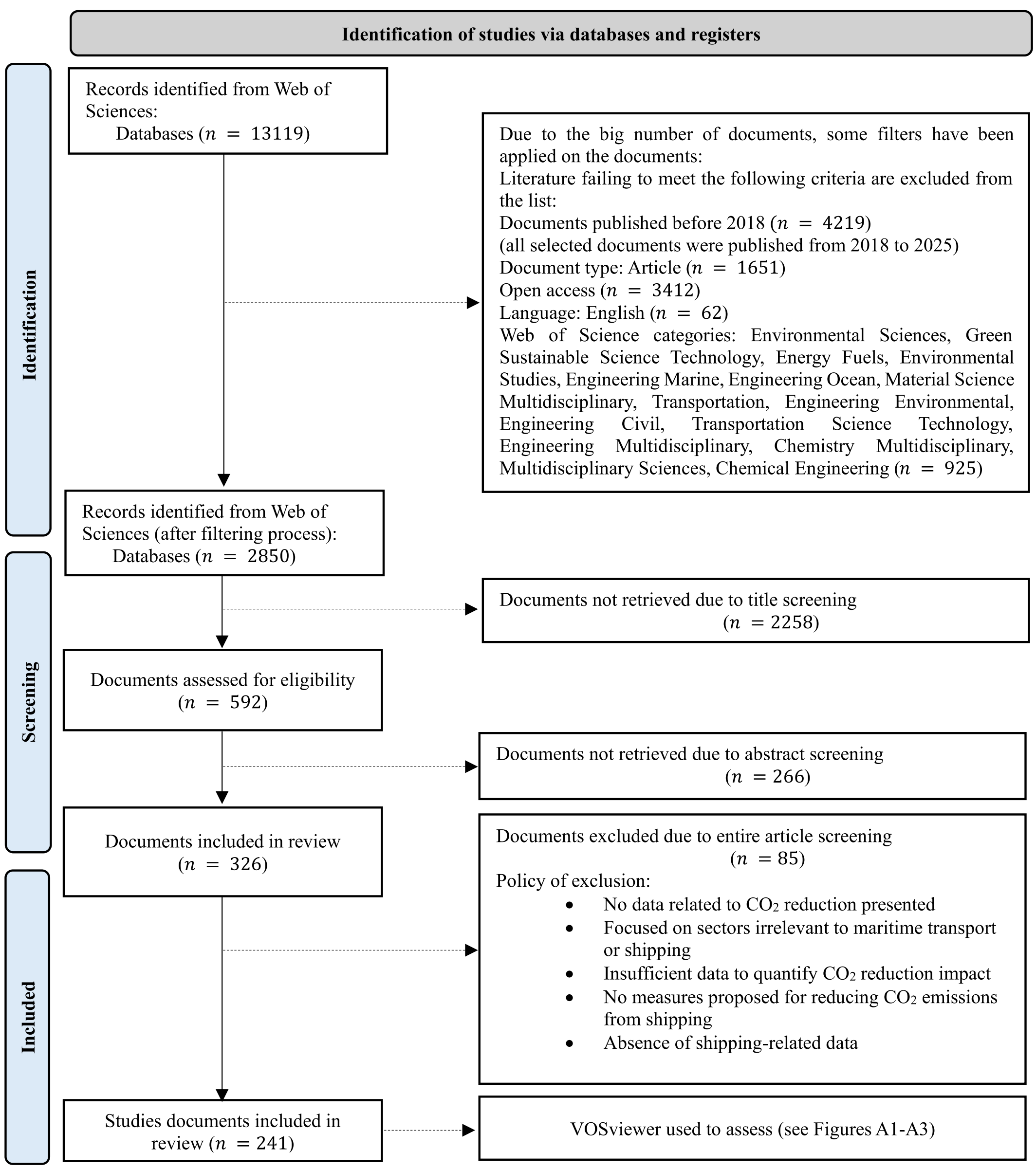


Fig. 3. PRISMA flow diagram detailing the present systematic review methodology, adapted from the template provided by [40].

screening resulted in the exclusion of 2258 documents. The abstracts of the remaining papers were then reviewed, and a further 266 were excluded due to irrelevance. Full-text screening was conducted on the remaining 326 articles, with 85 subsequently excluded based on content. Reasons for exclusion at this stage included: absence of data related to CO_2 reduction, focus on sectors unrelated to maritime transport or shipping, insufficient data to quantify CO_2 reduction impacts, lack of proposed measures for reducing CO_2 emissions in shipping, and absence of shipping-specific data.

Ultimately, 241 articles met all eligibility criteria and were included in the final synthesis. The PRISMA flow diagram for this systematic review, outlining the step-by-step selection process, is presented in Fig. 3.

Bibliometric and network analysis (VOSviewer)

To complement the systematic literature review, a bibliometric and network analysis was conducted using VOSviewer (version 1.6.20). Bibliometric analysis refers to the quantitative assessment of academic publications, aiming to uncover trends, research dynamics, and the structural evolution of a field [41]. Network analysis, in this context, is used to visualise and interpret connections between key components such as authors, institutions, countries, or keywords, providing insights into patterns of collaboration and thematic groupings [42].

This approach enabled the identification of key themes, influential publications, collaboration trends, research and temporal trends within the selected body of literature on maritime decarbonisation. The dataset comprising 241 eligible articles, as determined through the (PRISMA)-based screening process, was exported from the Web of Science database in a format compatible with VOSviewer (plain text). The analysis focused on keyword co-occurrence, authorship collaboration, country linkages, and time trends. It examined temporal and geographical patterns to reveal the intellectual structure of the field.

For the keyword co-occurrence analysis, full counting was applied, whereby each occurrence of a keyword is counted equally, providing a comprehensive view of keyword frequency. A minimum threshold of 5 occurrences per keyword was set to ensure the clarity and relevance of the results. In this context, co-occurrence analysis refers to the examination of how frequently keywords appear together within the dataset, revealing patterns and thematic connections. Additionally, the author keywords field was selected for the analysis, meaning that only the keywords provided by the authors of the original publications were used, which typically reflect the core focus of each study.

The co-authorship analysis was conducted at the country level, considering total link strength. This metric reflects both the number of collaborating countries and the frequency of jointly authored publications, indicating the overall intensity of international research collaboration. This provided insight into the geographical distribution of expertise and the degree of international collaboration within the field of maritime decarbonisation.

Lastly, the overlay visualisation was employed to capture the temporal development of research themes by colour-coding keywords according to their average year of appearance. This enabled the identification of emerging trends and shifts in research focus over time, offering a dynamic perspective on how the field has evolved. The results of bibliometric and network analysis are presented in Appendix A.

Results

The main categories of emission reduction strategies identified, along with their associated individual measures, will be summarised in this section based on the systematic literature review. Following the presentation of the annual number of relevant publications from 2018 to 2025 (25th February), and the contribution of each country to maritime decarbonisation, the paper presents the potential of each measure to reduce CO_2 emissions. This includes the reported ranges of CO_2 emission reductions for each individual measure, as found in the literature.

Systematic literature review

This section presents the results of the systematic literature review, including publication count and country of origin of selected articles, and maritime decarbonisation measures with reported CO_2 emission reductions, comparison with literature [1], and mapping the measures to the type of vessels.

Publication count and country of origin of selected articles

Based on the results, Fig. 4 illustrates the annual number of publications related to maritime decarbonisation. The colour intensity of each bar corresponds to publication volume, with darker shades indicating higher counts. A clear exponential growth pattern is evident, as highlighted by the red dashed trend line, which closely fits the data from 2018 to 2024. It should be stated that, as 2025 is an incomplete year, its data has not been included. The number of relevant publications increased steadily from 6 in 2018 to 92 in 2024, reflecting growing academic interest in maritime decarbonisation. This pronounced increase in publication frequency suggests a rapid expansion of research activity following the IMO's adoption of its initial GHG strategy in 2018. The upward trend underscores both the increasing urgency of the topic and the wide range of technological, regulatory, operational, and other approaches currently being explored in the literature.

The findings point to a pronounced geographical concentration of research. Most of the selected articles originate from China, while the United Kingdom, comprising publications from England and Scotland, contributes the second largest share. Fig. 5 shows the distribution of publications by country. Darker colours in the bars indicate higher publication counts, highlighting regional disparities in maritime decarbonisation research.

Maritime decarbonisation measures with reported CO_2 emission reductions

This section presents the measures and technologies identified as having the potential to reduce CO_2 emissions and thereby support maritime decarbonisation. As noted by [43], strategies are generally grouped into two broad categories: technical and operational. Technical measures involve improvements to ship design, propulsion systems, and fuel type, with some suitable for retrofitting and others more appropriate for new builds. Operational measures focus on optimising vessel performance such as slow steaming, route planning, and energy management, and can be applied across most vessel types [43]. Twenty-two individual measures were identified by [1]. The present study has collated 32 distinct measures from the recent literature, grouped into six principal categories: alternative fuels, alternative energy sources, power and propulsion systems, operational practices, hull design, and other measures comprising carbon capture and storage as well as policy measures (market-based measures have been considered under the broader category of policy measures) based on reliable and available data from the reviewed literature. These categories are illustrated in Fig. 6.

Table 1 presents the individual measures alongside their respective ranges of CO_2 emission reduction, together with the relevant references. The minimum and maximum values reflect the full set of data reported in the literature, excluding outliers identified through statistical analysis.

To present all individual measures alongside their corresponding CO_2 mitigation potential, the results are shown in Fig. 7 as box-and-whisker plots arranged in order. For comparison, the median value of each data set is used to represent the CO_2 reduction potential of each measure, which is calculated by the following formulation

$$M = \begin{cases} x_{\frac{n+1}{2}} \\ \dfrac{x_{\frac{n}{2}} + x_{\frac{n}{2}+1}}{2} \end{cases} \tag{1}$$

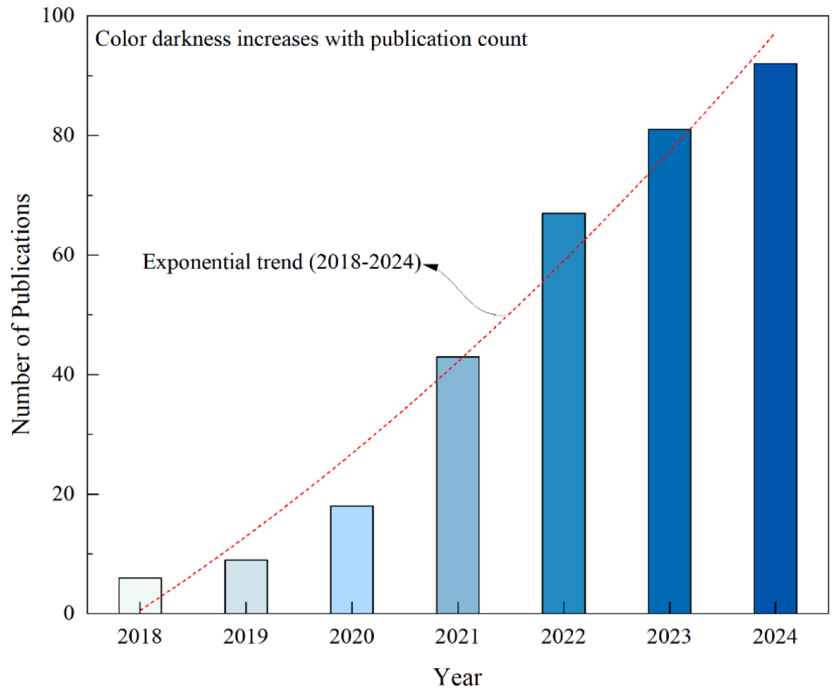


Fig. 4. Publication year of the selected articles and exponential trendline based on the data from 2018 to 2024.

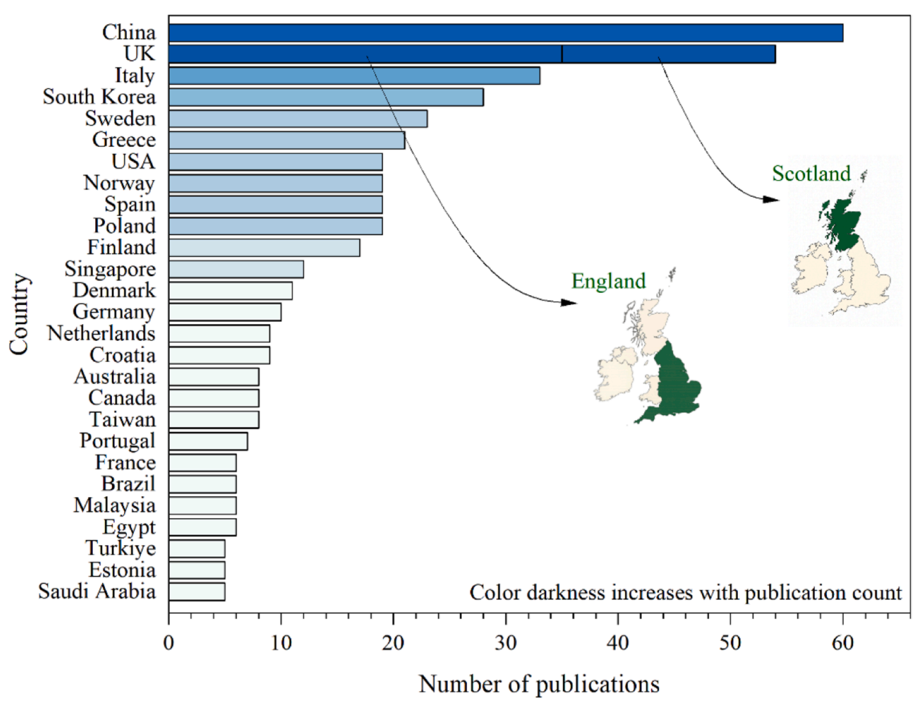


Fig. 5. Country of origin of the selected articles.

where M is the median value, and x_i and n represent individual value, and total number of values, respectively. This approach is selected due to the considerable variability in emission reduction estimates for some measures. The outliers and wide disparities could otherwise distort the mean, making the median a more robust and representative metric. Reductions of 0–25 % are classified as limited, 26–50 % as moderate, 51–75 % as significant, and 76–100 % as high. As depicted in Fig. 7, each box plot represents the range of CO_2 reduction potential for each given measure, displaying the interquartile range (IQR), the median (marked by a line within the box), the mean (shown as a square), and outliers (indicated by diamond symbols with red colour). The whiskers extend from the box to the smallest and largest values within 1.5 times the IQR, providing insight into the typical spread of the data while excluding extreme values identified as outliers.

Among all the measures, alternative fuels (particularly hydrogen, ammonia, and bio-based fuels) show the greatest potential for reducing emissions. Nuclear energy under the category of alternative energy sources also demonstrates the highest potential, with some estimates approaching or even reaching to 100 % CO_2 reduction. In addition,

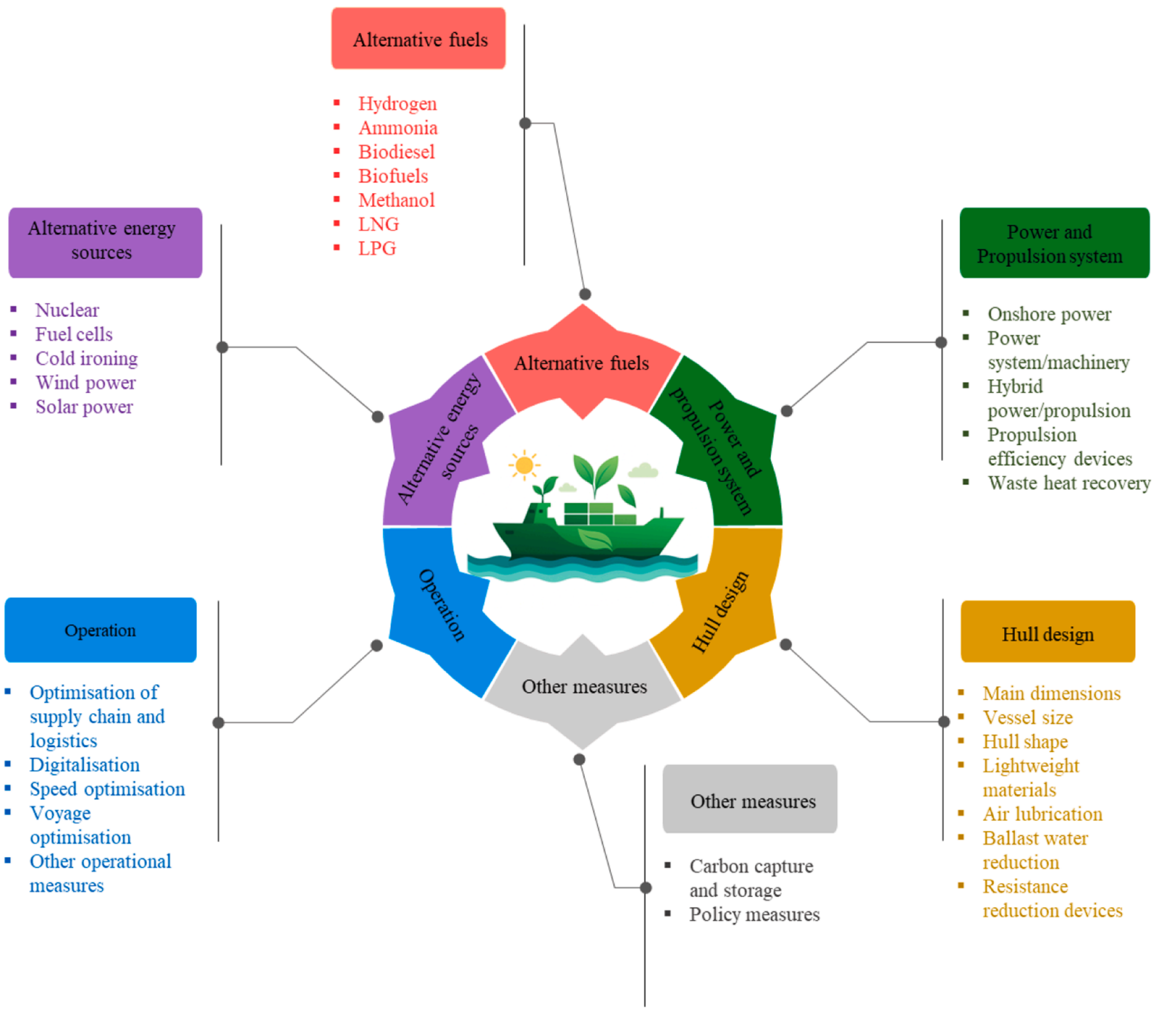


Fig. 6. Classification of maritime decarbonisation measures, grouped into six principal categories and thirty-two distinct measures.

methanol shows significant potential for maritime decarbonisation. However, the widespread of values and the presence of outliers indicate variability and a degree of uncertainty in its performance. This uncertainty is particularly notable for methanol. This variability can be attributed to several factors. First, methanol remains one of the least explored alternative marine fuels, and the limited number of empirical studies constrains the reliability and comparability of the available data. Second, methodological differences across studies, particularly regarding system boundaries (tank-to-wake versus well-to-wake), assumptions about feedstock origin, and the inclusion or exclusion of upstream emissions introduce significant inconsistencies. In some cases, methanol derived from fossil-based sources yields only marginal emission reductions, whereas renewable (bio- or e-methanol) pathways can achieve near-zero or even negative life-cycle emissions. Third, variations in engine technology, blending ratios, and operational profiles further complicate performance assessments. In addition, the higher CO_2 intensity of methanol compared with other fuels, and its strong dependence on the production pathway, could be another reason for the significant disparity. Biofuels and Biodiesel also show significant to high potential, showing more consistent results, albeit based on a smaller number of data points. Biofuels, with the exception of a few data points, show reliable and consistent results, with an interquartile range (IQR) of 15.5 % compared to other alternative fuels. This could be due to the more mature state of these alternative fuels and their better compatibility with the infrastructure of the maritime sector in recent years. While the results for LNG are relatively robust and consistent compared with other alternative fuels, its overall limited reduction potential makes it a less promising long-term solution for achieving clean maritime targets. However, LNG can be considered a short-term option to support the transition towards reduced CO_2 emissions over time, due to its cost-effectiveness and compatibility with existing facilities and infrastructure. Moreover, it is evident that hydrogen, ammonia, methanol, and LNG are the most frequently reported measures in the literature, reflecting their prominence and growing interest in recent years, as confirmed by the quantitative analysis conducted using VOSviewer.

Carbon capture and storage also demonstrates significant potential, with a relatively balanced interquartile range of approximately 17 %, spanning both the upper and lower quartiles. This suggests a consistent variation in reduction outcomes across different studies, highlighting its promise as a complementary measure depending on context and implementation. Moreover, policy measures also show notable disparity, that might be due to differences in the types of policies assessed and the capacity and size of vessels subject to each regulatory framework.

Alternative energy sources, such as solar power, also contribute to emissions reduction, although they exhibit limited potential compared to other measures. Nevertheless, the consistency of the reported data suggests they offer a reliable option for integration with other technologies. Similarly, cold ironing and fuel cells demonstrate moderate potential for mitigating CO_2 emissions, supporting their suitability for integration into broader decarbonisation strategies. The disparity observed in the reported CO_2 reduction potential of fuel cells can be attributed mainly to differences in the type of fuel used and the associated fuel-feeding methods. Fuel cells powered by renewable fuels offer

Table 1
Measures and corresponding ranges of CO_2 emission reduction potential.

Main Category	Individual measure	Range of CO_2 emission reduction (minimum-maximum)	References
Alternative fuels	Hydrogen	48–100 %	[9,44–94]
	Ammonia	49.95–100 %	[44,45,47–49,54–59,61–63,65,75,76,80,81,84,88,89,93–117]
	Biodiesel	66.7–100 %	[49,65,70,87,88,110,118,119]
	Biofuel	50–90 %	[35,78,81,87,89,118,120–129]
	Methanol	7–100 %	[45,47–49,56,58,59,63,70,73,81,87–89,91,101,103,110,118,119,129–143]
	LNG	5–40.5 %	[9,35,46–48,53,56,59,63,66,70,73,75,76,80,81,88,90,91,99,101,103,104,110,113,116,120,126,127,133,134,138,143–182]
	LPG	7.97–50.04 %	[46,87,88,134,144,173,183,184]
Alternative energy sources	Nuclear	95–100 %	[185–187]
	Fuel cells	7.1–90.45 %	[35,188–193]
	Cold ironing	6.5–87 %	[104,136,155,176,191,194–199]
	Wind power	3.6–40 %	[35,48,63,136,151,197,200–205]
	Solar power	0.2–11.65 %	[101,151,165,176,197,206–209]
Power and propulsion system	Onshore power	1.5–85 %	[35,186,210–217]
	Power system/ machinery	6.1–50 %	[50,69,87,90,126,131,138,166,188,218–224]
	Hybrid power/ propulsion	3.7–100 %	[35,62,76,175,220,224–233]
	Propulsion efficiency devices	1–13 %	[35,48,101,180,197,211,234–237]
	Waste heat recovery	1.3–11 %	[35,48,101,188,197,237–239]
Operation	Optimisation of supply chain and logistics	27.5–41.85 %	[126,240]
	Digitalisation	1–33 %	[4]
	Speed optimisation	4.5–70 %	[35,46–48,65,66,101,113,126,146,241–251]
	Voyage optimisation	2.4–32.69 %	[126,145,151,181,252–255]
	Other operational measures	0.5–30 %	[35,101,156,159,188,197,256–260]
Hull design	Main dimensions	1–18 %	[261]
	Vessel size	15–20 %	[35,47,146]
	Hull shape	4.5–16 %	[35,126,197]
	Hull coating	1.5–19 %	[101,146,262,263]
	Light Weight (LW) materials	5–11.75 %	[35,167]
	Air lubrication	5.5–6.8 %	[35,63,101]
	Ballast water reduction	2.75–5 %	[101,197]
	Resistance reduction devices	1–3 %	[264]
Other measures	Carbon capture and storage	37.26–98.7 %	[103,104,123,177,265–269]
	Policy measures	2.46–56.5 %	[33,45,63,148,270–276]

low emissions, whereas those supplied with fossil-based fuels, result in significantly higher CO_2 intensity. In addition, while nuclear energy demonstrates very high potential for CO_2 reduction (with a median value of 100 %) it is less frequently discussed in the literature [185–187], largely due to practical challenges and regulatory constraints that limit its widespread application in the maritime sector.

Within the power and propulsion category, onshore power emerges as the most promising measure in terms of CO_2 emission reduction compared to others. Power system/machinery and hybrid power and propulsion systems also demonstrate a potential, with a narrow interquartile range positioned near the lower end, indicating more consistent but relatively modest reductions in CO_2 emissions. However, their effectiveness is likely to depend on technological maturity and the availability of supporting infrastructure. These systems also offer potential for integration with other decarbonisation measures. Similarly, waste heat recovery shows reliable and consistent data, suggesting it could complement other technologies. Despite its relatively low standalone potential for CO_2 reduction, it remains a valuable component within combined strategies.

Operational measures, such as voyage optimisation and speed optimisation, offer limited to moderate but variable CO_2 reduction potential. These measures are particularly attractive due to their relatively low implementation barriers when compared to alternative fuels or technological approaches. However, the wide disparity in reported emission reduction values warrants further discussion which will be explored in the discussion section.

As can be seen in Fig. 7, hull design improvements, such as air lubrication and resistance reduction devices, typically offer more limited CO_2 emission reductions less than 20 %. However, they can be effectively combined with other measures to enhance overall decarbonisation performance.

As a summary drawn from Fig. 7, Table 1, and the accompanying analysis, the greatest decarbonisation potential lies in fuel switching, particularly to hydrogen or ammonia, as well as in the implementation of carbon capture and storage (CCS). In contrast, operational and design-based strategies offer more modest reductions but remain practical and valuable when integrated with other measures. Despite their relatively low CO_2 reduction potential, several measures demonstrated consistent and robust results across the reviewed studies. Waste heat recovery showed consistent data points, suggesting it is a dependable technology, especially when used in combination with other approaches. Hull design improvements also exhibited limited but steady reductions, typically below 20 %. Although these measures may not achieve high reductions individually, their reliability and ease of integration make them important components of a broader, multi-measure decarbonisation strategy. Moreover, onshore power, power system/machinery, and hybrid power and propulsion systems showed considerable variation in reported CO_2 reduction values. Nevertheless, the results indicated generally consistent performance in achieving moderate emission reductions, depending on the context and the level of technological maturity. It is also worth noting that the underlying reasons for the disparities observed in the data points will be addressed in the discussion section.

Comparison

In this section, the findings of the present study are compared with those reported by [1]. The shaded boxes reproduce the results of Bouman et al., depicting the interquartile range (IQR), against which the values from the present study, shown in solid colours, are compared. Fig. 8 presents this comparison.

As shown in the present study, biofuels exhibit more consistent data points and a slightly higher median than those reported by [1], although there is still substantial overlap. By contrast, LNG follows virtually the same trend in both investigations, which supports its classification as a short-term option for maritime decarbonisation. Alternative energy sources have shown a marked change in their reported ability to reduce CO_2 emissions in recent years, accompanied by greater variability. This is particularly evident for fuel cells, whose upper quartile now approaches 80 %. A similar upward shift is observed for power-and-propulsion technologies and for operational measures, indicating a higher expected potential than that presented by [1]. In

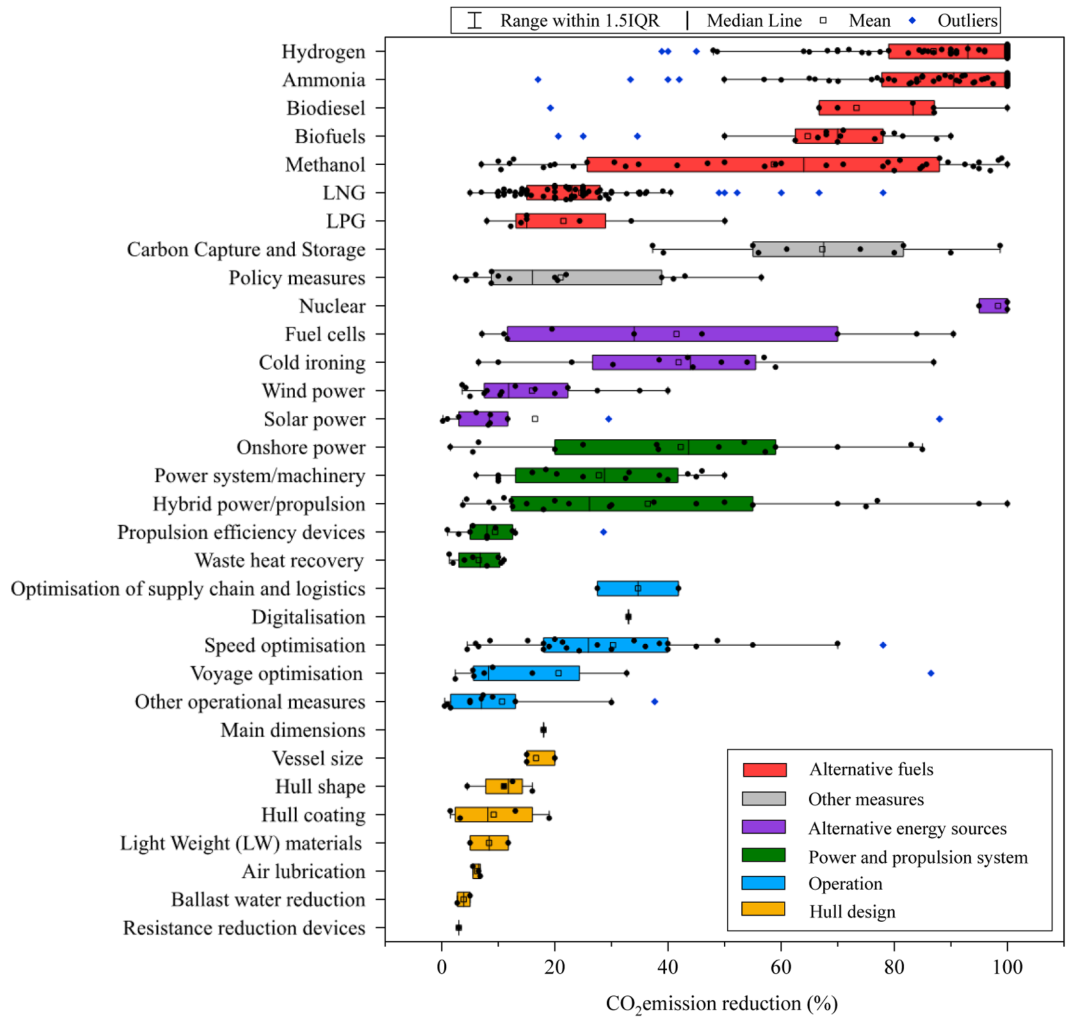


Fig. 7. CO_2 emission reduction potentials of individual measures, grouped into six principal categories and thirty-two distinct measures.

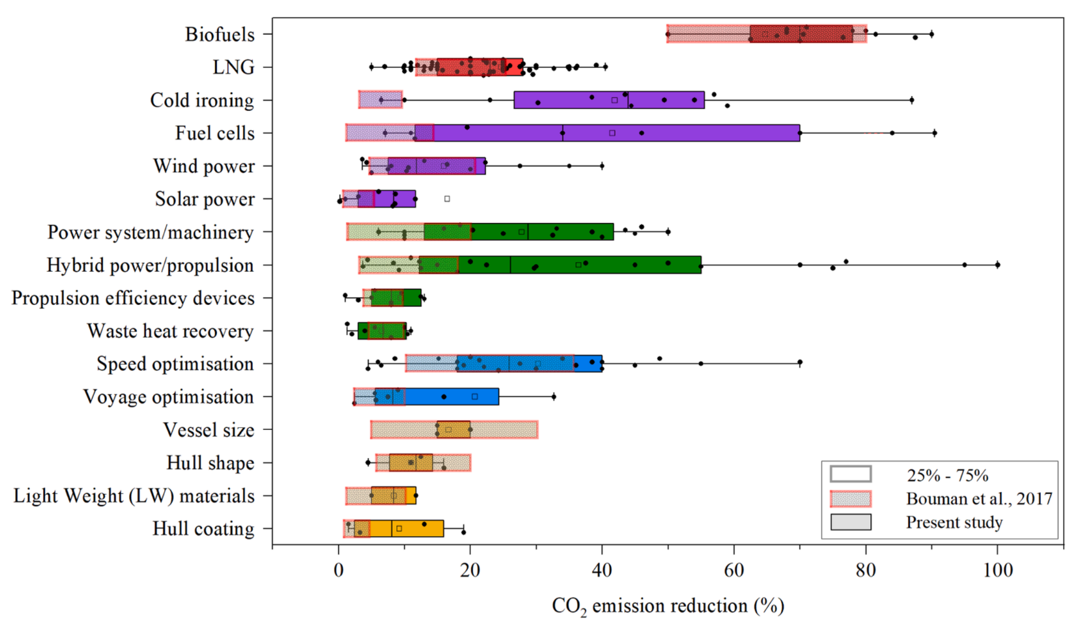


Fig. 8. Comparison of CO_2 emission reduction potentials of individual measures with [1].

contrast, the hull-design category shows substantial overlap between datasets, suggesting little change during the current decade. This stability may reflect the inherently lower mitigation potential of such measures.

Overall, the present study reports broader and generally higher ranges of CO_2 reduction potential across most individual measures. This may stem from updated data sources, recent technological advances, or a wider variety of operational scenarios considered. Notably, cold ironing, fuel cells, hybrid power and propulsion, and voyage optimisation display markedly higher maximum potentials, along with greater dispersion, in the current analysis.

Mapping the measures to the type of vessels

To explore the application of decarbonisation measures across different vessel types, a Sankey diagram was developed using data from studies that reported relevant quantitative results. The diagram illustrates the relationships between individual alternative fuels (selected for their high potential in long-term maritime decarbonisation) and the vessel types with which they are associated (Fig. 9). The thickness of each flow represents the average CO_2 reduction reported in the reviewed studies, which was calculated based on the following formulation

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{2}$$

where $\bar{x}$ is the mean value, x_i represent an individual value, and n is the total number of values. The visualisation clearly indicates that hydrogen and ammonia exhibit high potential for reducing CO_2 emissions across a wide range of vessel types. This finding is based on the number and strength of connections shown in the Sankey diagram, which reveal that these fuels are associated with multiple vessel categories and consistently demonstrate high reported emission-reduction average values in the reviewed studies. Moreover, the potential of methanol appears to vary depending on vessel type: it shows high mitigation potential for tanker ships and bulk carriers, but relatively lower potential for passenger ships, cargo vessels, and fishing vessels. In contrast, although LNG is applied across all vessel types mentioned, its overall decarbonisation potential remains limited. Among the alternative fuels, LPG is mainly associated with fishing vessels, and the reported mitigation values indicate that its role in maritime decarbonisation is still relatively limited.

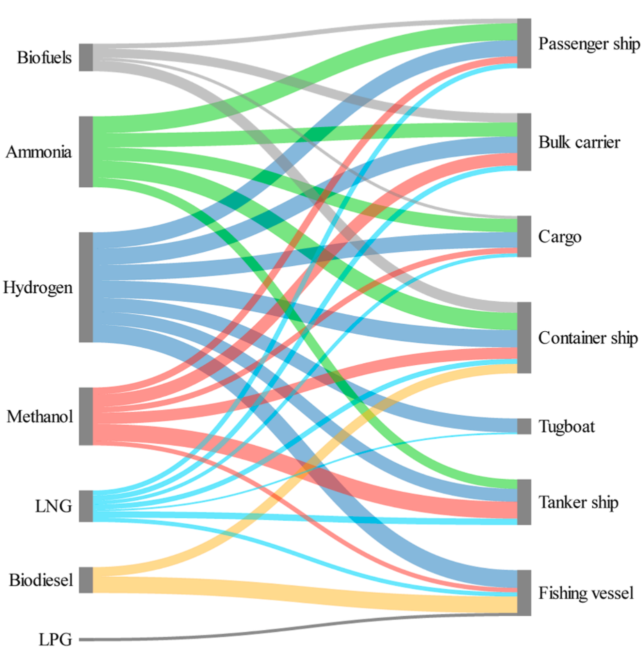


Fig. 9. Mapping of alternative fuels and type of vessels: flow of CO_2 reduction potential from measures to vessel types (flow thickness represents average CO_2 reduction from selected studies).

Fig. 10a presents a heatmap illustrating the CO_2 emission reduction potential of alternative fuels in relation to the corresponding vessel types. In parallel, a heatmap analysis was conducted to quantify the frequency with which each vessel type is referenced across the reviewed literature (Fig. 10b). The heatmap reinforces the findings of the Sankey diagram, highlighting that passenger ships are the most frequently discussed vessel type in the literature. Following this, container ships and bulk carriers are also commonly explored in the context of decarbonisation. These findings suggest that research efforts have predominantly focused on large commercial vessels, which are typically responsible for the majority of CO_2 emissions in the maritime sector. In contrast, vessel types such as tugboats and fishing vessels are mentioned less frequently, indicating possible research gaps or practical challenges in applying alternative fuels to these categories.

Additionally, LNG is the most frequently associated fuel with passenger vessels, reflecting the compatibility of this vessel type with LNG and the availability of supporting infrastructure. Hydrogen and ammonia also emerge as the most frequently discussed fuels for container ships, bulk carriers, and passenger ships. It should also be noted that although some alternative fuels demonstrate high potential for CO_2 emission reduction, these findings are sometimes based on a single study. For instance, the reported potential of hydrogen for fishing vessels originates from just one case study.

Together, these visualisations offer a comprehensive overview of how decarbonisation measures are currently distributed across vessel types in the literature. They also highlight the need for further research into underrepresented segments and the most promising future pathways for decarbonising the global fleet.

To further explore the relationship between individual measures and vessel types, both in terms of CO_2 emission reduction potential and frequency of use, Fig. 11a and 11b present the corresponding results. It is evident that alternative fuels are not only among the most promising measures for maritime decarbonisation but are also the most widely studied. As shown, passenger ships, container ships, and bulk carriers are the most frequently examined vessel types in the literature. In addition to alternative fuels, the most commonly investigated decarbonisation measures include alternative energy sources, power and propulsion system upgrades, and speed and voyage optimisation strategies within the operational category. Furthermore, carbon capture and storage (CCS) demonstrates significant potential for integration with other technologies and measures to reduce CO_2 emissions. It should also be noted that, although nuclear energy shows a high mitigation potential, its adoption remains extremely limited due to policy restrictions and regulatory concerns.

Discussions

Within this section, the potential reasons for the significant disparities in reported CO_2 emission reduction potential values are discussed. The main sub-sections cover: variation in CO_2 emission reduction, temporal alignment of CO_2 reduction measures, and a case study.

Variation in CO_2 emission reduction

The study identifies significant variation in the reported CO_2 emission reduction potentials of maritime decarbonisation technologies. This variation is mainly attributable to methodological differences, especially in the system boundaries and underlying assumptions used in different studies. From each main category defined, measures with significant disparity were selected to investigate the key reasons behind the wide range of CO_2 reduction values. In this study, a measure was selected for further assessment if the interquartile range (IQR) exceeded 20 %.

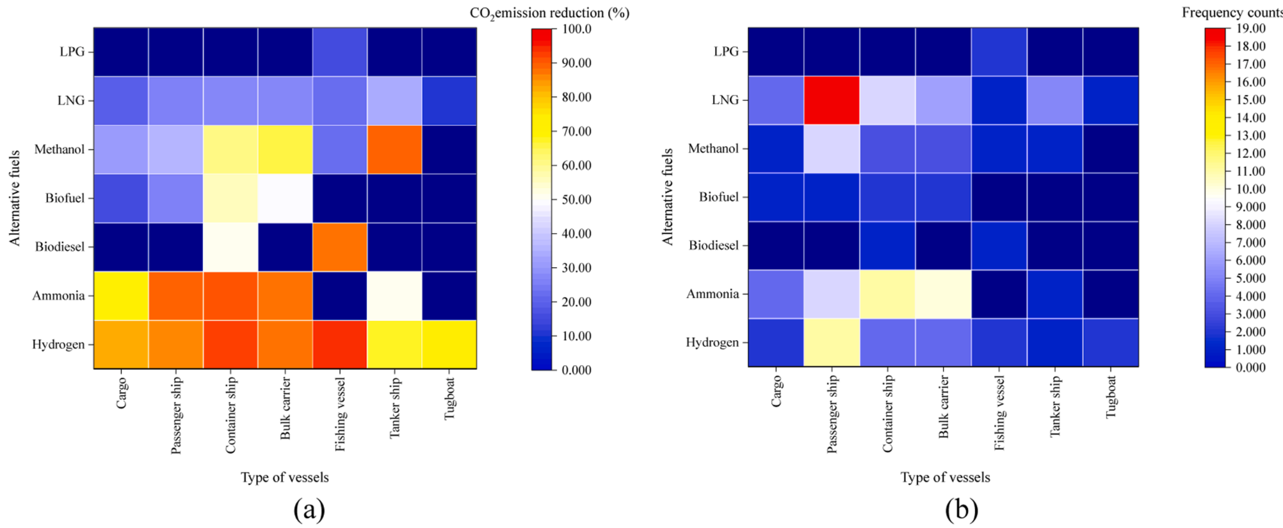


Fig. 10. Mapping of alternative fuels and type of vessels: (a) Heatmap of CO_2 emission reduction related to the alternative fuels; (b) frequency counts in the selected studies.

In this context, hydrogen, ammonia, methanol, biodiesel from alternative fuels, hybrid power/propulsion, onshore power, and power system/machinery from the power and propulsion system, speed optimisation and voyage optimisation from operational measures, and fuel cells and cold ironing from alternative energy sources were selected. Carbon capture and storage (CCS) was also assessed as a measure since it meets this criterion. It should be stated that the hull design was excluded from this section due to its relatively low variability in data points of CO_2 emission reduction.

Alternative fuels category

A review of the literature reveals several reasons behind the wide disparity in reported CO_2 emission reductions from the use of alternative fuels in maritime transport [277]. For the alternative fuels that met the policy criteria for further evaluation, 58 studies were identified for hydrogen, 54 for ammonia, 38 for methanol, and 8 for biodiesel.

According to the findings, one of the primary factors is the variation in system boundaries used in life cycle assessment (LCA). Studies that focus solely on the tank-to-wake (TTW) phase tend to report higher reductions than those adopting broader well-to-wake (WTW) perspectives.

For example, [278] reported a 40 % CO_2 reduction, adapting a WTW life cycle approach to assess CO_2 emissions in maritime transport, accounting for all major stages from fuel origin to end use. In contrast, [47] presented a significantly higher reduction potential up to 100 % for large bulk carriers using green hydrogen, where the TTW CO_2 emissions are considered. As another example, despite employing green hydrogen, a maximum reduction of 78.8 % was reported in [48]. This value is based on a WTW life cycle analysis that includes emissions from the manufacturing of fuel cell stacks and storage systems, energy use in electrolysis (which may still partially depend on grid electricity), and emissions from hydrogen liquefaction, compression, and long-distance transport. Only the TTW phase, during which the fuel cell emits no CO_2, is considered truly zero-emission. According to [94], they also estimated a slightly lower maximum emission reduction of 93 % for hydrogen carriers. Like what stated in [48], they included upstream emissions in their analysis, noting that while the TTW stage may be zero-carbon, the WTW life cycle still involves emissions from infrastructure, electrolysis (powered partly by the grid), and the energy-intensive processes of hydrogen handling. For other alternative fuels such as ammonia, methanol, biofuels, and biodiesel, the boundary of the life cycle assessment also has a similar effect.

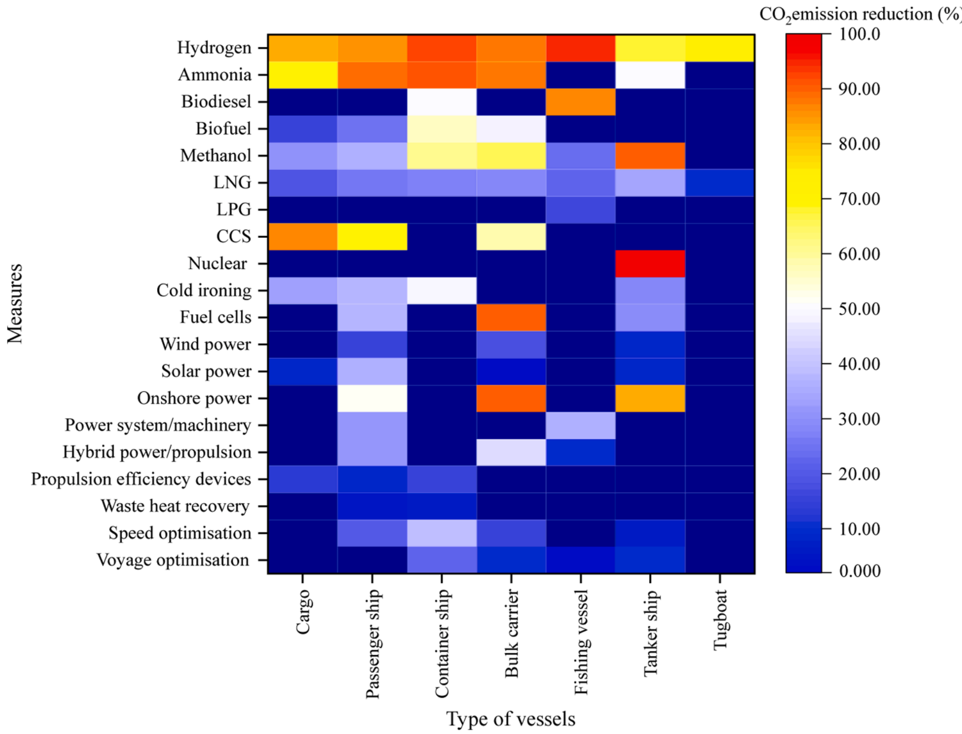
As another reason, the source of fuel is another critical variable [279]; for instance, while green hydrogen produced via renewable-powered electrolysis can lead to near-zero emissions [47], hydrogen derived from fossil fuels or grid electricity results in significantly higher life-cycle emissions. For instance, in the study by [99], rather than modelling ammonia as a fully green fuel, the authors based their analysis on production via electrolysis powered by a mixed electricity grid that still includes a substantial share of fossil energy (40 % CO_2 emission reduction).

Furthermore, blending ratios and operational configurations play a role. For instance, some studies assess scenarios where alternative fuel only partially replaces conventional fuels, naturally yielding lower emission reductions compared to full substitution. In the context of dual-fuel configurations analysed in the study, [278], assumed ships derive 50 % of their energy requirements from a clean alternative fuel, either hydrogen or ammonia, and the remaining 50 % from conventional heavy fuel oil. They assessed energy contributions based on lower heating values with 40 % CO_2 emission reduction. Based on [60], they estimated hydrogen-related CO_2 emission reductions in the range of 30–66 % for tugboats, attributing this to the limited blending ratio of hydrogen with conventional fuels, specifically a 30 % hydrogen blend with natural gas, highlighting that only partial displacement of fossil fuels is achieved in this application [63] proposed a blend of methanol with marine diesel oil in a dual-fuel methanol, diesel engine, observing a reduction of 18 % in CO_2 emissions [280] used methanol in dual-fuel engines, which require a pilot injection of marine diesel oil (MDO) to sustain combustion, achieving a 7 % CO_2 emission reduction [281] reported CO_2 emission reductions ranging from 1−100 % for biofuels, depending on the proportion of renewable source replacement. According to their study, using a linear assumption, a complete substitution of conventional fuel with a green alternative would result in a full reduction of CO_2 emissions. Likewise, replacing 50 % of the fuel with a green option would allow half of all voyages to be powered by low-carbon fuels, leading to a 50 % cut in CO_2 emissions.

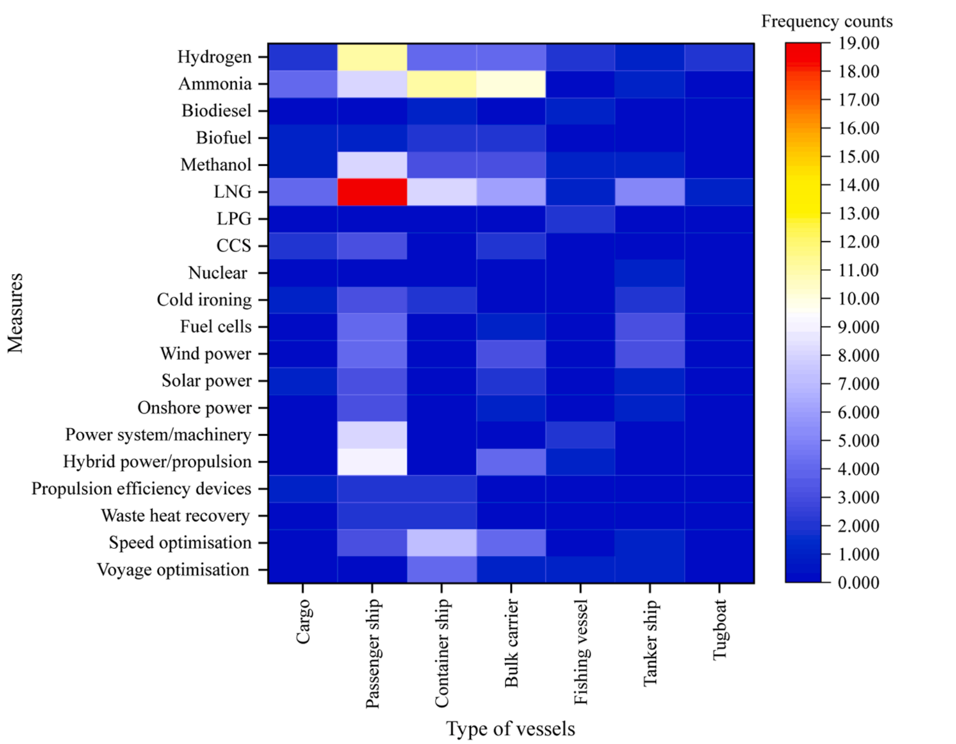
In summary, while alternative fuel has been identified as a promising measure with high potential for CO_2 emission reduction in maritime applications, the extent of reduction is highly dependent on the scope of life-cycle analysis, the fuel source (green or blended), especially if the alternative fuel is not fully renewable, and the vessel's design and operational strategy. Studies employing full WTW assessments yield more conservative but realistic figures, highlighting the importance of comprehensive system boundaries when evaluating alternative fuels.

Carbon capture and storage (CCS)

For the Carbon Capture and Storage (CCS) studies that met the



(a)



(b)

Fig. 11. Mapping of individual measures to vessel types: (a) based on CO_2 emission reduction potential; (b) based on frequency of occurrence in the selected studies.

selection criteria for further assessment, 10 studies were identified. According to the findings, one factor influencing CO_2 emission reduction values is whether the CCS system is applied to an existing ship (as a retrofit) or integrated into a newbuild configuration. In other words, capture efficiency varies significantly depending on the ship type and system configuration, leading to different ranges of potential reduction outcomes. For example, [265] reported that retrofitting an existing ship with carbon capture and storage (CCS) technology achieved an estimated CO_2 emission avoidance rate of around 70 %, while integrating CCS into a newbuild vessel configuration aimed for a higher rate of approximately 90 %. The lower effectiveness in retrofit cases is primarily due to challenges such as limited space availability, as well as the additional power and heat requirements of the system. In particular, accommodating CO_2 storage without compromising cargo capacity presents a significant constraint in existing vessels.

Moreover, the type of fuel used plays a crucial role. In the context of newbuilds, an important consideration is the selection of the most suitable engine to pair with the CCS system. For instance, liquefied natural gas (LNG) is stored at extremely low temperatures (−162 °C), and the abundant cold energy available on board can be utilised to support the CCS system, for example, by liquefying captured CO_2 for storage. The better the alignment between the ship's existing conditions and the CCS system requirements, the lower the additional fuel consumption.

Furthermore, the use of renewable fuels can inherently result in lower CO_2 emissions. For instance, in [269], it was examined the potential of integrating CCS with bio-methanol, achieving up to a 90 % reduction in CO_2 emissions.

The configuration of the CCS system, whether pre-combustion or post-combustion, also affects emission reduction outcomes. Post-combustion capture can achieve high efficiency (up to 90 %) due to the ample heat supply from the engine, which supports the thermal demands of the capture process. In contrast, pre-combustion capture is typically more limited, achieving around 37 % efficiency, as the fuel reformer requires higher temperatures than are generally available [269].

Alternative energy sources

Nine studies on fuel cells and fourteen on cold ironing met the selection criteria for further evaluation. These studies reveal a similar trend of variability in the estimated CO_2 emission reduction potential of alternative energy sources in maritime transport. As with alternative fuels, the range of reported reductions stems from differences in system configuration, fuel origin, fuel cell technology, and the boundaries used in life cycle assessments. The performance of alternative energy sources is also influenced by whether the system is installed as a supplementary or primary power source, and whether it is paired with energy recovery systems such as batteries or waste heat recovery units.

For example, in [192], it is reported a relatively modest CO_2 reductions of 5.4–8.8 % for a crude oil tanker equipped with a solid oxide fuel cell (SOFC). These gains are largely attributed to the higher efficiency of the SOFC compared to traditional diesel generators, which are then able to operate closer to their optimal load. In contrast, [191] present a more substantial reduction of 46 % in annual CO_2 emissions for LNG tankers, achieved by replacing auxiliary diesel generators with a 3MW proton exchange membrane fuel cell (PEMFC) powered by hydrogen. In [193], it is reported even greater reductions, in the range of 88.93–91.79 %, for bulk carriers equipped with hybrid systems that integrate SOFC or PEMFC units, batteries, and waste-heat recovery systems. Their WTW analysis captures emissions from hydrogen production through to onboard use, underscoring the compounded benefit of using green fuels alongside onboard efficiency-enhancing technologies. Moreover, [136] reported 23.4−75.5 % CO_2 emission reduction by the combination of cold ironing with speed reduction. They also stated concluded that the improvement would be small when comparing the total emissions intensity of the service (considering the full voyage), with short shipping.

Other studies provide additional insights into the role of fuel origin and technology selection. In [69], it is estimated an 84 % CO_2 reduction for a Ro-Ro passenger ferry powered by green ammonia and fuel cells. Their findings underscore that only fuels derived from renewable or low-carbon sources (green or blue hydrogen/ammonia) yield meaningful environmental benefits; in contrast, fuel cells running on grey hydrogen or grey ammonia fail to offer significant CO_2 savings. Moreover, their analysis shows that SOFC systems outperform PEMFCs in most configurations, owing to their higher electrical efficiency and fuel flexibility. The poorest performance is associated with PEMFCs operating on grey ammonia, due to the combination of high upstream emissions and the PEMFC's requirement for pure hydrogen feedstock [199] reported 87 % CO_2 emission reduction employing cold ironing by means of renewable energy sources (RES) installation.

At the lower end of the spectrum, [189] reported a CO_2 emission reduction of just 11.64 % for a ferry powered by low-temperature PEMFCs (LT-PEMFCs), based on a full LCA using the Carbon Footprint Design Index (CFDI). This relatively limited reduction is primarily due to upstream emissions from hydrogen production, compression, and liquefaction, especially when the electricity used for electrolysis is not entirely renewable. Additionally, LT-PEMFCs operate at lower temperatures, making them unsuitable for integration with onboard heat recovery systems, thereby missing opportunities for additional efficiency gains that would be available with high-temperature SOFC configurations. Moreover, whether cold ironing is either replacing with the main engine or auxiliary diesel engine might affect the CO_2 emission reduction value as well [198] reported 38.44 % CO_2 emission reductio replacing ferry auxiliary diesel engines with shore-to-ship, cold ironing power.

Taken together, these studies highlight the complex interplay of factors that govern the effectiveness of alternative energy systems in reducing CO_2 emissions. For example, while fuel cells offer clear potential for decarbonising maritime transport, especially when integrated into hybrid systems and powered by green fuels, the actual impact depends heavily on fuel sourcing, system architecture, and operational context. As with hydrogen, comprehensive well-to-wake assessments that consider all upstream and onboard processes are critical to accurately quantify the environmental benefits of fuel cell technologies and to avoid overestimating their contribution based on overly narrow system boundaries.

Power and propulsion system

In the category of power and propulsion systems, onshore power, power system/machinery, and hybrid power and propulsion systems were selected for further evaluation, with 15, 16, and 22 studies identified respectively. As with alternative fuels and energy sources, a key factor influencing the reported figures is the degree of system electrification and the source of the primary fuel [220], for instance, reported relatively modest CO_2 emission reductions of 1.4–6 % for a hybrid system combining solid oxide fuel cells (SOFCs), photovoltaic (PV) panels, wind turbines, and energy storage. Despite incorporating renewable components, the model prioritised economic efficiency over maximum decarbonisation, resulting in limited emissions savings. The dominant contribution of SOFCs, powered by fuel-based energy sources (e.g., hydrogen, methanol, or natural gas), and the relatively small output from renewables constrained the overall decarbonisation impact. Moreover, [188] reported 1−20 % CO_2 emission reduction as the SOFCs are integrated as auxiliary power units rather than replacing the main propulsion system. Additionally, their study did not involve full electrification of the ship, unlike others that assume battery-electric or fully fuel-cell-powered configurations. By contrast, [62] report much more substantial reductions across several demonstration projects. Hybrid diesel-battery systems achieved reductions of up to 70 %, while fully battery-electric ferries and hydrogen fuel cell-powered ferries reached over 95 % CO_2 reduction, primarily due to the complete elimination of onboard combustion. In addition, a hybrid LNG-electric cruise ship configuration yielded a 30 % reduction, while an ammonia-fuelled tanker, designed for zero-emission operation, was projected to eliminate greenhouse gas emissions entirely. These results demonstrate that the extent of combustion-free operation and the carbon intensity of the energy source critically influence total reductions.

In [232], a wide range of outcomes based on hybrid architecture and operational context is further illustrated. Their modelling results show that electric-hydrogen and electric-ammonia hybrid systems can eliminate CO_2 emissions entirely, while diesel-electric and electric-mechanic hybrid configurations yield more variable reductions ranging from 5 % to 60 %. Several variables explain this disparity. Vessel size and operational profile are critical: ocean-going ships tend to achieve lower reductions (5–15 %) due to limited access to charging infrastructure, whereas smaller coastal vessels benefit more from electric-only operation. The design and flexibility of the hybrid configuration also matter. For example, electric-mechanic systems, which allow switching between electric-only, diesel, or combined drive modes, enable more efficient operation at low speeds and thus higher emission savings. The induced emissions depend on the energy mixture that the port relies on, and this varies regionally and internationally. While some ports have invested in small power units or renewable energy sources (RES) for their own needs, the majority would rely on the grid to meet the energy demands from hoteling vessels. Furthermore, as stated in [210], 48−70 % CO_2 emission reduction depends on visiting fleet, berthing durations, and baseline operating pattern of calling ships. Lastly, assumptions about shore power availability and constant energy demand across configurations influence the modelled outcomes. Coastal vessels are typically assumed to have more frequent access to shore charging, which increases electric propulsion share and associated CO_2 reductions.

Operation

Speed optimisation with 24 studies met the policy, is another widely studied operational measure for reducing CO_2 emissions in maritime transport with a broad range of reported outcomes. This variation stems from several technical, operational, and methodological factors. Fundamentally, the relationship between ship speed and power demand is cubic in nature meaning that small reductions in speed can yield disproportionately large decreases in fuel consumption and emissions. For instance, [46] highlight that even modest slow steaming can lead to significant CO_2 savings due to the nonlinear scaling of power with speed ($P \propto v^3$). However, the extent of the speed reduction itself critically influences the magnitude of the benefit. Small decreases in vessel speed often produce limited CO_2 savings, while more extensive deceleration strategies can substantially enhance emission reductions.

Operational context further determines the effectiveness of speed optimisation. Interventions limited to port approaches or constrained zones yield different results compared to speed reductions applied across entire voyages. Studies combining slow-steaming with the use of onshore (cold ironing) power report exceptionally high reductions, reaching up to 71–91 % CO_2 savings depending on vessel type and conditions. The frequency of port calls also matters; vessels that revisit ports more often have greater opportunities to benefit from reduced-speed approaches and shore-based electricity.

Vessel-specific characteristics, including hull form, design speed, and propulsion efficiency, play a key role as well. Slender, high-speed ships respond more favourably to speed reductions than the ships with bluff hulls. In one port-area case study, the same speed restriction produced only a 14 % CO_2 reduction for a bulk carrier, compared to 41 % for a container ship. Methodological choices also shape outcomes: some studies are based on idealised simulations, while others rely on real-world operational data; some include only TTW emissions, while others adopt a WTW perspective.

Economic modelling assumptions introduce yet another layer of variation. Studies that consider time-loss penalties, opportunity costs, or fuel pricing typically report more conservative savings, whereas environmentally focused assessments project the highest potential reductions. In [249], this variability, estimating CO_2 reductions ranging from 1.52 % to 42.63 % across different speed reduction scenarios (5 %, 10 %, 15 %, and 20 %) has been confirmed. These findings reinforce that while speed optimisation offers a highly flexible and low-cost emissions reduction strategy, its actual effectiveness depends on how extensively and consistently it is applied, as well as on vessel design, operational routines, and policy enforcement.

To better understand the reasons behind the wide disparity in reported CO_2 abatement potentials, Table 2 summarises the key factors identified in the literature as sources of variability for alternative fuels (hydrogen and ammonia, the two leading measures for cutting CO_2 emissions) and carbon capture and storage, both considered as high-impact measures. These factors include vessel type, partial-blend scenarios, operational conditions, integration with other measures, application as a retrofit to an existing ship or as part of a newbuild configuration, the energy source used in fuel production, production pathways, feedstock origin, analytical assumptions (e.g. well-to-wake versus tank-to-wake boundaries), and transport requirements for fuels or feedstocks. Although additional reasons may also contribute to variations in reported CO_2 reduction values, the factors presented here are based on drivers identified in the literature reviewed in this study. They are structured to clarify why abatement ranges differ so widely across studies and to highlight the importance of standardising assumptions in future analyses. The classification of impact is based on how numerically significant and consistently reported each factor is in the literature.

Temporal alignment of CO_2 reduction measures

While the preceding discussion has examined a range of individual CO_2 reduction measures, their comparative effectiveness also depends on when and how they can be implemented. Technological maturity, infrastructure readiness, cost, and regulatory frameworks all influence their deployment timelines. To synthesise these findings within a strategic context, it is useful to align them with the International Maritime Organization's (IMO) decarbonisation roadmap. A temporal framework that categorises measures into short-, mid-, and long-term horizons offers a structured lens through which to guide implementation priorities, policy development, and investment planning.

Short term

In the short term (up to 2030), measures that are operationally focused and require minimal retrofitting offer the most immediate impact. Among these, speed optimisation stands out, with reported CO_2 reduction potential ranging from 1.5 % to over 90 %, depending on vessel type, voyage scope, and extent of speed reduction. This makes it particularly suitable for bulk carriers and container ships, where operational flexibility allows for speed adjustments without compromising schedules. However, its applicability is more limited for time-sensitive trades such as passenger ferries. Other short-term strategies include

Table 2

Factors contributing to variability in reported CO_2 abatement potentials for alternative fuels (hydrogen, ammonia) and carbon capture and storage (CCS).

Measures	Factors									
	Type of vessel	Partial-blend scenarios	Operational factors	Integrated with other measures	Retrofit/ newbuild integration	Energy sources	Fuel production pathway	Fuel origin	Analytical approach	Fuel/ feedstock transport
Alternative fuels (hydrogen and ammonia)	++	++	++	++	++	+++	+++	+++	+++	++
Carbon capture and storage	++	–	++	++	+++	++	–	–	++	+

Note: (Impact: + = low, ++ = moderate, +++ = high); – indicates not applicable or rarely considered in the reviewed studies.

weather routing, hull maintenance (e.g., hull coatings), and improved capacity utilisation. While their individual impacts may be more modest, these measures are relatively low-cost and widely deployable. Cold ironing (shore power) is another short-term solution, especially for vessels with prolonged port stays, such as cruise ships and Ro-Pax ferries. Its effectiveness, however, is contingent on the carbon intensity of the port's electricity grid.

Mid-term

Mid-term measures (2030–2040) involve greater technological integration and investment, often through retrofitting or inclusion in newbuilds. Hybrid propulsion systems combining batteries with internal combustion engines are one such example, especially in ferries and coastal vessels. Fuel cells, particularly when powered by green hydrogen or ammonia, demonstrate high potential in this period, depending on system configuration and fuel source. Waste heat recovery systems, another mid-term option, can achieve reductions of up to 20 % by capturing and repurposing engine exhaust energy. liquefied natural gas (LNG) continues to be explored as a transitional fuel, offering moderate CO_2 reductions. However, the risk of methane slips and infrastructure lock-in raises concerns about its long-term climate effectiveness, though its current availability and global infrastructure support its role in the mid-term strategy. Biofuels represent another mid-term measure with highly variable, yet potentially high, CO_2 reduction potential. Some studies report reductions of up to 100 %, particularly for fuels derived from waste biomass. However, the environmental efficacy of biofuels depends greatly on feedstock origin, land use change, and life cycle emissions. Moreover, widespread adoption is constrained by limited availability, competition with other sectors, and uncertain regulatory frameworks for sustainability certification. Nevertheless, blended use of biofuels in existing engines may provide a transitional pathway for emission reductions in certain fleet segments. Another promising measure in the medium term is carbon capture and storage (CCS), which entails the extraction of carbon dioxide directly from ship exhaust systems, followed by onboard containment and subsequent offloading at port facilities for permanent storage or industrial reuse. According to the data extracted from the literature, CCS has been predominantly developed for land-based power plants, recent initiatives have begun to explore its application aboard large ocean-going vessels (more than 220 m length), particularly those that are expected to rely on fossil fuels such as heavy fuel oil or liquefied natural gas in the foreseeable future. Technologically, marine CCS systems have demonstrated capture rates of 12.5−98 %. However, the operational viability of such systems remains constrained by several factors. The energy demand associated with the capture process can partially offset the emissions savings, and the requirement for onboard CO_2 storage presents challenges related to volume, mass, and crew safety. Moreover, the lack of established infrastructure at ports for receiving, transporting, and sequestering captured carbon represents a significant barrier to widespread implementation. Despite these limitations, CCS holds potential as a transitional solution for vessel types or trades where alternative fuels and full electrification are presently infeasible. It may be particularly relevant for long-haul vessels operating on fixed schedules, where emissions intensity is high, and port connectivity is consistent.

Long term

In the long term (post-2040), achieving deep decarbonisation will require a systemic transition toward zero-emission fuels and renewable energy. Hydrogen and ammonia, when produced from renewable electricity, are considered key candidates for zero-carbon shipping. Hydrogen offers near-complete CO_2 reduction potential but presents challenges in storage, volatility, and energy density. Ammonia, while easier to store, raises safety concerns due to its toxicity. Both fuels require significant advances in production infrastructure and onboard handling technology. Renewable energy sources, such as wind-assisted propulsion and solar panels, can supplement main engines and contribute additional CO_2 savings, typically in the range of 4–35 % for wind and 0.2–30 % for solar, depending on vessel size and voyage conditions. Though not sufficient as standalone solutions for most large vessels, they represent viable complementary technologies in a diversified decarbonisation strategy. Nonetheless, these options are constrained by issues of availability, cost, and technological maturity. Although fuels such as hydrogen and ammonia show strong potential for long-term sustainability, their widespread adoption will depend on continued development and significant investment.

Case study

Domestic maritime activities in the UK were estimated to have produced approximately 8 million tonnes of CO_2 equivalent ($MtCO_2e$) on a Well-to-Wake basis, and around 6.9 $MtCO_2e$ on a Tank-to-Wake basis [37]. This represented roughly 5.5 % of the UK's total domestic transport emissions, exceeding the combined emissions from buses (3.0 $MtCO_2e$), rail (1.9 $MtCO_2e$), and domestic aviation (1.4 $MtCO_2e$) [37]. In the context of maritime decarbonisation research, England emerges as a central and influential hub within the global co-authorship network (see Fig. A.2.). Represented by one of the largest nodes, England demonstrates a high Total Link Strength, indicating extensive international collaborations with key research nations across Europe, Asia, and Oceania. Notably, Scotland also features prominently in the network, reinforcing the broader contribution of the United Kingdom to this critical field. The strong presence of both England and Scotland highlights the UK's collective leadership in maritime decarbonisation, serving as a bridge between diverse global research communities. This underscores the UK's strategic role in advancing low-carbon innovations, policy development, and cross-border knowledge exchange essential for driving sustainable transformation in the maritime sector.

To illustrate how the reviewed decarbonisation measures could be applied in practice, a case study was considered based on a passenger ship (cruise ship) voyage between Southampton (UK) and Stavanger and Haugesund (Norway). Passenger ships are not only the most commonly studied vessel type in the literature, but also one of the largest contributors to CO_2 emissions in the UK [3]. The length of the ship is about 350 m, with 180,000 Gross Tonnage (GT, a dimensionless index of a ship's internal volume). The route covers approximately 660 (NM), equivalent to about 1223 (km) [72]. Based on voyage data, a baseline CO_2 emission of 211,200 t CO_2 per year was used as a reference for comparison. Four decarbonisation measures were applied sequentially: Ammonia fuel, speed optimisation, fuel cells, and waste heat recovery. The reduction potential for each measure was calculated based on median values identified through the systematic review. Ammonia fuel (90.5 % reduction potential) was assumed to replace 50 % of the conventional fuel. A 50 % replacement of conventional marine fuel with ammonia was assumed to reflect a realistic near- to mid-term transition scenario. Full substitution of fossil fuels with ammonia remains technically challenging due to infrastructure limitations, safety concerns, engine compatibility, high costs, and regulatory constraints. Therefore, the 50 % assumption serves as a conservative yet practical estimate, capturing partial integration within existing vessel systems while acknowledging the progressive nature of fuel-switching strategies. Speed optimisation (25.9 % reduction), fuel cells (reduction 34 %), and waste heat recovery (6.75 %) offer operational, alternative energy source, and power and propulsion system improvements, respectively. These measures have been selected not only for their potential in port development and vessel compatibility, but also for the possibility of future fuel conversion to ammonia. Moreover, the selection aimed to incorporate measures from as many main categories as possible. Rather than summing individual CO_2 reduction potentials, this study applies mitigation effects sequentially to avoid overestimation due to overlapping impacts [282]. This approach provides a more realistic estimate of combined decarbonisation potential across multiple measures. The total emissions remaining after implementing a combination of measures is given by

$$E_{\text{residual}} = E_0 \prod_{i=1}^{n} (1 - R_i) \tag{3}$$

where, E_{residual} is the residual CO_2 emissions after all measures have been applied, E_0 is the baseline CO_2 emissions for the reference scenario, R_i is the reduction potential of the i th measure, expressed as a proportion, n is the total number of measures applied, and $\prod$ denotes the product operator. As a result, total CO_2 emissions were reduced from 211,200 tonnes per year to approximately 52,734 tonnes per year, representing an overall reduction of around 75.1 %. The corresponding results are presented in Figure 15.

Building on the findings of this study, the combined decarbonisation potential of maritime measures can be estimated through a compounding-effect approach (Eq. (3)). This formulation shows that each measure applies to the remaining emissions, preventing double counting and enabling a more accurate calculation of the total emission reduction. In addition, optimisation could be a key factor in achieving cost-effective and promising decarbonisation outcomes across different timeframes in maritime transport. This may involve not only the analysis of data points [283,284] but also the optimisation and assessment of applied measures such as voyage planning, speed reduction, dimensional improvements, and partial blending using advanced mathematical methods [285–287].

Finally, it is crucial to conduct uncertainty, and sensitivity analyses due to the varying assumptions considered in life cycle assessments of measures and technologies across the maritime sector [288,289].

In summary, this study provides a novel and comprehensive synthesis of maritime decarbonisation strategies through an integrated bibliometric, network-mapping, and systematic review. By mapping the intellectual landscape, quantifying mitigation ranges, and revealing methodological inconsistencies, the review offers researchers, industry stakeholders, and regulators an evidence-based framework for navigating the sector's transition to net zero. It bridges a critical gap between academic inquiry and practical application by listing all identified measures alongside their corresponding CO_2 mitigation potential. These insights are expected to support data-driven and context-appropriate decision-making, thereby contributing to international decarbonisation goals.

Moreover, the implementation of alternative fuels requires addressing technical feasibility, infrastructure availability, production scalability, and energy-system integration. For example, recent studies have shown that a highly decarbonised energy system will depend heavily on integrated alternative fuels infrastructure and renewable power generation, reinforcing the need to align maritime fuel transitions with regional energy-planning strategies. While the growing number of ships capable of operating on alternative fuels is an encouraging step, this does not automatically translate into proportional emissions reductions due to persistent challenges of cost, availability, and technological readiness. Among the measures examined, hybrid strategies that combine energy-efficiency technologies with lower-carbon fuels appear to offer the most practical route. Overall, the findings presented here are expected to support decision-makers in identifying effective, context-appropriate strategies for international decarbonisation efforts and ensuring long-term maritime sustainability. The discussion of the underlying causes of variability in decarbonisation potential, grounded in life-cycle assessment perspectives, may also inform other sectors. Finally, the systematic methodology used to identify, categorise, and evaluate decarbonisation measures can be adapted to other hard-to-abate industries such as aviation, road freight, or heavy manufacturing. The classification framework (technical, operational, fuel-based, etc.) and the mapping of measures to different asset types (e.g., vessel types) can be generalised to other transport and energy systems to assess technology applicability across heterogeneous fleets Fig 12.

Conclusion

Based on findings in this study, green hydrogen, ammonia, biofuels, and nuclear energy each demonstrate potential CO_2 reductions of up to

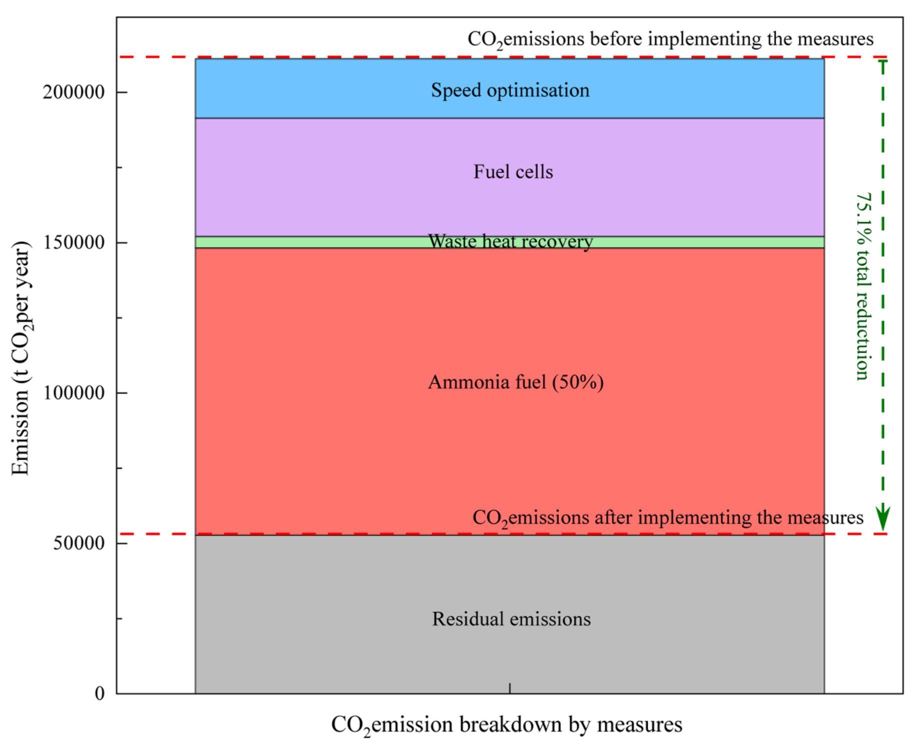


Fig. 12. Decarbonisation potential assessment: Southampton (UK) - Stavanger and Haugesund (Norway) shipping route.

100 %, making them particularly promising for achieving net-zero targets, although the range of decarbonisation achieved is wide. Methanol has most potential but also carries most uncertainty. CCS has significant potential: generally, less than alternative fuels. However, there is wide variability, and care would be needed to ensure that the particular CCS strategy chosen is delivering at the upper end of the range discovered.

Alternative energy sources cover a very wide range of potential decarbonisation impacts. Nuclear is notable for an extremely high decarbonisation potential with apparently high certainty, but care should be taken because there have been relatively few published studies in this area from which to draw data.

Fuel cells have moderate potential. However, it should be remembered that in many cases fuel cells will be deployed with alternative fuels, in which case the combined impact could be very high. Cold ironing has moderate potential, with high sensitivity to the carbon intensity of the electricity delivered to the vessel e.g. studies which assume 100 % "green" electricity will have higher impact than those using "grid mix". Wind has low potential; solar very low. However, it should be noted that these can be combined with cold ironing or in dual-fuel modes with alternative fuels, increasing the combined impact to high/very-high.

Power and propulsion system has been considered as a separate category here from alternative energy sources to focus on the physical modifications that could be made to a vessel while still using traditional liquid or gaseous fuels. Those that involve electrical fuel sources are moderately effective (though that will vary with electricity carbon intensity) and hybrid system/machinery modifications can have a moderate impact. However, both efficiency and waste heat recovery have very low levels of decarbonisation potential.

Operational measures relating to supply chains, logistics, voyages and speed have low to moderate potential and there is very limited data to be confident on digitalisation impacts.

Hull design measures including vessel size have low to very low impact with a high degree of confidence.

A key take-away from this work is that none of the measures or groups of measures are likely to deliver required levels of decarbonisation on their own. A combination of measures is very likely to be needed in order to achieve significant maritime emission reductions. Among the options considered, vessel-specific measures appear to offer limited value except in cases of fleet renewal, while speed optimisation stands out as the most promising operational intervention. Onshore power and cold ironing can play an important supporting role, though their viability may be constrained in areas with limited grid capacity. Renewable options such as solar and wind are unlikely to warrant significant investment at present. Nuclear and carbon capture technologies, meanwhile, show long-term promise but require considerable further development. There remains an urgent need to better understand the factors behind variations in methanol performance.

Therefore, in the near term, fuel switching is likely to be the most impactful measure, with biofuels offering a drop-in solution that is easiest to implement quickly. In the medium term, hybrid options combining shore-side power or cold-ironing with fuel switching could be effective, though these would entail significant cost implications and thus require careful techno-economic consideration. Looking further ahead, nuclear, hydrogen, and ammonia are likely to form the backbone of long-term decarbonisation strategies. While vessel design improvements can deliver incremental benefits, they are best pursued as part of replacement cycles rather than as standalone investments.

It is anticipated these findings will support policy makers in reaching data-informed decisions for maritime decarbonisation strategies.

CRediT authorship contribution statement

Sina Fadaie: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Patricia Thornley:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Jean-Baptiste Souppez:** Writing – review & editing, Supervision, Project administration, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This work was supported by the UK Department for Transport, as part of the UK Shipping Office for Reducing Emissions (UK SHORE) Programme and the UK Engineering and Physical Sciences Research Council (EPSRC) [grant number EP/Y024605/1].

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.adapen.2025.100255.

Appendix A. Bibliometric and network analysis

In this section, the results of the bibliometric and network analyses are presented. These include keyword co-occurrence analysis to identify the principal research themes, country linkage analysis to explore collaboration networks among researchers and institutions, and an examination of time trends in research activity, all related to the decarbonisation of the maritime sector.

Keyword co-occurrence analysis

The keyword co-occurrence analysis produced a visualisation that revealed distinct clusters of frequently co-occurring terms, highlighting dominant key themes such as decarbonisation, alternative fuels, hydrogen, ammonia, and shipping. Fig. A.1, VOSviewer term-co-occurrence map, provides a comprehensive visualisation of the principal research themes and their interrelations within the clean maritime domain. Each circle represents a key term extracted from the analysed literature; its size is proportional to the term's frequency, while the thickness of connecting lines indicates the strength of co-occurrence between terms. Coloured clusters group together terms that frequently appear in concert, signalling distinct but interlinked thematic areas. The number of co-occurrences of keywords is calculated by [290]

$$S_{ij} = \frac{C_{ij}}{\sqrt{C_i \cdot C_j}}, \tag{A.1}$$

where C_{ij} is the number of co-occurrences of keywords i and j, and C_i , C_j are their respective total occurrences.

At the heart of the map lies the term "decarbonisation", underscoring its pivotal role as the overarching objective of clean maritime studies. Closely linked are terms such as "alternative fuels", "sustainability" and "marine transportation", indicating that strategies to reduce the sector's carbon footprint are primarily pursued through the exploration and implementation of novel energy carriers and sustainable operational practices.

Surrounding the central cluster are several fuel-specific communities of research: Green Cluster highlights broad discussions on "alternative fuels", "maritime transport", "IMO" regulations, "carbon capture" and "green shipping", pointing to system-level policy and regulatory frameworks. Yellow Cluster encapsulates investigations into hydrogen production, storage, fuel-cell propulsion and their integration into shipping, reflecting the intense interest in hydrogen as a zero-carbon marine energy vector. Red Cluster ("LNG", "natural gas", "GHG emissions") groups studies examining liquefied natural gas's role as a transitional fuel, its greenhouse-gas emissions profile and compatibility with existing marine engines. Purple/Blue Cluster ("ammonia", "methanol", "LCA") brings together research on next-generation energy carriers such as ammonia and methanol, alongside "life cycle assessment" (LCA) methodologies that critically evaluate their full environmental impacts from production to end-use.

The dense web of interconnecting lines emphasises that these thematic areas are not pursued in isolation. For instance, LCA links the ammonia/methanol cluster with both hydrogen and LNG clusters, signifying that comparative environmental assessments are essential across all fuel options. Similarly, "cold ironing" appears at the interface between decarbonisation and alternative fuels, illustrating how shore-power supply as alternative energy source measures complement fuel switching Fig A.1

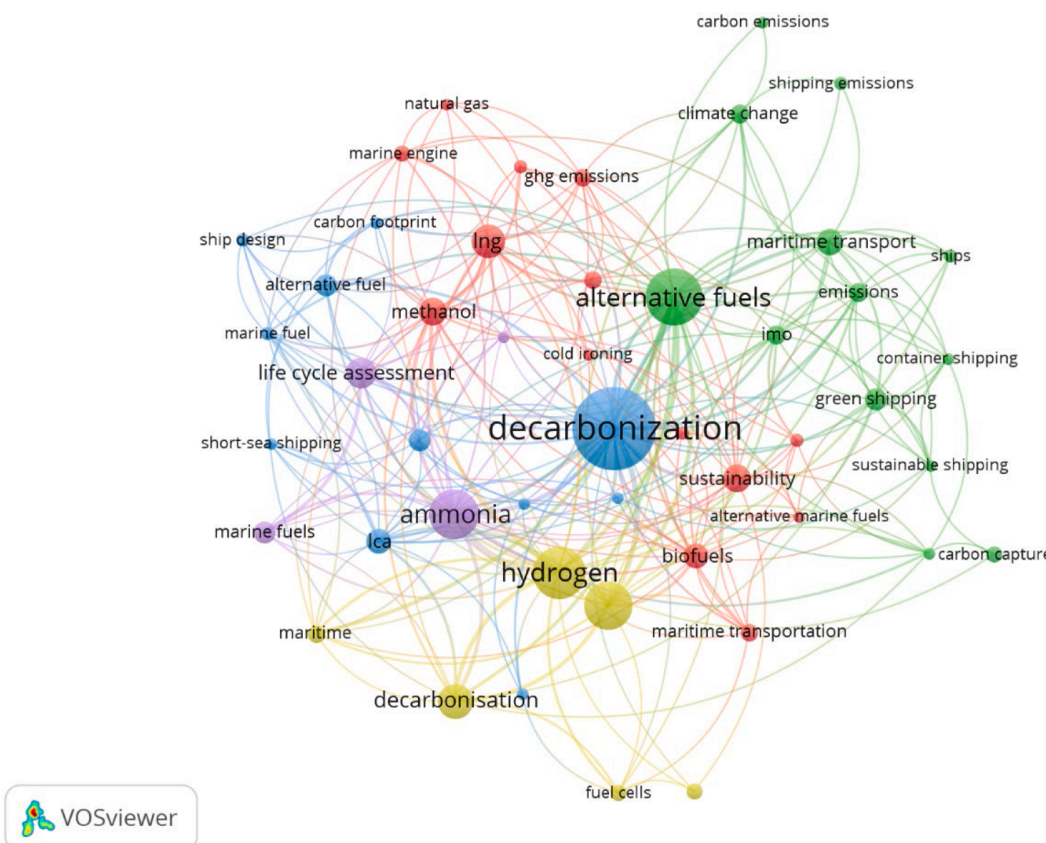

Fig A.1. Keyword co-occurrence analysis: principal research themes and their interrelations within the clean maritime domain.

Countries/regions co-occurrence analysis

A co-authorship analysis was conducted to explore collaboration networks among researchers and institutions. This analysis offered valuable insights into the geographical and institutional distribution of expertise within the field of maritime decarbonisation. At this stage, the total strength of co-authorship (a measure of the number and intensity of collaborative publications between countries) was considered, and countries with the highest total link strength were identified. As shown in Fig. A.2, the findings indicate that England, and China (shown as peoples r China in Fig. A.2) are the most prominent contributors in this research area Fig A.2

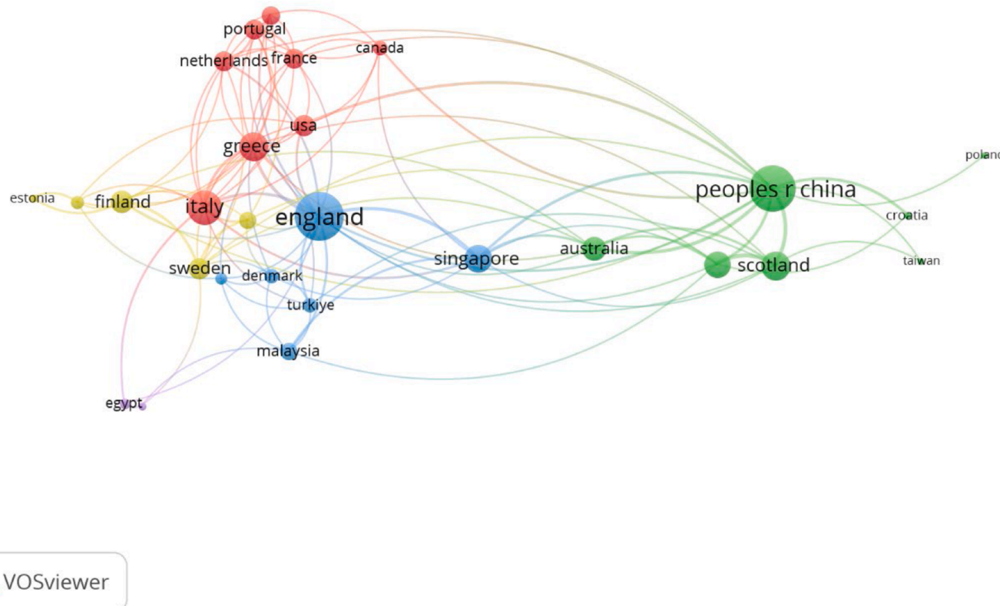

Fig A.2. Country linkages: the geographical and institutional distribution of expertise within the field of maritime decarbonisation.

Time trends

While the previous analyses shed light on the structure and collaboration patterns of the field, the overlay visualisation offers insight into its chronological development (seeFig. A.3). By assigning colours based on the average publication year of each keyword, the map reveals how research themes in maritime decarbonisation have evolved over time. Earlier studies, represented by darker shades such as blue, primarily focused on maritime transport, life cycle assessment, and biofuels. These were followed by a growing body of research centred on decarbonisation strategies and alternative fuels, particularly ammonia and hydrogen. In more recent years, as indicated by lighter colours such as yellow, the literature has increasingly turned towards advanced approaches including optimisation techniques and carbon capture solutions. This temporal shift underscores the field's movement from foundational assessments toward innovative, technology-driven strategies for achieving maritime sustainability Fig A.3

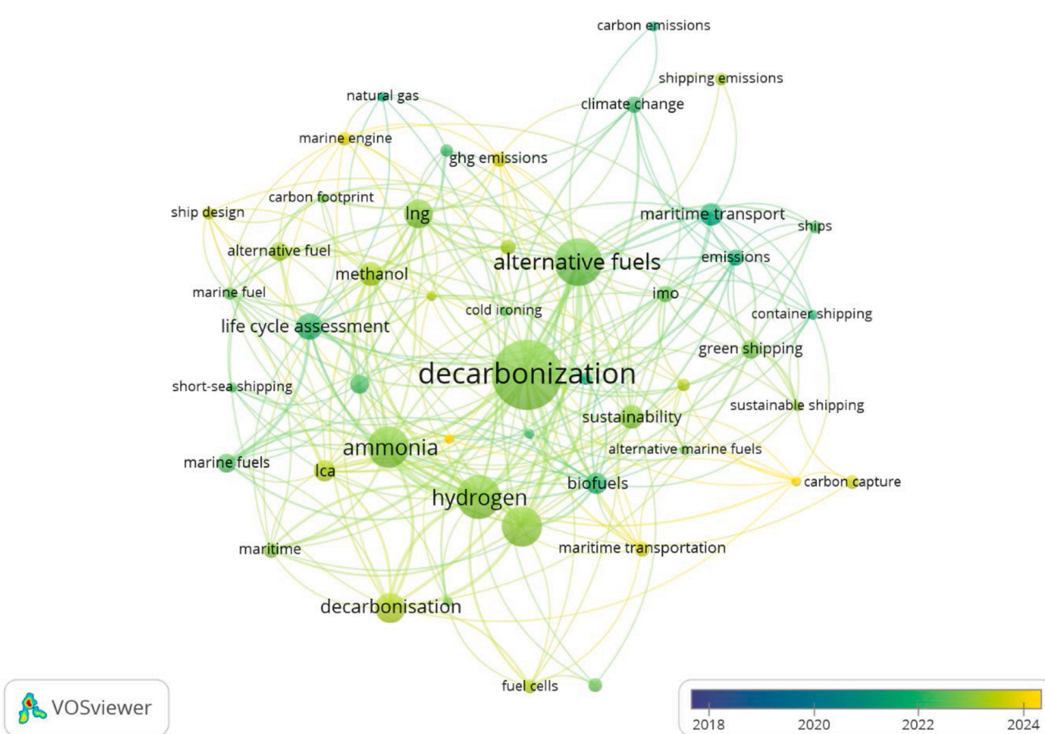

Fig A.3. Time trends in maritime decarbonisation research, based on selected articles and the average publication year of each keyword.

These findings not only reflect the maturation of the maritime decarbonisation research field but also signal a growing emphasis on innovation and cross-disciplinary collaboration in addressing its complex challenges. The progression from foundational topics such as maritime transport and life cycle assessment to more advanced areas, including alternative fuels, optimisation, and carbon capture, demonstrates a clear shift towards technological solutions. Among the emerging themes, ammonia and hydrogen appear particularly promising as alternative fuels, while optimisation methods and carbon capture technologies offer significant potential for enhancing operational efficiency and emissions reduction. Collectively, these developments suggest a dynamic and increasingly solution-oriented research landscape, paving the way for more effective strategies to support the maritime sector's transition towards sustainability.

Declaration of AI use

During the preparation of this work, AI based platforms have been used in order to check the grammar and writing style. After using, the authors reviewed and edited the content as needed and take responsibility for the content of the published article.

Data availability

Data will be made available on request.

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