Sustainable
Energy & Fuels

ROYAL SOCIETY
OF CHEMISTRY

PAPER

View Article Online
View Journal | View Issue

Cite this: *Sustainable Energy Fuels*, 2025, **9**, 6506

Quantitative sustainability assessment of e-fuels for maritime transport

Francesco Zanobetti,[abc] Andrea Bernardi,[ac] Gianmaria Pio,[b] Diego Freire Ordóñez,[ac] David Danaci,[acd] Benoît Chachuat,[*ac] Valerio Cozzani[b] and Nilay Shah[ac]

Reducing the carbon intensity of maritime transport is essential to achieve global emission reduction targets. Electro-fuels (e-fuels) represent a promising cleaner alternative to conventional marine fossil fuels, offering potential lifecycle greenhouse gas reductions when synthesised from renewable electricity and low-carbon feedstocks. While techno-economic and environmental assessments of e-fuels exist, their broader sustainability implications, spanning technological, economic, environmental and safety factors together, remain largely unexplored. This study introduces a quantitative framework to assess the sustainability of ship fuel systems that integrates key performance indicators (KPIs) across these four areas. A case study is conducted to compare the sustainability of carbon-based e-fuels (e-methanol and e-diesel) and carbon-free e-fuels (hydrogen and ammonia) against marine diesel oil (MDO) under multiple decision-making perspectives. The robustness of the overall sustainability-based ranking of fuel alternatives, as derived under each perspective, against uncertainties in the individual KPIs is confirmed *via* sensitivity analysis. Environmental and safety aspects are found to be critical in comparing the sustainability of alternative fuels. Both e-methanol and e-diesel achieve higher overall sustainability than MDO, irrespective of the decision-making perspective. Ammonia and hydrogen are hindered by safety concerns in the short term, although ammonia also shows long-term potential for sustainable shipping subject to appropriate risk management and the implementation of inherently safer design measures. Overall, the proposed framework enables a comprehensive assessment of alternative fuel systems for cleaner shipping, guiding future sustainability-driven policy and technology development.

Received 12th June 2025
Accepted 10th October 2025

DOI: 10.1039/d5se00821b

rsc.li/sustainable-energy

1 Introduction

There is a growing consensus on the urgency of decarbonising maritime transport, which alone accounts for approximately 3% of global CO_2 emissions.[1] These emissions are projected to continue rising, with an average annual increase of nearly 1.5% over the past decade.[2] In response, the International Maritime Organization (IMO) outlined a climate strategy in 2018 targeting a 50% reduction in shipping-related greenhouse gas (GHG) emissions by 2050 compared to 2008 levels.[3] This ambition was recently reinforced through a commitment to reach net-zero GHG emissions from shipping by around 2050, with binding reduction checkpoints set for 2030 and 2040.[4,5] To date, most decarbonisation efforts have focused on improving the design and operational features of ships.[6] However, these strategies primarily enhance the energy efficiency and, alone, will be insufficient to meet the set net-zero targets by 2050. The widespread adoption of clean marine fuels to complement these energy efficiency measures will be essential, therefore, for transitioning towards a carbon-neutral maritime industry.[7,8] Liquefied natural gas (LNG) can reduce shipping-related carbon emissions by about 30% compared to conventional marine fuels,[9] but methane slip limits its overall decarbonisation potential.[10] Onboard carbon capture and storage (OCCS) could also mitigate residual emissions, but its implementation on ships remains technologically challenging, reinforcing the need for cleaner fuels at scale.[11] Of the alternatives, biofuels have been investigated as potential low-carbon solutions, particularly when produced from sustainable feedstocks.[12–14] Their large-scale deployment in shipping, however, is hindered by limited sustainable biomass availability, land-use requirements, regional supply restrictions, and indirect sustainability concerns such as biodiversity loss.[14–17] Additionally, the scale of marine fuel demand makes it unlikely that biofuels will be able to provide a long-term sector-wide solution without competing with other sectors, including food production, road transport,

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[a] *The Sargent Centre for Process Systems Engineering, Imperial College London, London, SW7 2AZ, UK. E-mail: b.chachuat@imperial.ac.uk*

[b] *LISES – Laboratory of Industrial Safety and Environmental Sustainability, Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Via Terracini 28, Bologna, 40131, Italy*

[c] *Department of Chemical Engineering, Imperial College London, London, SW7 2AZ, UK*

[d] *I-X Centre for AI In Science, Imperial College London, White City Campus, 84 Wood Lane, London, W12 0BZ, UK*

aviation, and bioenergy for power generation or BECCS.[15–17] For these reasons, international decarbonisation roadmaps increasingly consider biofuels as temporary measures, while highlighting synthetic electro-fuels (e-fuels) as scalable and long-term solutions for maritime decarbonisation.[16,18–20]

Accordingly, attention has shifted to e-fuels, produced from renewable electricity and broadly distinguished into two categories: carbon-free and carbon-based.[16,21–23] Carbon-free e-fuels, such as hydrogen and ammonia, lead to zero direct CO_2 emissions during onboard use.[24–26] However, their overall climate benefits depend critically on the carbon intensity of upstream production pathways.[27,28] Carbon-based e-fuels, on the other hand, represent synthetic alternatives that can be seamlessly integrated into existing ships and bunkering infrastructure.[21,29] These can be produced using CO_2 from direct air capture (DAC), avoiding the sustainability concerns associated with biomass-derived sources and offering a scalable, long-term alternative to biofuels.[22,30,31] In particular, e-diesel, produced *via* Fischer–Tropsch synthesis,[32] and e-methanol are gaining momentum as low-carbon substitutes for conventional marine diesel oil (MDO).[21,33] Various industry-led studies point to e-methanol as a leading candidate among synthetic fuels, supported by ongoing pilot projects and early commercial deployment in shipping.[34,35]

Table 1 presents a comparative overview of the prominent e-fuels considered for maritime applications, outlining their feedstocks, production pathways, development stage, and key adoption challenges.

Previous studies on marine e-fuels have focused primarily on their economic and environmental performance.[29,33,45] Techno-economic analyses indicate that e-fuels can substantially reduce GHG emissions, but bridging the cost gap with conventional marine diesel requires carbon pricing or comparable policy measures.[46–49] Environmental assessments have largely relied on life-cycle assessment (LCA) methodologies, which may adopt different system boundaries: fuel production and transportation (well-to-tank), onboard use (tank-to-wake), or the full fuel value-chain from production to end-use (well-to-wake).[21] Recent LCA studies[21,27,50–52] have adopted the well-to-wake perspective for marine fuels, providing valuable insights into the life-cycle environmental impacts of marine fuels across different production pathways. For instance, Guyon *et al.*[50] assessed methanol and ammonia as marine fuels, considering several synthesis pathways for each across diverse regions and projected timelines through 2050. E-methanol and green ammonia, produced from renewable electricity, emerged as promising options for low-carbon shipping, with projected well-to-wake GHG emissions around 5 g CO_2 per MJ by 2050, approximately 94% lower than those of conventional MDO. Wang *et al.*[27] similarly showed that green ammonia can achieve substantially lower life-cycle emissions than fossil marine fuels, whereas brown ammonia from unabated fossil pathways was found to perform worse, underscoring the critical role of production routes. However, LCA results remain highly sensitive to methodological choices, including system boundaries and allocation methods, as well as the quality and availability of input data.[53,54] Often, LCA studies rely on incomplete or

Table 1 Comparative overview of the prominent e-fuels for maritime applications

e-Fuel type	Feedstocks	Production pathways	Development stage	Adoption challenges
Carbon-free				
Hydrogen	Water (*via* electrolysis, powered by renewable electricity)[36]	Electrolysis[36,37]	Pilot- and demonstration-scale projects (*e.g.* ferries, auxiliary power systems)[35,38] [TRL 6–7]	Very low volumetric energy density; cryogenic or high-pressure storage requirements; lack of port and bunkering infrastructure[38,39]
Ammonia	Renewable H_2 + N_2 (from air separation)[36]	Electrolysis + Haber–Bosch synthesis[16,36]	Several large-scale projects announced; first maritime pilots under development[35,40] [TRL 5–6]	High toxicity and handling risks; limited maturity of engines and fuel cells; infrastructure adaptation required[40,41]
Carbon-based				
e-Methanol	Renewable H_2 + CO_2 (from DAC or point-source capture)[36]	Electrolysis + CO_2 hydrogenation[16,36]	Early commercial deployment (containerships in operation; initial bunkering facilities available)[34,42] [TRL 7–8]	Lower energy density than conventional marine fuels; requirement for dedicated storage and distribution systems; dependence on large-scale renewable H_2 and sustainable CO_2 supply[34,42]
e-Diesel	Renewable H_2 + CO_2 (from DAC or point-source capture)[36]	Electrolysis + Fischer–Tropsch synthesis[16,36]	Feasibility and concept studies[43] [TRL 4–5]	High production cost; energy- and capital-intensive synthesis; limited demonstration at scale[29,44]

inaccurate mass flow balances, while environmental impact assessment databases may contain outdated information or build upon data from similar (but not identical) technologies, introducing further uncertainties.[53,55] Most LCA studies furthermore prioritise global warming potential, while neglecting other impact categories and overlooking potential burden-shifting, which can introduce biases.[33] The International Council on Clean Transportation (ICCT) has also emphasised the need for harmonised well-to-wake methodologies in the maritime sector to reduce inconsistencies.[56]

Beyond environmental considerations, cleaner maritime transportation must also meet key technological, economic, and social requirements within a holistic sustainability framework.[9,57] Existing LCA approaches primarily address the environmental pillar of sustainability, overlooking trade-offs with other key criteria such as economic viability and social impacts.[58] Multi-criteria decision analysis (MCDA) has been applied to shipping fuels to account for such trade-offs, but often relies on subjective scoring and weighting of criteria, which can bias the results.[59–62] Instead, a comprehensive sustainability assessment framework requires the definition and integration of multi-criteria metrics that objectively quantify impacts across all relevant sustainability dimensions, using rigorous system-level data (*e.g.*, energy and material flows) as inputs.[63,64] Recent studies have adopted such quantitative frameworks for evaluating the sustainability of maritime technologies, based on the definition and aggregation of indices encompassing techno-economic, environmental and safety-related social aspects.[9,25,57] However, the environmental dimension in these frameworks has so far been restricted to operational (tank-to-wake) emissions only, introducing a bias in the evaluation of the overall carbon footprint of e-fuels. In addition, they rely on midpoint indicators and do not extend to endpoint assessments, thus failing to quantify potential damages to human health and ecosystems.

From a social sustainability viewpoint, safety is a fundamental prerequisite for the widespread adoption of innovative, cleaner technologies.[65,66] Flammability and toxicity are among the main safety concerns associated with the onboard use of low-carbon marine fuels.[67] For instance, methanol may pose additional risks compared to conventional diesel, due to its lower flash point, increasing fire risks, and its acute toxicity upon exposure.[68] Ammonia also presents toxicity hazards that require robust risk mitigation measures, whereas hydrogen has distinct safety challenges pertaining to its extreme flammability.[35,69,70] Addressing such risks early in the development of new technologies is critical, as this is when the potential for modifications is the greatest.[71] In this context, inherent safety assessment tools (ISATs) are increasingly recognised for their ability to support early-stage risk evaluation,[72] and for their suitability for integration in sustainability assessment frameworks.[66] Despite its relevance, the safety aspect of marine e-fuels remains largely unexplored, which prevents a full understanding of the risks they present for large-scale implementation.

The novelty of this study, therefore, lies in the development of a sustainability assessment framework for e-fuel systems that addresses the identified research gaps by: (i) employing a set of complementary key performance indicators (KPIs) to quantify performance across the four pillars of sustainability; (ii) incorporating a well-to-wake environmental assessment that extends beyond global warming potential to include multiple midpoint and endpoint categories; (iii) embedding safety considerations within the social dimension through inherent safety indicators; and (iv) applying a robust multi-criteria decision-making procedure to integrate the KPIs into a unified sustainability evaluation. The framework is then applied to evaluate the sustainability of e-fuels for shipping and to benchmark their performance against conventional marine diesel oil (MDO).

The remainder of this paper is structured as follows: Section 2 presents the methodology, including the KPI definition to evaluate e-fuel systems across multiple sustainability dimensions and the procedure for combining these KPIs into a single-value index to assess overall sustainability. Section 3 applies the methodology to a case study comparing ship fuel systems based on carbon-free and carbon-based e-fuels with conventional MDO. Section 4 discusses the results, including a Monte Carlo-based sensitivity analysis for testing the robustness of the methodology against uncertainties in input data. Finally, conclusions are drawn in Section 5.

2 Methodology

2.1 Overview

The proposed framework for quantitative sustainability assessment of alternative marine fuels relies on the integration of multiple KPIs addressing the four key pillars of sustainability: technological, economic, environmental and societal performance.[73]

A multi-criteria decision-making (MCDM) approach is adopted to integrate the KPIs into an overall sustainability assessment framework. MCDM provides a structured procedure for combining indicators of different natures and scales,

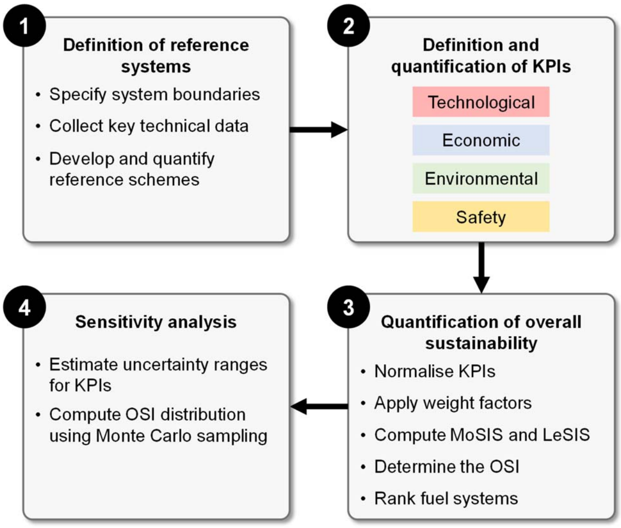

Fig. 1 Flowchart of the quantitative sustainability assessment framework.

ensuring that trade-offs across sustainability dimensions are systematically addressed.[74] It can also incorporate weighting schemes to reflect alternative decision-making perspectives[75] and can account for uncertainty in data quality and modelling assumptions through sensitivity analyses of the weights and indicators.[76,77]

Fig. 1 illustrates the workflow of the quantitative sustainability assessment. Step 1 defines a reference system for fuel storage and utilisation for each fuel candidate. This includes a process scheme specifying the operating conditions of onboard storage and processing units, along with the associated energy and material flow balances. Step 2 defines a set of KPIs to assess the performance of the reference systems across the four pillars of sustainability. Step 3 combines the KPIs into a single-value metric to quantify overall sustainability. For this purpose, the TOPSIS method[78] is employed as the MCDM technique (Section 2.4), which involves normalisation of KPIs, weighting based on decision-making priorities, and comparison with ideal benchmark systems (MoSIS and LeSIS). This yields a dimensionless index (OSI) for each reference system, enabling a consistent and comparative assessment of their overall sustainability performance. Lastly, Step 4 ranks the reference systems by their overall sustainability level and conducts a sensitivity analysis to assess the ranking's robustness against uncertainty in the various KPIs. Each of these steps is further detailed in the following sections.

2.2 Definition of reference systems

A reference system is defined for each fuel candidate to accurately model its onboard storage and utilisation. This requires setting the system boundary appropriately to establish a common design basis for the analysis. Here, the system boundary includes onboard fuel storage, the process units for conditioning the fuel prior to use (*e.g.*, heat exchangers, intermediate process vessels, pumps, and compressors), and the final utilisation technology (*e.g.*, combustion engine and fuel cell). Data on fuel storage conditions, key process operating parameters, and utilisation efficiency need to be collected at this stage for each reference system.

The common design basis is defined by the time distribution of ship power demand over a sea voyage, as per Zanobetti *et al.*;[25] refer to Section 3 for details on the common design basis adopted in the case study. The conceptual design of the reference ship fuel systems is developed on this basis by solving material and energy balances and sizing storage and processing units for each fuel candidate. Specifically, the storage units are sized to accommodate the fuel inventory required to meet the energy requirements of the ship, determined by integrating the power demand over the duration of a sea voyage. The peak fuel consumption rate during a voyage is used to conservatively design the process units.

2.3 Definition and quantification of KPIs

Specific KPIs are introduced in this step to quantify the performance of each fuel system across the four pillars of sustainability. An important consideration here is the ability to quantify each pillar by a single metric that can be computed using preliminary technical system data only. Moreover, tailored system boundaries can be applied to each KPI. Extending all indicators across the entire fuel life cycle, covering production, transport, and use, would introduce considerable complexity and require data that are often unavailable for emerging e-fuel technologies, where information is typically limited to conceptual or early design stages. To address this, the framework adjusts the scope of each indicator to capture the most relevant impacts, with certain KPIs evaluated only within selected stages of the life cycle. This ensures that the framework remains comprehensive yet practical.

The selected technological, economic, environmental, and safety-related social KPIs are detailed below, along with their respective calculation procedures. The specific boundaries applied in the analysis for each KPI are further described in Section 3, within the case study.

2.3.1 Technological. The technological feasibility of cleaner marine fuels is influenced by several factors, including the maturity of fuel utilisation technologies, the complexity of their integration into ships, and the associated maintenance requirements.[79] Here, the onboard volume requirement is used as a technological index, TI, to quantify the complexity involved in integrating cleaner technologies into ships.[25,57] Under the system boundary outlined in Section 2.2, the main contributors to onboard volumetric occupation are the storage tanks, while the process units and the fuel utilisation system are neglected due to their much lower space requirements relative to storage tanks and the lack of detailed geometric data available at early design stages.[25,57] Under this assumption, the technological index TI is given by the fuel storage volume:

$$\mathrm{TI} = \frac{\sum_j P_j \cdot t_j}{\rho \cdot \eta \cdot \mathrm{LHV}} \tag{1}$$

P_j and t_j represent the average power demand and time duration of the j-th shipping operational mode (*e.g.*, berthing, manoeuvring, and navigation), respectively. LHV denotes the lower heating value of the fuel candidate. The fuel density, ρ, is based on the onboard storage conditions (*i.e.*, temperature, pressure, and physical state). The energy conversion efficiency during fuel utilisation, η, is derived from literature data on fuel utilisation technologies in shipping, including internal combustion engines (*e.g.*, Iannaccone *et al.*;[9] Korberg *et al.*[29]) and fuel cells (*e.g.*, Ballard Power;[80] Tronstad *et al.*[81]). Overall, higher values of TI correspond to an increased onboard volume requirement for fuel system integration, thereby reflecting lower technological feasibility.

2.3.2 Economic. The economic index, EcI, to evaluate the cost performance of a fuel system is based on the net present cost.[82] Future revenues are excluded to enable a more consistent economic comparison across fuel technologies, as revenue projections are sensitive to external factors such as market dynamics and policy changes, making them difficult to quantify in early-stage assessments.[83] The EcI calculation therefore includes only capital expenditures (CAPEX), incurred at the beginning of the technology lifetime, and annual operating expenditures (OPEX), assumed to remain constant throughout a ship's lifetime. Under these assumptions, the EcI describes the total lifecycle cost of fuel system implementation, accounting for the time value of money:

$$\mathrm{EcI} = \mathrm{CAPEX} + \sum_{t=1}^{T} \frac{\mathrm{OPEX}}{(1+i)^t} \tag{2}$$

CAPEX and OPEX are the initial capital expenditures and the annual operating expenditures, respectively. The economic lifetime of the ship fuel system, T, and the discount rate, i, are set to 25 years and 8%, respectively.[9] The input cost items used to evaluate the CAPEX and OPEX for each fuel system are detailed in the SI (Section S2). All costs are expressed in 2023 currency, with costs originally reported for a different year adjusted for inflation according to trends in the European area, as per Thaler *et al.*[45] Overall, higher values of EcI correspond to higher net present costs, thereby indicating lower economic viability.

2.3.3 Environmental. The environmental index, EnvI, is derived from the environmental impact assessment methodology ReCiPe 2016.[84,85] This enables the calculation of a single aggregated environmental impact index by using pollutant emissions as inputs and applying specific midpoint, endpoint, and normalisation factors. Fig. 2 presents a flowchart of the EnvI calculation. Compared to the original ReCiPe 2016 methodology, which includes 17 midpoint categories and 3 endpoint categories,[84,85] EnvI only accounts for selected environmental impact categories linked to relevant pollutant emissions, namely CO_2, CH_4, NO_x, SO_x and PM. This selection is based on typical compositions of exhaust gases from shipping.[9,25] As illustrated in the flowchart, shipping-related pollution induces various midpoint environmental impacts, leading to damage across two primary endpoint targets: human health and ecosystems. The normalisation and aggregation of these endpoint damages ultimately produce a single aggregated environmental performance index. In line with common practice in environmental assessments of marine fuels,[86] impacts from capital goods and infrastructure, such as shipbuilding and propulsion-system manufacturing, are not considered, as their contribution is typically minor compared with the fuel life-cycle stages.[87]

The calculation of shipping-related pollutant emissions is based on an activity-based approach:[88]

$$E_i = e_i \sum_j \frac{P_j \cdot t_j}{\eta} \tag{3}$$

where E_i and e_i represent the total annual emissions (g per year) and the emission factor (g $\mathrm{kWh_{fuel}}^{-1}$) for the i-th pollutant, respectively. The evaluation of e_i follows the framework proposed by Law *et al.* for marine fuels.[89] For GHG pollutants (CO_2 and CH_4), well-to-wake emission factors are used to enable a comprehensive assessment of a fuel's carbon footprint from production to onboard use. For non-GHG pollutants (NO_x, SO_x, and PM), onboard use emission factors are applied as a proxy for well-to-wake values. This approach is consistent with IMO emission control area (ECA) regulations[10,89] and is further supported by life-cycle studies indicating that non-GHG emissions are generally dominated by onboard fuel use.[27,90,91] Refer to the SI (Section S3) for further details on the evaluation of pollutant emission factors for each fuel system.

The environmental impact assessment adopts a hierarchist perspective over a medium-term time frame of 100 years, as recommended by Pedersen *et al.*,[92] and uses characterisation factors from ReCiPe 2016 [84,85] to estimate the midpoint and endpoint environmental impacts (Fig. 2). The endpoint impacts are expressed in units of disability-adjusted life years (DALY) for damages to human health and species·year for damages to

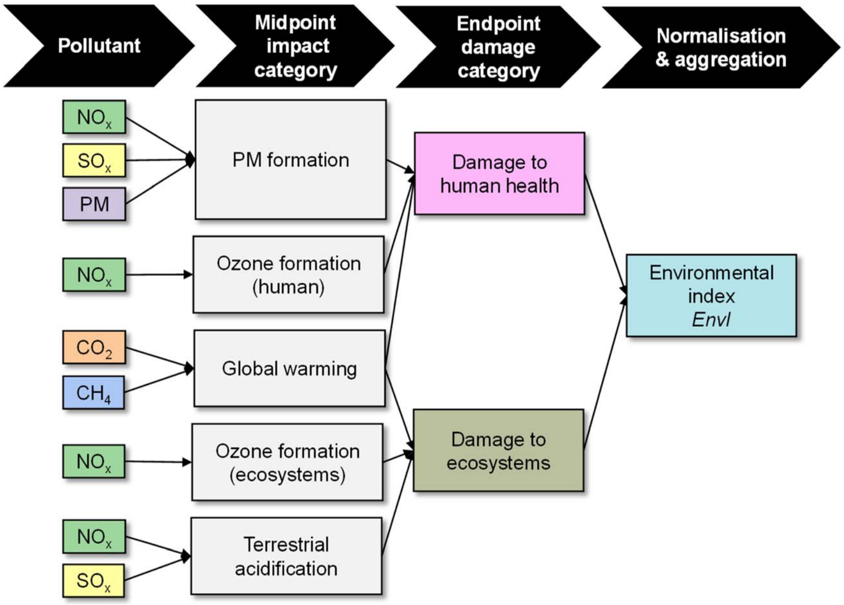

Fig. 2 Flowchart of the procedure for environmental index (EnvI) calculation.

ecosystems. The normalisation is performed by scaling the resulting endpoint impacts by specific factors: 41.7 for human health damage and 676 for ecosystem damage.[93] The aggregated environmental index EnvI, expressed in points, is obtained by summing both normalised endpoint impacts. Overall, a higher EnvI value indicates a greater environmental impact, translating into worse environmental sustainability.

2.3.4 Safety. Inherent safety is a key factor in the societal acceptability of technologies and is used as a proxy for the social sustainability of a fuel system here. Unlike most social sustainability criteria, inherent safety can be quantified based on technical data only.[65,66,94] In particular, the hazard index (HI) provides an early-stage assessment of onboard safety risk by quantifying the geographical area that would be affected in an accident caused by fuel being released:[57]

$$\mathrm{HI} = \sum_i \pi \cdot \sum_j cf_{ij} \cdot \max_k \left(d_{ijk}\right)^2 \tag{4}$$

cf_{ij} represents the credit factor (1 per year) and d_{ijk} denotes the damage distance (m), for the i-th equipment unit, j-th release mode and k-th accident scenario. Each equipment unit in the reference fuel system is assigned a set of release modes based on established guidelines.[95] The credit factor cf quantifies the propensity of an equipment unit to exhibit a specific release mode and is derived from statistical leak frequency data reported in the literature for standard process and storage equipment.[95,96] The damage distance d represents the spatial extent over which the physical effect of an accident scenario is above a predefined threshold. Standard consequence analysis models from the TNO "Yellow Book"[97] are applied to assess such damage distances. Additional details on the adopted release modes, credit factors, and threshold values used to evaluate damage distances are provided in the SI (Section S4). Overall, a higher HI value thus indicates a larger damage area and corresponds to lower safety performance.

2.4 Quantification of overall sustainability

The systematic procedure applied combines the four KPIs from Section 2.3 into a single sustainability index for each fuel system and is an adaptation of the well-established technique for order preference by similarity to an ideal solution (TOPSIS)[78] for multicriteria decision-making. TOPSIS was selected over alternative MCDM methods, such as the analytic hierarchy process (AHP) or the preference ranking organization method for enrichment evaluation (PROMETHEE),[98] due to its conceptual, methodological, and practical advantages: (i) conceptually, TOPSIS benchmarks alternatives directly against ideal and non-ideal reference systems, providing an intuitive and transparent representation of sustainability performance;[76,99,100] (ii) methodologically, TOPSIS requires only criterion weights and KPI data, unlike AHP, which demands extensive pairwise comparisons, or PROMETHEE, which requires preference-function definitions, thereby reducing complexity and limiting subjective inputs;[101,102] and (iii) in practical terms, TOPSIS is computationally efficient, scalable to a large number of criteria, and has been widely applied in sustainability research.[76,100,103]

The procedure starts by normalising the KPIs to make them dimensionless using the vector normalisation technique recommended by Vafaei *et al.*[104] for TOPSIS applications:

$$\mathrm{TI}_i{}^n = 1 - \frac{\mathrm{TI}_i}{\sqrt{(\mathrm{TI}_i)^2 + (\mathrm{EcI}_i)^2 + (\mathrm{EnvI}_i)^2 + (\mathrm{HI}_i)^2}} \tag{5}$$

$$\mathrm{EcI}_i{}^n = 1 - \frac{\mathrm{EcI}_i}{\sqrt{(\mathrm{TI}_i)^2 + (\mathrm{EcI}_i)^2 + (\mathrm{EnvI}_i)^2 + (\mathrm{HI}_i)^2}} \tag{6}$$

$$\mathrm{EnvI}_i{}^n = 1 - \frac{\mathrm{EnvI}_i}{\sqrt{(\mathrm{TI}_i)^2 + (\mathrm{EcI}_i)^2 + (\mathrm{EnvI}_i)^2 + (\mathrm{HI}_i)^2}} \tag{7}$$

$$\mathrm{SI}_i{}^n = 1 - \frac{\mathrm{HI}_i}{\sqrt{(\mathrm{TI}_i)^2 + (\mathrm{EcI}_i)^2 + (\mathrm{EnvI}_i)^2 + (\mathrm{HI}_i)^2}} \tag{8}$$

$\mathrm{TI}_i{}^n$, $\mathrm{EcI}_i{}^n$, $\mathrm{EnvI}_i{}^n$ and $\mathrm{SI}_i{}^n$ represent the normalised technological, economic, environmental and safety indices of the i-th fuel system, respectively, all ranging between 0 and 1, with higher values indicating better performance. To maintain consistency with this interpretation, note that the hazard index HI is renamed the normalised safety index (SI^n), so that higher values reflect improved safety performance rather than increased hazard levels.

Weighting factors (wf) are applied to the normalised indices (eqn (5)–(8)) to allow for specific sustainability criteria to be prioritised according to the selected decision-making perspective:

$$I_{ij}{}^w = wf_j \cdot I_i{}^n \tag{9}$$

$I_i{}^n$ and $I_{ij}{}^w$ denote normalised and weighted indices for the i-th fuel system and j-th sustainability domain, respectively, and wf_j is the corresponding weighting factor for that sustainability domain; refer to Section 3 for details on the decision-making perspectives and weighting factors adopted in the case study.

The overall sustainability performance considers two reference solutions as benchmarks: the most sustainable ideal solution (MoSIS) represents a hypothetical, best-in-class fuel system in which each sustainability domain is characterised by the highest weighted index value observed across all fuel systems; whereas the least sustainable ideal solution (LeSIS) corresponds to a hypothetical, worst-in-class fuel system in which each sustainability domain is characterised by the lowest weighted index value observed across all fuel systems:

$$\mathrm{MoSIS} = \left[\max_{i \in \{1,\ldots,N\}} I_{ij}{}^w : j \in \{1, \ldots, M\}\right] \tag{10}$$

$$\mathrm{LeSIS} = \left[\min_{i \in \{1,\ldots,N\}} I_{ij}{}^w : j \in \{1, \ldots, M\}\right] \tag{11}$$

where N is the number of candidate fuel systems and M is the number of sustainability domains considered. A candidate fuel system, therefore, is deemed more sustainable the closer it is to MoSIS and the farther it is from LeSIS. These distances from either MoSIS or LeSIS can be calculated in the Euclidean sense:

$$\mathrm{ED}_i^{\mathrm{MoSIS}} = \sqrt{\sum_{j=1}^{M} \left(I_{ij}{}^{w} - \max_{i \in \{1,\ldots,N\}} I_{ij}{}^{w} \right)^2} \tag{12}$$

$$\mathrm{ED}_i^{\mathrm{LeSIS}} = \sqrt{\sum_{j=1}^{M} \left(I_{ij}{}^{w} - \min_{i \in \{1,\ldots,N\}} I_{ij}{}^{w} \right)^2} \tag{13}$$

Finally, an overall sustainability index (OSI) for each fuel system is obtained as:

$$\mathrm{OSI}_i = \frac{\mathrm{ED}_i^{\mathrm{LeSIS}}}{\mathrm{ED}_i^{\mathrm{MoSIS}} + \mathrm{ED}_i^{\mathrm{LeSIS}}} \tag{14}$$

The OSI is a dimensionless coefficient ranging from 0 to 1, representing the relative position of a reference fuel system between MoSIS and LeSIS across the different sustainability domains. A higher OSI value indicates greater proximity to MoSIS and increased distance from LeSIS, translating into better overall sustainability performance, and *vice versa*. Ultimately, the candidate fuel systems can be ranked according to their overall sustainability by ordering them in descending order of OSI.

2.5 Sensitivity analysis

The previous step of the methodology compares and ranks the candidate fuel systems according to their overall sustainability performance. To confirm the robustness of this ranking against uncertainties in input data, a sensitivity analysis is implemented at this stage. The approach used is based on Monte Carlo sampling to propagate uncertainties from input data to KPIs according to specified probability distribution functions. Triangular probability distributions are assumed for each uncertain input due to their suitability for representing uncertainty with minimal statistical assumptions,[64,105] considering a compact support of ±20% around the corresponding baseline input value.[106] Random sampling is conducted over 10^6 scenarios to ensure reliable summary statistics while keeping the computational effort manageable.[25,63] The rankings examined for sensitivity analysis, along with the uncertain input variables of interest, are detailed later in Section 4.

3 Case study

3.1 Reference ship fuel systems

The reference ship for this analysis is a passenger vessel with a nominal onboard power capacity of 36 MW, operating 6264 hours annually.[9] The onboard fuel storage system is designed to sustain continuous operation over a sea voyage duration of 10 days.[25] The power demand profile of the ship during a sea voyage is formulated in an activity-based form using data from the technical literature, including the power demand P (eqn (1) and (3)) and time duration t (eqn (1) and (3)) of each operational mode (manoeuvring, berthing, and navigation). Further details on the design features of the vessel, as well as the activity-based distribution of its power demand, are available elsewhere.[9,25]

Fig. 3 presents the four fuel systems under consideration. Two of them utilise carbon-based e-fuels, namely e-methanol (Fig. 3a) and e-diesel (Fig. 3d), which are gaining traction in the maritime industry for their potential to reduce carbon emissions while retaining compatibility with existing shipping infrastructure.[29] Both systems employ internal combustion engines (ICEs), with the e-methanol system (Fig. 3a) incorporating a dual-fuel engine in which combustion is sustained by a small quantity of diesel-like pilot fuel.[107] To support low-carbon operation, hydrotreated vegetable oil (HVO) is considered as the pilot fuel here. HVO is a second-generation biodiesel derived from waste or residue feedstocks such as tallow, waste oils, and fats,[108,109] and is selected for its high ignition quality and increasing use as a drop-in fuel in maritime applications.[29,108] A pilot fuel share of 1% by volume is assumed, based on values reported for methanol-fuelled dual-fuel engines.[110] The requirement of HVO as pilot fuel in the e-methanol system is accounted for across all four KPIs defined in Section 2.3: (i) additional fuel storage volume (TI); (ii) capital and operating costs associated with HVO storage, processing, and fuel price (EcI); (iii) pollutant emissions attributable to HVO use (EnvI); and (iv) the inherent safety profile of HVO-related equipment (HI). The other two fuel systems are based on carbon-free e-fuels: green hydrogen (Fig. 3b) and green ammonia (Fig. 3c), which are included to assess the performance of carbon-based e-fuels relative to intrinsically zero-carbon energy carriers. Cryogenic liquefied hydrogen at atmospheric pressure and pressurised liquefied ammonia at ambient temperature are considered for onboard fuel storage. Proton exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs) are selected for their energy-efficient onboard utilisation of hydrogen and ammonia, respectively.[25] Although SOFCs capable of direct ammonia utilisation are not yet commercially available for maritime applications,[111] they are considered here as a prospective technology for longer-term utilisation of ammonia as a marine fuel. Lastly, a conventional marine diesel oil (MDO)-fuelled system, following the same reference scheme as e-diesel (Fig. 3d), is defined as the baseline technology for benchmarking. In all reference schemes depicted in Fig. 3, the storage system is designed by distributing the estimated total volumetric fuel inventory required for a single sea voyage across tanks of equal nominal capacity. All e-fuels considered in the reference systems are produced using renewable electricity for electrolysis. For carbon-based e-fuels, the required CO_2 for synthesis is assumed to be supplied *via* direct air capture (DAC). These assumptions are consistently applied across the KPI assessments, for instance, in fuel cost estimation within the economic dimension (see Section S2, SI) and in the evaluation of carbon emission factors within the environmental dimension (see Section S3, SI). Further details on the reference fuel systems considered in this analysis and their operating conditions are provided in the SI (Sections S1.1–S1.4).

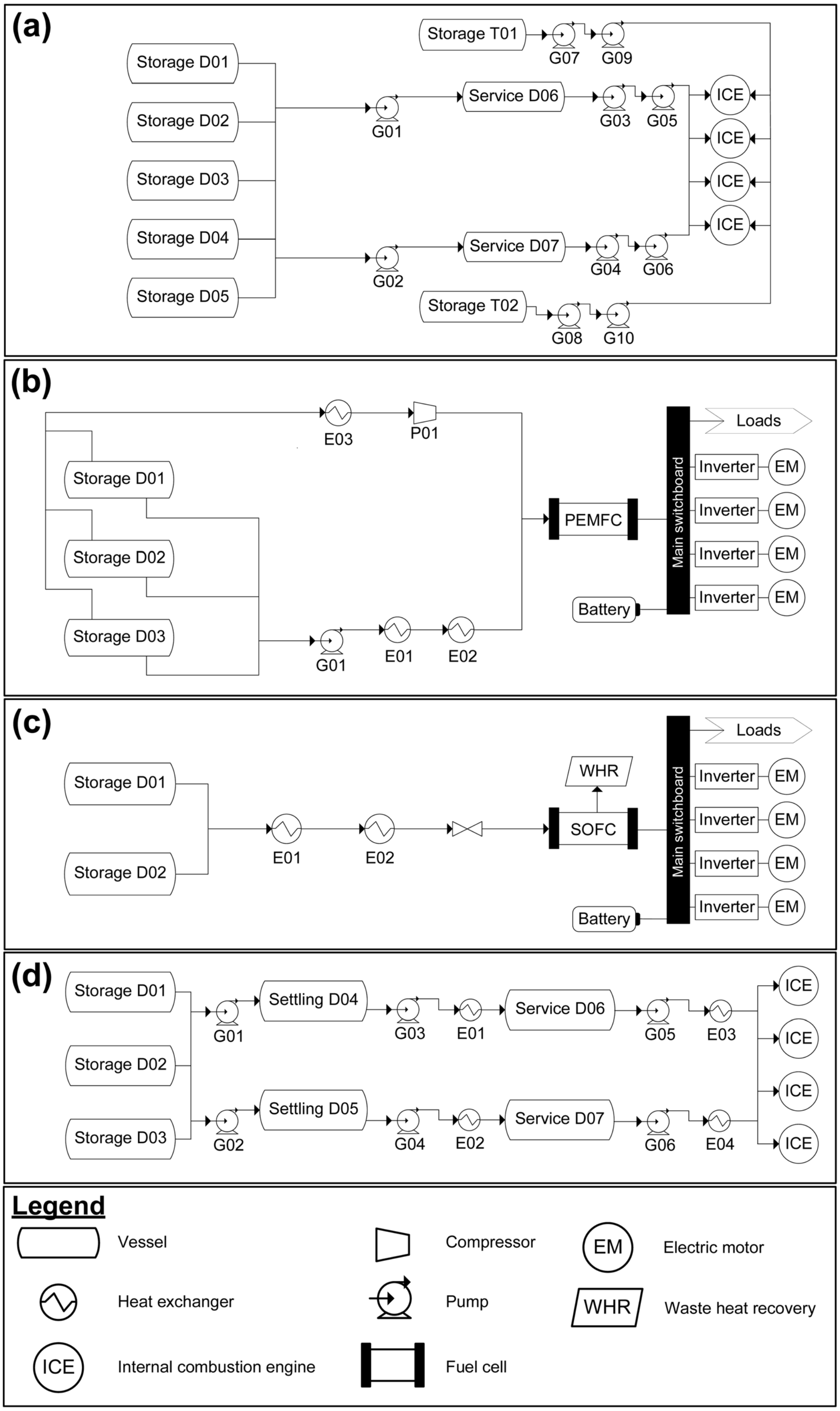

Fig. 3 Reference schemes for the fuel systems under consideration: (a) e-methanol with an internal combustion engine (ICE); (b) hydrogen with a proton exchange membrane fuel cell (PEMFC); (c) ammonia with a solid oxide fuel cell (SOFC); (d) e-diesel/marine diesel oil (MDO) with an internal combustion engine (ICE).

3.2 System boundaries for KPI evaluation

As introduced in Section 2.3, the case study applies tailored system boundaries for each KPI. This approach enables the analysis to address the impacts most relevant to each dimension, while remaining feasible within the data constraints typical of assessments of emerging fuel technologies. The e-fuel value chain is defined as comprising three stages: production, transport and distribution, and onboard use. Depending on the KPI, only a subset of these stages may be considered.

Table 2 summarises the system boundaries applied for each KPI.

The technological KPI is confined to the onboard use phase, as it captures the space required for fuel storage on board. Of the various technological aspects that could be assessed for maritime decarbonisation technologies, volume occupation at the ship level is especially critical, since tanks and processing equipment must be integrated within limited hull dimensions and inevitably compete with cargo or passenger capacity.[11,112]

Likewise, the safety assessment is restricted to the use phase. Onboard storage, handling, and utilisation involve risks that must be managed in confined spaces with limited emergency response capacity, making them more critical than in upstream facilities such as production plants or bunkering terminals, where risk management frameworks are generally more established.[113,114]

In the economic assessment, the boundaries extend across production, transport & distribution, and onboard use within the e-fuel value chain. Investment and operating costs are included for onboard equipment and storage, while upstream costs are embedded in unitary fuel prices treated as variable operating expenditures. Full cost assumptions and data sources are detailed in Section S2 of the SI.

Environmental performance spans all stages of the value chain as well. A well-to-wake perspective is essential for ensuring a consistent and transparent comparison of alternative e-fuels, particularly in terms of their decarbonisation potential.

Table 2 System boundaries adopted for each key performance indicator (KPI)

KPI	Production	Transport & distribution	Onboard use
Technological	✗	✗	✓
Economic	✓	✓	✓
Environmental	✓	✓	✓
Safety	✗	✗	✓

Table 3 Weighting factors associated with the decision-making perspectives considered in this analysis

Decision-making perspective	Indicators			
	TI	EcI	EnvI	HI
Individualist	0.05	0.17	0.14	0.64
Egalitarian	0.36	0.08	0.53	0.03
Hierarchist	0.22	0.10	0.58	0.10
Equal weighting	0.25	0.25	0.25	0.25

3.3 Decision-making perspectives

The quantitative sustainability assessment (Section 2.4) considers four decision-making perspectives, namely individualist, egalitarian, hierarchist, and equal weighting.[66,115] This selection allows for variations in sustainability assessment outcomes to be captured across a representative set of decision-making perspectives. The weighting factors (eqn (9)) associated with each decision-making perspective are determined from the literature[63,73,115] and incorporate time, space and receptor (*e.g.*, humans and ecosystems) considerations. Table 3 summarises the weighting factors assigned to the four sustainability KPIs within each of the analysed decision-making perspectives. Further details on the characteristics of these decision-making perspectives and the time-space-receptor approach used for weighting factor evaluation can be found elsewhere.[73,115]

4 Results and discussion

4.1 Sustainability KPIs

Fig. 4 presents the KPI values for each reference fuel system, calculated as per Section 2.3.

From a technological feasibility standpoint (Fig. 4a), diesel-based ship fuel systems (e-diesel and conventional MDO) achieve the highest performance, with a TI approximately three times lower than that of the worst option (H_2). This outcome is primarily attributed to the high volumetric energy density of diesel-like fuels. The ranking in Fig. 4a also identifies NH_3 and e-MeOH as the second and third best options, respectively, with NH_3 benefiting from both a high volumetric energy density and high fuel utilisation efficiency in SOFCs. As noted in Section 3.1, the ammonia-SOFC system analysed here represents a prospective configuration. The results should therefore be interpreted as indicative of the long-term potential of ammonia as a marine fuel, contingent upon further technological advances, rather than as evidence of its current technological readiness.

The economic viability index EcI (Fig. 4b) follows a similar pattern to that observed for TI, with the exception of e-diesel, which has a significantly worse economic performance than that of the other fuel candidates. This is primarily due to the high cost of synthetic diesel, resulting in an EcI 2.7 times higher than that of a conventional MDO fuel system. The economic performance of all fuel systems appears to be largely driven by operating costs, including fuel consumption, operations and maintenance. Notably, the CAPEX of both carbon-free e-fuel systems (H_2 and NH_3) is 40% higher or more than that of the other fuel systems, mainly due to the higher cost of pressurised or cryogenic storage tanks and fuel cell-based technologies for energy conversion. In addition, their O&M costs are up to seven times higher than those of combustion-based systems (e-MeOH, e-diesel, and MDO), reflecting the shorter lifetime of fuel cells and the need for stack renewal within the system lifetime. It is worth noting that the analysis does not consider landside infrastructure requirements, which could further affect the overall economic assessment. Among the options assessed, e-diesel would likely require minimal or no additional

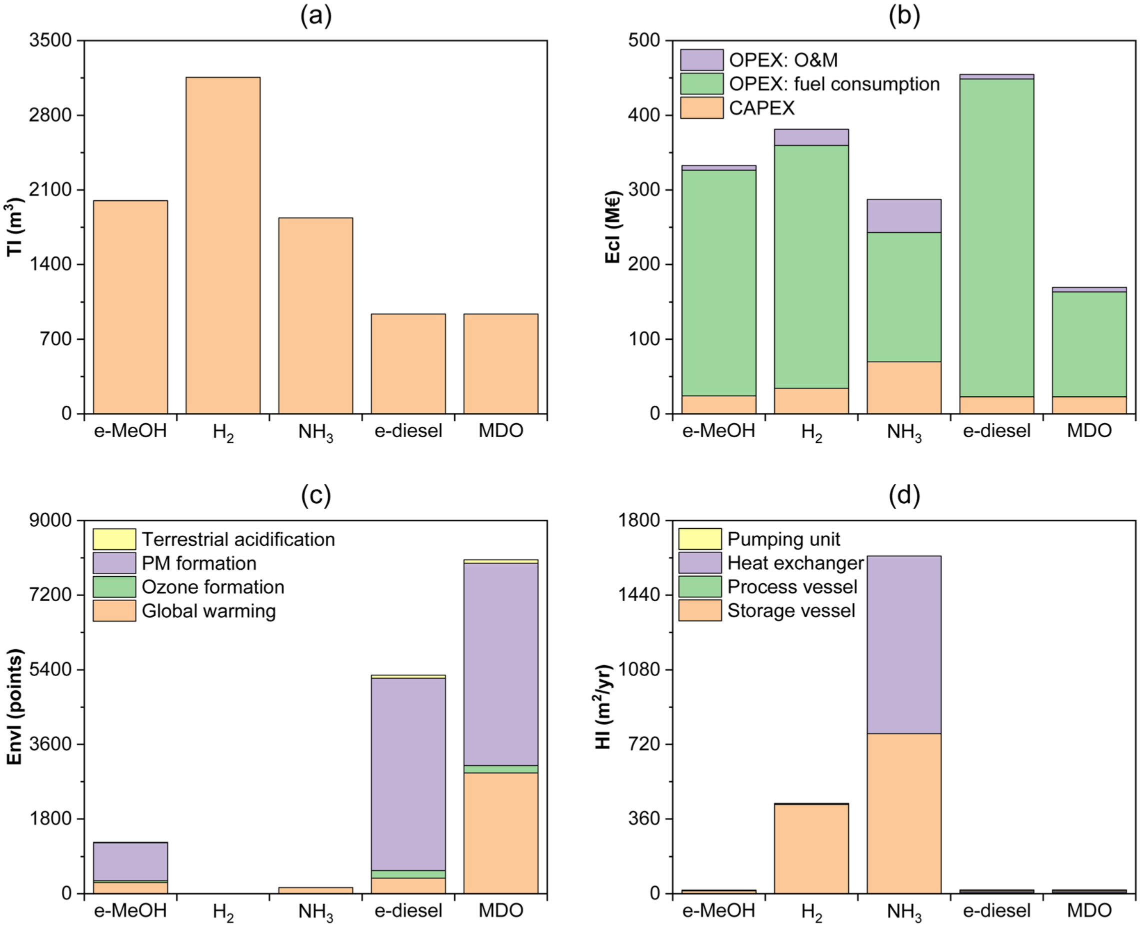

Fig. 4 Sustainability KPIs calculated for the candidate fuel systems: (a) technological index (TI); (b) economic index (EcI); (c) environmental index (EnvI); (d) hazard index (HI).

infrastructure, representing a potential advantage not captured in the present evaluation.

The environmental index EnvI (Fig. 4c) identifies the business-as-usual fuel system with an MDO engine as the worst option, which is expected. The alternative fuel systems, whether powered by carbon-based e-fuels (e-MeOH and e-diesel) or carbon-free e-fuels (H_2 and NH_3), all reduce the carbon footprint of ship operation substantially, decreasing the global warming impact by at least 87% compared to conventional MDO. H_2 demonstrates the best environmental performance, effectively minimising all major environmental impacts associated with ship operation. Carbon-based e-fuels still exhibit a much higher environmental impact than H_2 and NH_3, primarily due to particulate matter (PM) emissions, which contribute close to 90% of the EnvI index for e-diesel.

The trends in hazard index HI (Fig. 4d) are diametrically opposed to those of EnvI, with carbon-free e-fuels (H_2 and NH_3) increasing onboard hazard levels by 24 times or more than those of carbon-based fuel systems (e-MeOH, e-diesel, and MDO). This low inherent safety performance of H_2 and NH_3 is primarily attributed to the severe consequences of vapour cloud fires and explosions in the case of hydrogen release and toxic dispersion in the case of ammonia release. However, it is important to note that this study reflects the level of detail available at an early design stage and, therefore, the effectiveness of risk mitigation strategies and systems is not accounted for. This is particularly relevant for ammonia-related accidents, where water-based mitigation systems have been shown to be effective.[116] Still, such measures may be largely ineffective at protecting the crew and passengers aboard a ship due to limited safety distances and the complexity of the onboard layout.[117] Of the alternative fuel systems considered for decarbonising ship operations, only e-MeOH appears to be competitive with conventional MDO, with a HI value 5% lower. Although both rely on a similar ICE-based fuel system (Fig. 3), the need for heat exchangers to reduce diesel viscosity before combustion penalises the safety performance of diesel-based technology, given its propensity for loss of containment.

4.2 Quantitative assessment of overall sustainability

The radar plot in Fig. 5 presents the normalised indices calculated for each fuel system as part of the overall sustainability quantification (see Section 2.4).

It shows substantial performance differences between fuel systems across all four domains of technological, economic, environmental and safety-related social sustainability. A key finding is the presence of burden shifting between these

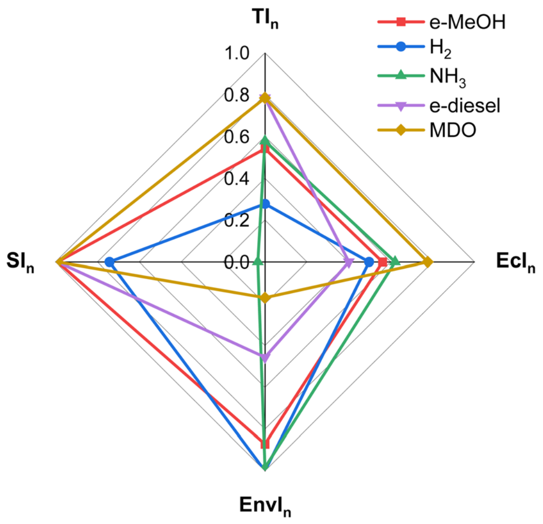

Fig. 5 Normalised indices for the candidate fuel systems.

dimensions. While reducing the environmental footprint (EnvI) of shipping argues in favour of the adoption of carbon-free e-fuels such as hydrogen and ammonia, their adoption introduces significant trade-offs. Their safety performance (HI) is significantly lower than that of other alternatives, and their technological feasibility (TI) may also present challenges. In contrast, carbon-based e-fuels (e-MeOH and e-diesel) demonstrate significantly higher safety performance and greater technological feasibility compared to H_2 and NH_3. Yet, these benefits are compromised by a large drop in environmental sustainability and, in the case of e-diesel, a much higher net present cost (EcI) as well. These observations emphasise the need for a comprehensive sustainability assessment framework that effectively integrates multiple KPIs to identify trade-offs and ultimately feed into decision-making.

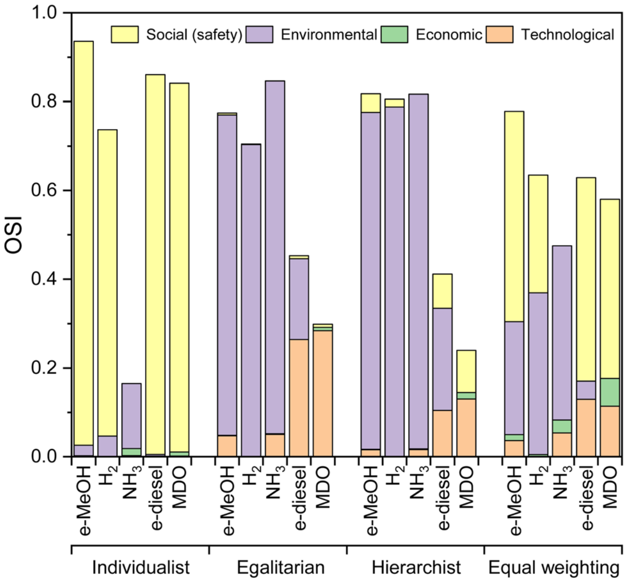

Fig. 6 OSI values for the candidate fuel systems under various decision-making perspectives.

Fig. 6 presents the OSI values (Section 2.4) for each fuel system according to the various decision-making perspectives (Section 3.3).

The environmental and safety aspects make a significant contribution to the OSI. Under the individualist perspective, which prioritises short-term social impacts, safety emerges as the dominant factor in achieving high OSI values. Under the egalitarian and hierarchist perspectives, which emphasise medium- to long-term ecosystem preservation, the environmental footprint of shipping becomes primordial and hence promotes the adoption of cleaner marine fuels (e-MeOH, H_2, NH_3, and, to a lesser extent, e-diesel). This highlights the importance of incorporating environmental and safety evaluations alongside conventional techno-economic metrics to allow for a more comprehensive sustainability assessment.

NH_3 emerges as the worst option from an individualist perspective, with an OSI value significantly lower than that of the other fuel systems. This is primarily due to the significant risks that accidental ammonia releases could incur on the onboard crew and passengers. In contrast, NH_3 emerges as the best option under the egalitarian perspective, and among the top-ranked alternatives under the hierarchist perspective, due to the considerable environmental benefits it may offer. These findings indicate that if short-term safety concerns are effectively managed, ammonia could serve as a key marine fuel in advancing the sustainability of future shipping.

Among the cleaner fuel systems considered, both e-MeOH and e-diesel consistently outperform MDO across all decision-making perspectives. Notably, e-MeOH remains the top option under every perspective except the egalitarian one, where it ranks second. Its superior overall sustainability performance is primarily linked to relatively high environmental benefits combined with moderate inherent hazard levels (Fig. 4). Methanol thus appears as a strong contender for sustainable maritime decarbonisation, particularly while the technical and safety challenges associated with hydrogen- and ammonia-based technologies are being addressed.

Finally, Table 4 summarises the results of a sensitivity analysis (Section 2.5) for the OSI calculation (eqn (14)) against uncertainties in the four sustainability KPI values. The Monte Carlo sampling assumes triangular probability distributions for the KPIs, with ±20% variations centred around the baseline KPI values (Fig. 4). The results of the sensitivity analysis express the probability (in %) of a candidate fuel system achieving the highest OSI value, under a given decision-making perspective.

Table 4 Sensitivity analysis showing the probability (in %) of each fuel ranking first under various decision-making perspectives

	Probability (in %) of ranking first				
Decision-making perspective	e-MeOH	H_2	NH_3	e-diesel	MDO
Individualist	100.0	0.0	0.0	0.0	0.0
Egalitarian	0.3	0.0	99.7	0.0	0.0
Hierarchist	46.4	13.7	39.8	0.0	0.0
Equal weighting	100.0	0.0	0.0	0.0	0.0

The analysis confirms the top overall sustainability performance of e-MeOH, with a 100% probability of ranking first under the individualist and equal-weighting perspectives, while NH_3 ranks first with a probability close to 100% under the egalitarian perspective. The analysis also suggests that the rankings under the hierarchist perspective are the most sensitive to input uncertainties, corroborating Fig. 6, where the OSI values of e-MeOH, H_2 and NH_3 are comparable, although e-MeOH retains a probability close to 50% of ranking first. This is largely driven by the substantial environmental benefits shared by these fuels, including reduced well-to-wake GHG emissions and, in the case of H_2 and NH_3, negligible contributions to non-GHG-related impacts, *i.e.* terrestrial acidification, particulate matter formation, and ozone formation (Fig. 4c). As the hierarchist perspective places the greatest emphasis on the environmental dimension (58% weighting in this study; Table 3), these common attributes dominate the overall sustainability assessment, thereby reducing the differences in OSI values among the top-performing options. Overall, the sensitivity analysis supports the main conclusions presented in Fig. 6 by confirming that the rankings are robust against uncertainty in the estimated KPIs.

4.3 Discussion

This study offers new insights into maritime decarbonisation by introducing a holistic perspective on the sustainability of marine e-fuels and revealing key trade-offs across technological, economic, environmental, and safety dimensions. The results demonstrate that moving beyond GHG- and cost-centric assessments can lead to substantially different conclusions, redefining priorities for future fuel transitions.

The findings remain broadly consistent with previous studies that identified e-methanol and ammonia as promising fuels for cleaner shipping.[17,50,51] In particular, the favourable onboard integration characteristics and significant GHG-reduction potential of e-methanol reported in previous work[21,35,50] align with its strong overall sustainability performance observed here (Fig. 6). At the same time, this study advances prior work by demonstrating that the comparative performance assessment of marine e-fuels can be substantially reshaped when assessed through a holistic framework that integrates techno-economic, environmental, and safety-related social criteria. This is evident for hydrogen and ammonia, which are frequently presented as leading candidates for shipping decarbonisation,[21,27,118] yet show markedly reduced sustainability performance once safety aspects are incorporated.

The comparison in Fig. 6 also illustrates how strongly overall sustainability metrics may be influenced by the weighting of environmental and safety dimensions under different decision-making perspectives. Safety dominates under the individualist perspective, leading to the low ranking of ammonia and hydrogen, while environmental performance is decisive under egalitarian and hierarchist perspectives, which raises their ranking. Linking these patterns to the timing of fuel adoption highlights that the near-term deployment of e-methanol is supported not only by its consistently strong sustainability performance across perspectives but also by its higher technological readiness and compatibility with existing infrastructure. By contrast, hydrogen and ammonia, despite offering substantial long-term environmental benefits under perspectives prioritising ecosystem preservation, are likely to play a significant role only in later phases of the maritime transition once advances in technology, infrastructure, and risk management mitigate their current drawbacks.

The results carry direct implications for both industry stakeholders and academia. For fuel producers, they underscore the importance of prioritising carbon-based e-fuels such as e-methanol in the near term, while sustaining investment in research and development to address the safety and feasibility challenges associated with hydrogen and ammonia. For shipowners and operators, the framework offers a structured approach to balancing techno-economic performance, environmental benefits, and safety considerations, thereby supporting more informed investment strategies and fleet-planning decisions. Policymakers may draw on these insights to design regulatory and incentive schemes that move beyond a sole focus on GHG reduction and explicitly integrate safety and societal acceptability, ensuring that maritime fuel transitions are both environmentally effective and socially viable. For academic research, the study highlights the importance of embedding multi-criteria approaches into sustainability assessments and offers opportunities for methodological innovation, particularly in linking quantitative social indicators with sustainability-oriented decision-making approaches relevant to policy and practice.

Finally, while the framework provides a structured and holistic assessment, it does not come without limitations. The system boundaries for certain indicators, notably technological performance and inherent safety, were intentionally restricted to maintain a comprehensive yet feasible analysis under the limited data typically available for emerging cleaner fuel systems, particularly at early design stages. As technologies mature and more detailed life-cycle data become available, extending these boundaries to encompass upstream and downstream processes to capture impacts more comprehensively will become increasingly feasible and desirable. Similarly, reliance on a single metric per sustainability domain, while suitable for early-stage assessments, could be addressed in future work by incorporating multiple indicators within each domain, thereby enabling a more comprehensive evaluation of trade-offs across techno-economic, environmental, and social aspects of sustainability.

5 Conclusions

This study introduced a novel framework for the quantitative sustainability assessment of carbon-based and carbon-free e-fuel systems for maritime applications. A comprehensive set of key performance indicators (KPIs) was developed to evaluate system performance across four critical sustainability dimensions: technological feasibility, economic viability, environmental impact, and safety. These KPIs were systematically integrated into a unified metric for overall sustainability quantification.

The methodology was applied to benchmark conventional marine diesel oil (MDO) against carbon-based e-fuels (e-methanol and e-diesel) and carbon-free e-fuels (hydrogen and ammonia). From a techno-economic standpoint, these cleaner fuels are currently less competitive than MDO, primarily driven by higher onboard volume requirements and costs. Nonetheless, they offer substantial environmental benefits, reducing the overall environmental impact of shipping by at least one-third with carbon-based e-fuels and almost completely with hydrogen and ammonia.

Despite their environmental merits, hydrogen and ammonia face significant barriers to widespread adoption due to low societal acceptability and high inherent hazard levels. Out of the alternatives evaluated, carbon-based e-fuels (e-methanol, e-diesel) stand out as the only cleaner fuels that consistently surpass MDO in overall sustainability, independent of the decision-making perspective. Ammonia also shows promise, if safety challenges can be effectively overcome. This underscores the need for inherently safer design principles and tailored risk mitigation strategies for ammonia storage and use onboard ships.

A Monte Carlo-based sensitivity analysis confirmed the robustness of the proposed ranking approach subject to KPI uncertainty. The findings align with earlier studies that identified e-methanol as a promising candidate for shipping decarbonisation, yet they extend prior analyses by demonstrating that the sustainability of hydrogen and ammonia, often regarded as leading alternatives for cleaner shipping, remains strongly contingent on overcoming their safety-related limitations. Beyond the case-specific outcomes, this study contributes to the broader knowledge base by demonstrating that integrating environmental and safety dimensions with conventional techno-economic metrics within a holistic framework can substantially reshape the comparative evaluation of marine e-fuels. Overall, the proposed framework advances methodological development in the sustainability assessment of marine e-fuel systems, while also offering practical insights to support the prioritisation of near-term fuel choices and to highlight where further progress is required for broader adoption.

Nomenclature

Acronyms and abbreviations

BECCS	Bioenergy with carbon capture and storage
DAC	Direct air capture
DALY	Disability-adjusted life year
ECA	Emission control area
e-diesel	Electro-diesel
e-fuel	Electro-fuel
e-MeOH	Electro-methanol
GHG	Greenhouse gas
H_2	Hydrogen
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
IMO	International Maritime Organization
ISAT	Inherent safety assessment tool
KPI	Key performance indicator
LCA	Life cycle assessment
LNG	Liquefied natural gas
MCDA	Multi-criteria decision analysis
MCDM	Multi-criteria decision-making
MDO	Marine diesel oil
NH_3	Ammonia
OCCS	Onboard carbon capture and storage
PEMFC	Proton exchange membrane fuel cell
PM	Particulate matter
ReCiPe	Life cycle impact assessment method
SOFC	Solid oxide fuel cell
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRL	Technology readiness level

Indices and symbols

TI	Technological index (onboard volume requirement) [m^3]
EcI	Economic index (net present cost) [€]
EnvI	Environmental index (aggregated environmental impact) [points]
HI	Hazard index (inherent safety indicator) [m^2 per year]
OSI	Overall sustainability index [-]
η	Fuel utilisation efficiency [-]
ρ	Fuel density under storage conditions [kg m^{-3}]
LHV	Lower heating value of the fuel [MJ kg^{-1}]
P_j	Average power demand in operational mode j [kW]
t_j	Time duration of operational mode j [h year^{-1}]
E_i	Total emissions of pollutant i [g year^{-1}]
e_i	Emission factor for pollutant i [g kW^{-1} h^{-1}]
cf_{ij}	Credit factor for unit i, release mode j [1 per yr]
d_{ijk}	Damage distance for unit i, release mode j, accident scenario k [m]
CAPEX	Capital expenditures for the fuel system [€]
OPEX	Operating expenditures for the fuel system [€ per year]
T	Lifetime of the ship fuel system [yr]
i	Discount rate [-]
TI_i^n	Normalised technological index for fuel system i [-]
EcI_i^n	Normalised economic index for fuel system i [-]
EnvI_i^n	Normalised environmental index for fuel system i [-]
SI_i^n	Normalised safety index for fuel system i [-]
I_i^n	Normalised index for fuel system i [-]
wf_j	Weighting factor for sustainability domain j [-]
$I_{ij}w$	Weighted index for fuel system i, sustainability domain j [-]
MoSIS	Most sustainable ideal solution [-]
LeSIS	Least sustainable ideal solution [-]
ED_i^{MoSIS}	Euclidean distance of fuel system i from the most sustainable ideal solution [-]
ED_i^{LeSIS}	Euclidean distance of fuel system i from the least sustainable ideal solution [-]

Author contributions

Francesco Zanobetti: investigation, data curation, conceptualization, methodology, writing – original draft. Andrea Bernardi: conceptualization, methodology, writing – review & editing. Gianmaria Pio: conceptualization, methodology, writing – review & editing. Diego Freire Ordóñez: conceptualization, methodology, writing – review & editing. David Danaci: conceptualization, methodology, writing – review & editing. Benoît Chachuat: conceptualization, methodology, supervision, writing – review & editing. Valerio Cozzani: conceptualization, methodology, supervision, funding acquisition, writing – review & editing. Nilay Shah: conceptualization, methodology, supervision, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: **https://doi.org/10.1039/d5se00821b**.

Acknowledgements

Bernardi, Chachuat, Freire Ordoñez and Shah gratefully acknowledge funding by the EPSRC under grants EP/V011863/1 and EP/V042432/1. Danaci acknowledges support *via* the Eric and Wendy Schmidt AI in Science Postdoctoral Fellowship, a Schmidt Futures program. Cozzani, Pio and Zanobetti gratefully acknowledge funding by the Italian Ministry of University and Research under the National Recovery and Resilience Plan, Mission 4, Component 2, Investment 1.3, NextGenerationEU, Project "Network 4 Energy Sustainable Transition", PE00000021, CUPJ33C22002890007.

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