Journal of Cleaner Production 417 (2023) 137989

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Decarbonization of maritime transport: Sustainability assessment of alternative power systems

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ARTICLE INFO

Handling Editor: Giovanni Baiocchi

Keywords:
Maritime transport
Ship power systems
Clean fuels
Sustainability assessment
Key performance indicators

ABSTRACT

The growing concern for the emission of greenhouse gases and several recent international regulations promote the introduction of innovative solutions aiming at the reduction of pollutant production in all human activities, including maritime transportation. Phasing out conventional marine gas oil engines is a key strategy to limit the pressure on the environment exerted by maritime transport. Considering the strategic relevance of this sector, the sustainability of innovative clean technologies proposed for ship power systems is crucial. In the present study, a multi-criteria sustainability assessment methodology, based on specific indicators addressing the technological, economic, environmental, and safety performance of ship power systems is developed. Normalization and aggregation perspectives are proposed to provide key performance indicators describing and ranking the overall sustainability performance of the alternative power systems considered. A sensitivity analysis is performed to identify the most impacting parameters in each domain. The methodology is tested considering a case study representative of large-scale maritime transportation. The robustness of the sustainability performance-based ranking is assessed by a Monte Carlo analysis. The results suggest that the ranking of alternative power systems obtained considering only techno-economic factors may be strongly affected by highly fluctuating parameters, such as fuel cost. Conversely, the inclusion of environmental and safety aspects increases the robustness of the results. A trade-off between the environmental and societal domains is also observed, indicating that the performance of cleaner solutions may be strongly improved if safety issues are properly addressed.

1. Introduction

The emission of pollutants and greenhouse gases related to maritime transport represents a growing concern for the environment, also considering climate change issues. It is estimated that approximately 3% of sulfur oxides (SO_x), 15% of nitrogen oxides (NO_x) and 2.5% of carbon dioxide (CO_2) globally emitted per year are due to shipping activities (Sofiev et al., 2018). Moreover, the soaring maritime traffic due to the growth in the world population may triple the CO_2 emissions from maritime transport by 2050 if no measures are taken (OECD/ITF, 2018). In this context, the phase-out of conventional marine gas oil (MGO) engines emerges as a crucial measure to reduce the impact of maritime transportation on the environment (Ye et al., 2022). Natural gas, biofuels, hydrogen and ammonia are identified as possible alternative fuels to drastically reduce emissions from the shipping industry (Ampah et al., 2021). In particular, the use of hydrogen and ammonia in power systems based on fuel cells has been gaining increasing interest due to the possibility of achieving near-zero emissions of greenhouse gases while ensuring high energy conversion efficiencies (Ye et al., 2022), provided that these chemical energy vectors are produced from renewable energy.

The adoption of alternative clean fuels for ship power units results in evident important environmental benefits, substantially reducing the environmental impact of maritime transport. However, the application of concepts based on fuels alternative to conventional MGO in ship power systems poses several concerns that need to be addressed.

Most of the alternative fuels proposed are in the gas phase at ambient temperature and pressure. Thus, different solutions are proposed to optimize the fuel storage on board ships. When considering natural gas

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https://doi.org/10.1016/j.jclepro.2023.137989
Received 13 February 2023; Received in revised form 5 June 2023; Accepted 2 July 2023

as a marine fuel, the adoption of cryogenic tanks retaining liquefied natural gas (LNG) is widely recognized as the most effective storage strategy (Banaszkiewicz et al., 2020). Emerging concepts of hydrogen-fueled ship power systems are largely based on hydrogen storage either as a highly compressed gas at 350 bar and ambient temperature or as a liquid at −253 °C and atmospheric pressure (Gomez Trillos et al., 2019; Shakeri et al., 2020; Van Hoecke et al., 2021). Cryogenically liquefied hydrogen stored under pressure, namely cryo-compressed hydrogen, is also gaining momentum as a solution to limit evaporative losses during the exploitation of highly dense hydrogen (Yanxing et al., 2019). Conversely, storage in the liquid form at about 10 bar and room temperature is suggested for ammonia-fueled vessels (Zincir, 2020). In general, all the storage solutions available for alternative clean fuels have an increased technological complexity and a higher cost per volume of fuel stored with respect to MGO fuel tanks (Ampah et al., 2021; DNV GL, 2019; Xing et al., 2021a). It should also be remarked that the energy density of all storage systems available for alternative fuels is lower than that of MGO tanks, thus resulting in the need of more space on board ships dedicated to fuel storage (Chiong et al., 2021; DNV GL, 2019; McKinlay et al., 2021).

Moreover, several properties of clean fuels proposed as alternatives to MGO are critical from the point of view of safety. In particular, most of the clean fuels have a much higher flammability than MGO and, being in the gaseous phase at ambient conditions, leaks may cause the formation of flammable gas clouds that, in case of ignition, may cause relevant damage (Zanobetti et al., 2023). Ammonia also has a relevant toxicity, able to affect crew members and passengers on board the ship in case of leaks (Dolan et al., 2021; Zanobetti et al., 2023).

Therefore, besides technical issues, if a holistic sustainability perspective is considered, moving from MGO to alternative clean fuels may cause a burden shift between the environmental, safety and economic compartments (Kim et al., 2020). In developing such concepts, a trade-off is thus necessary between the impacts concerning the different sustainability dimensions (Trivyza et al., 2022).

A relevant effort was dedicated in the literature to develop methods addressing the holistic assessment of the sustainability performance of technological alternatives. However, as discussed in section 2, addressing an extended state of the art concerning multi-criteria sustainability assessment methods focusing on alternative marine technologies, several gaps are still present. In particular, existing methodologies lack of a systematic quantification of the social sustainability performance, specifically with respect to the safety sub-domain (Trivyza et al., 2022), and the technological component of sustainability is often given for granted and not assessed through proper quantitative metrics (Andersson et al., 2020). Moreover, available methodologies often do not address sensitivity and uncertainty analysis of the results (Trivyza et al., 2022).

The present study aims at contributing to the quantification of the sustainability of maritime transportation while accounting for the knowledge gaps identified in section 2. An innovative methodology for the comparative assessment of the sustainability performance of alternative ship power systems for the decarbonization of maritime transport is developed.

The methodology extends the sustainability assessment to include metrics addressing the technological, environmental, economic and safety performance of alternative technological concepts. A set of multi-criteria key performance indicators (KPIs) is adopted to quantify the impacts of the technologies under investigation on the various sustainability dimensions. The KPIs introduced are specifically conceived to allow their application in the early stages of technology development and design.

The KPIs are normalized and aggregated to obtain an overall assessment of the sustainability performance. Different aggregation perspectives are considered to study the effect of subjectivity in prioritizing the various aspects (i.e., the technological, economic, environmental, and social dimensions) while determining the overall sustainability profile, allowing the ranking of the sustainability performance of alternative technologies and concepts.

A specific approach is included in the methodology to address sensitivity and uncertainty analysis of the results, thus providing the identification of the more influential parameters in the input data and the assessment of the robustness of the ranking.

The methodology is specifically conceived to support decision making in the early design of alternative power systems for ships, identifying the critical impacts that should be considered in design and the required trade-offs among the different sustainability compartments. The approach also allows the benchmarking to conventional solutions, providing a preliminary quantitative assessment of the expected benefits of the alternative concepts considered for implementation.

To exemplify the application of the methodology, reference power systems exploiting hydrogen, ammonia, and natural gas as marine fuels are defined, together with a reference solution based on conventional MGO used as a benchmark. The outcome of the study allows a thorough comparison of the sustainability performance of alternative power systems, based on data typically available during early design stages.

2. State-of-the-art of sustainability assessment methods for ship power systems

The assessment of sustainable marine technologies is a challenging task due to the possible conflicts among sustainability objectives and to stakeholders' preferences that need to be considered (Andersson et al., 2020). Techno-economic analysis (TEA) is widely employed to support the early stages of the development of innovative technologies (Mahmud et al., 2021; Thomassen et al., 2019; Zimmermann et al., 2020). The rigorous application of TEA consists in the combination of process modelling and design with the evaluation of capital and operating costs (Khodabandehloo et al., 2020). However, the safety and environmental aspects are given little attention in conventional TEA approaches (Mahmud et al., 2021). A comprehensive assessment of the potential environmental impacts due to the emission of pollutants is paramount to ramp-up the widespread and sustainable deployment of emerging ship power systems (Fernández-Ríos et al., 2022; Gilbert et al., 2018). A consensus exists on the need for holistic assessment tools based on a comprehensive and integrated set of criteria addressing both the reduction of harmful emissions and the maximization of socioeconomic benefits (Ashrafi et al., 2022; Kim et al., 2020). Specifically, sustainability objectives considered in the evaluation of cleaner ship power systems should encompass minimum environmental, technical, economic and social factors (Andersson et al., 2020; Ashrafi et al., 2022). The available methodologies can be classified into six categories: models for the simulation of systems' sustainability performances, optimization tools, hybrid (e.g., simulation combined with optimization) approaches, life cycle assessment (LCA)-based, multi-criteria decision analysis (MCDA) and experimental (Trivyza et al., 2022). LCA approaches proved to be effective in supporting decision-making among alternative ship power systems from an environmental point of view (Bicer and Dincer, 2017; Bilgili, 2021; Hwang et al., 2020). MCDA is considered the most appropriate technique for a structured assessment among the abovementioned approaches (Andersson et al., 2020; Trivyza et al., 2022). Within MCDA, further distinctions can be introduced. Most of the studies currently available in the literature are based on three domains, extending the TEA to include environmental and safety aspects. Indeed, minimizing the risk for passengers and workers represents a key element to guarantee societal acceptability in the scale-up of innovative energy systems (Mangla et al., 2020). The sustainable development of new ship power systems should therefore be oriented by an integrated evaluation of multiple criteria spanning different dimensions (e.g., techno-economic performance, environment, society) (Ashrafi et al., 2022; Jeong et al., 2018; Kim et al., 2020), as the analysis performed by Jeong et al. (2018) investigating marine gas oil (MGO)-based electric, mechanical and hybrid propulsion technologies. In this case, the method defined the overall sustainability performance as the sum of the equivalent monetary values of the impacts on the three sustainability dimensions considered. Hybrid propulsion systems were found to enhance both safety and environmental sustainability. Different factors can be considered to quantify system performance with respect to each domain. Rivarolo et al. (2021) applied a MCDA comparing technological aspects (i.e., volume, weight), economic aspects (i.e., cost) and environmental aspects (i.e., emission amounts) of ship power systems. Nevertheless, some analysis combining four domains can be retrieved. Ren and Liang (2017) performed a MCDA to combine environmental, economic, technological and social aspects of low-carbon fuels for cleaner maritime transport by means of weighting factors defined by expert judgment. Ren and Lützen (2017) also included socio-political criteria and employed a combination of analytical techniques to identify the most suitable alternative based on the involved maritime stakeholders' preferences. The former study indicated LNG and hydrogen as the marine fuels with the best sustainability fingerprint, whereas in the latter, nuclear power emerged as the most sustainable energy source, followed by LNG. Hansson et al. (2019) presented a multi-criteria sustainability assessment of alternative fuels for marine technologies, considering a 1–4 scoring system combined with inputs from selected decision-makers (e.g., authorities, shipowners, fuel producers). This approach is strongly affected by the background of the selected experts. Indeed, industrial stakeholders were found to attribute the highest sustainability fingerprint to LNG and heavy fuel oil, whereas renewable hydrogen followed by renewable methanol and hydrotreated vegetable oil represented the preferred choice of authority representatives. A similar analysis reported by Inal et al. (2022) indicates ammonia-based fuel cells as the most sustainable power systems for the decarbonization of maritime transport. The unpredictability of the overall sustainability performances can be reduced by means of a fundamental-based approach, as proposed by Iannaccone et al. (2020), based on sustainability KPIs.

The above analysis of previous studies on the topic of sustainability performance of clean fuels for maritime transportation unveils some weak points in existing multi-criteria sustainability assessment methods of alternative marine technologies: (i) subjectivity in the determination of the system performance and/or relative weights of criteria; (ii) lack of a systematic quantification of social sustainability performance, in particular with regard to the safety sub-domain; (iii) technological component of sustainability is often given for granted and not assessed through proper quantitative metrics; (iv) non-inclusion of ship type and operational features in the analysis; (v) lack of integrated sensitivity and uncertainty analysis considering critical input variables, such as fuel and emerging technology costs. Hence, an innovative methodology was developed in the present study to address these gaps emerging from the analysis of the previous literature.

3. Methodology

A systematic procedure based on the evaluation of multi-criteria KPIs was further developed and adapted to the comparative assessment of the sustainability of alternative ship power systems. The method is derived from the extension and modification of the approach originally proposed by Iannaccone et al. (2020) to assess the sustainability aspects of ship fuel technologies based on MGO and LNG. Based on the gaps and limitations of previous methodologies discussed in the literature review provided in section 2, several innovative elements were introduced: (i) the inclusion of a quantitative technological performance metric in the analysis; (ii) the adoption of different sustainability-oriented decision--making perspectives to address the sensitivity of the results considering the preferences of the involved stakeholders; (iii) the introduction of a specific procedure to manage the uncertainty of the results given by critical input variables identified by a sensitivity analysis.

The proposed method consists of a sustainability assessment based on four domains: technological performance, economic performance, environmental impact, and safety. A layered approach was applied to define the set of key performance indicators used in the present study. The overarching methodology applied to derive the impact tree used for the definition of the specific indicators was originally proposed by Tugnoli et al. (2011). A "stemming and pruning" procedure was then applied in several previous studies with the aim of identifying a limited number of representative indicators, able to capture the overall trend and magnitude of the environmental impact, limiting however the complexity of the assessment. Each indicator is based on evidence provided in previous studies and/or on the definition of a specific metric needed to capture a relevant impact evidenced in the stemming procedure. In particular, the safety, economic and environmental indicators are mostly derived from previous studies (e.g., see Iannaccone et al. (2020) and references cited therein), while the technological indicator was defined according to a specific metric, discussed in the following.

The different archetypes adopted in the aggregation procedure of KPIs allow for the identification of the most convenient solutions from medium-term and/or long-term sustainability perspectives. Eventually, an *a-priori* screening based on a brute force sensitivity analysis was introduced to identify the most influential parameters to be considered in the assessment of the uncertainty of the results. Fig. 1 summarizes the workflow of the methodology developed in the present study.

The methodology is based on the definition and characterization of reference process schemes for the alternative ship power systems considered (Step 1), followed by the calculation of a set of KPIs (Step 2) addressing the different aspects of sustainability. The KPIs are then normalized (Step 3). An aggregation procedure is then applied to provide a single overall sustainability index (Step 4). A sustainability index-based ranking of ship power systems is thus obtained and complemented with a sensitivity and uncertainty analysis to verify the robustness of the results (Step 5). In the following, the specific steps of the procedure are described in detail.

3.1. Collection of input data

A comparative sustainability assessment of alternative ship power systems requires to define a common reference basis and system boundaries for the analysis. In step 1 of the methodology (see Fig. 1), the time distribution of the power demanded by the ship under analysis and the duration of the sea voyage constitute the common reference basis.

The system boundaries adopted for the definition of ship power systems include fuel tanks and all the auxiliary units (e.g., heat exchangers, pumps, and compressors) required to utilize the fuel. Alternative power systems to be considered in the analysis are identified by the combination of the type of fuel and technology for energy production installed on board.

Data on the main operating conditions, fuel conversion efficiency, capital and operating cost items, and emissions generated during operation need to be collected for each selected system.

When not available, the conceptual design of fuel storage and preparation needs to be performed for each system to obtain a set of reference process flowsheets to be considered in the following steps of the analysis. Energy and material balances are considered at this stage to retrieve the operating parameters of the reference power systems and the inventory of fuel stored on board. The preliminary design of the process units in the flowsheets (e.g., fuel storage tanks, heat exchangers, fuel preparation equipment, etc.) is conducted to evaluate the key features of the equipment layout.

Power demand is a key input data that deeply influences the sustainability performance. In order to perform a significant comparison, power demand on representative ship itineraries should be determined, considering extended time intervals (several days up to yearly averages). When relevant, geographical factors should also be considered in determining the power demand (e.g., the influence of meteorological conditions, tidal and maritime currents, etc.). Time resolution of the data needs to be sufficiently detailed to ensure the significance of the data, also considering that the power units operating may be different

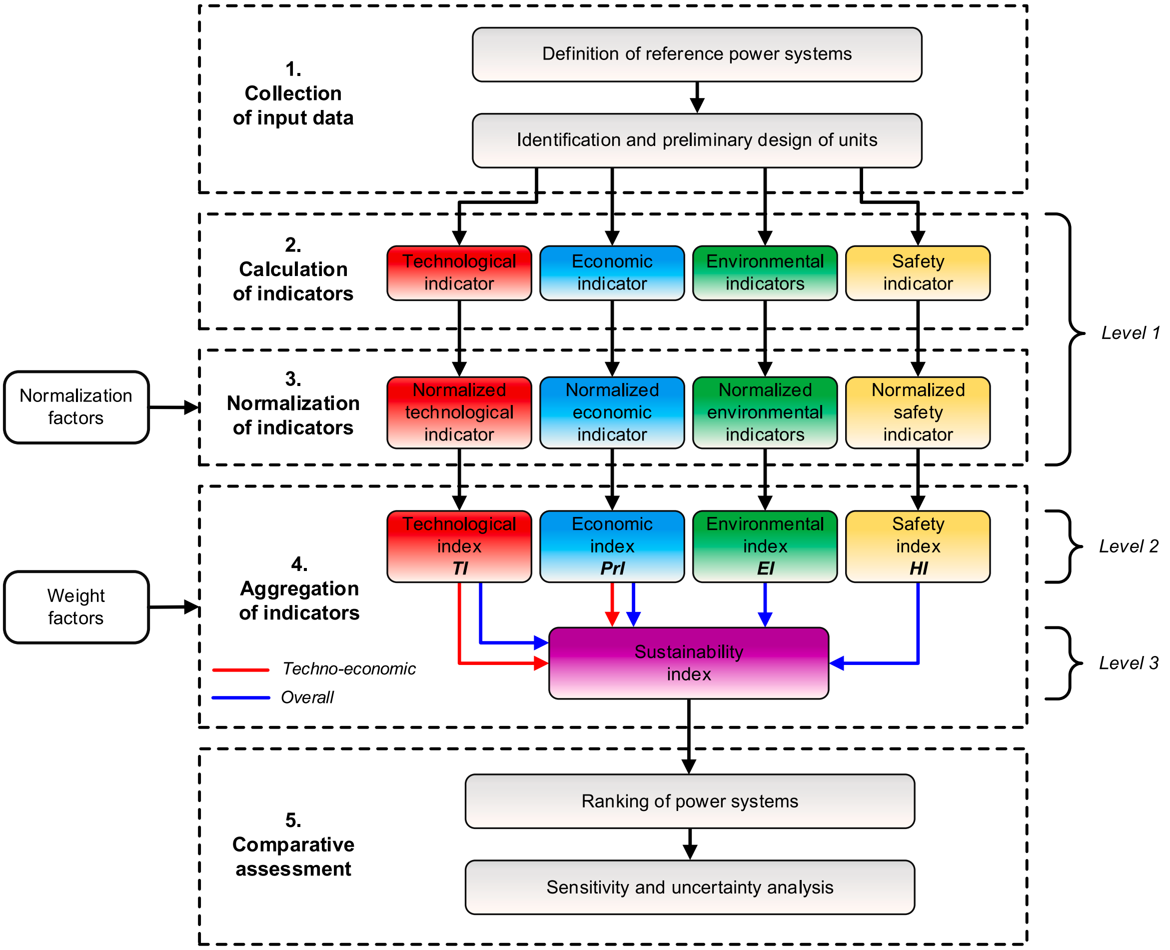

Fig. 1. Flowchart of the approach developed for sustainability assessment.

for different power requirements. Moreover, time resolution is also affected by the operating mode of the ship, the maneuvering phase being that where a more significant and rapid change in the power requirements with respect to time may be present. Finally, a trade-off may be needed among resolution and resources required by the management of an extended data set. In general, hourly time averages may be sufficient to address the power demand at berth and during navigation, while a lower time resolution, of the order of minutes, is advised when maneuvering.

Nevertheless, it should be considered that when examining alternative power system concepts in early design, time and spatial averaged data may be sufficient to allow a significant comparison, as discussed in the case study introduced in the following.

3.2. Calculation of indicators

Level 1 key performance indicators are calculated in step 2 of the methodology (see Fig. 1) with reference to the four sustainability dimensions considered in this study: the technological, economic, environmental, and safety domains. In the following, the definition and the procedure for the calculation of each indicator are reported.

3.2.1. Technological indicator

The volume occupied by the fuel (i.e., the technological index *TI,* Eq. (1)) needed for the duration of the sea voyage, assumed in step 1 as a common reference basis for the assessment, is selected as a key indicator representative of the technological performance of alternative power systems. Indeed, the above parameter significantly affects the space requirements of the power system and thus measures the technological complexity related to its installation on board (Andersson et al., 2020; Mandić et al., 2021; Rattazzi et al., 2021). Since the same duration of sea voyage is assumed as a basis of comparison, the amount of fuel that needs to be stored accounts also for the energy efficiency of the power system.

$$TI = \frac{\int_0^{t_{act}} P dt}{\rho_{fuel} \bullet \eta_{system} \bullet \Delta H_{c,fuel}} \tag{1}$$

In Eq. (1), *TI* is defined as the volume of stored fuel needed per trip, t_{act} is the trip duration, P is the power demand at a given time, ρ_{fuel} is the density of the fuel under the specific storage conditions, η_{system} is the energy efficiency of the fuel utilization system and $\Delta H_{c,fuel}$ is the energy that is produced oxidizing the fuel (e.g., by a combustion process).

It should be remarked that the density of the fuel in Eq. (1) is influenced by the storage conditions (i.e., physical state, temperature and pressure) considered for each ship power system during the conceptual design stage. Thus, different densities may correspond to the same fuel depending on the storage system (e.g., compressed or liquid hydrogen).

As discussed above, in Eq. (1), the power demand with respect to time, *P*, can be derived statistically from the collection of historical operational data for the ship type considered (Yeh et al., 2022). The energy efficiency, η_{system}, expresses the amount of the chemical energy provided by the energy vector considered that is converted to mechanical energy. This parameter is determined on the basis of available technical data reported in the literature for fuel cells and conventional combustion engines (e.g., see Tronstad et al. (2017)). As an alternative, actual data concerning the fuel consumption on the trip considered may be used if a ship with the power system of interest is operating.

Clearly enough, the technological indicator defined by Eq. (1) implies that a higher value of TI, corresponding to a higher volume of fuel needed on board for a given sea voyage, leads to a lower technological performance of the ship power system.

3.2.2. Economic indicator

A profitability index (*PrI*), defined in Eq. (2) as the opposite of the net present value (NPV), is introduced to evaluate the economic viability of alternative ship power systems. Such index aims at providing a straightforward evaluation of the potential of a project in creating an economic return over its whole lifespan while considering the time value of money (Hopkinson, 2017).

$$PrI = CAPEX + \sum_{t=1}^{n} \frac{OPEX_t}{(1+r)^t} \tag{2}$$

In Eq. (2), $CAPEX$, $OPEX_t$ and n are respectively the initial capital expenditure, the operating expenditure at time t and the economic lifespan of the ship power system. The variable r represents the discount rate. In Eq. (2), the economic lifespan and discount rate are set equal to 25 years and 6%, respectively (Sekkesæter, 2019). The evaluation of CAPEX and OPEX is performed by an economic assessment model based on unitary costs gathered from the technical literature (Iannaccone et al., 2020). The cost assumptions adopted for the economic assessment are detailed in the following (see section 4) with reference to the specific alternative ship power systems defined in the study.

Based on the above definition, a higher value of PrI corresponds to a higher cost and thus to a higher economic impact associated with the ship power system considered.

3.2.3. Environmental indicators

Environmental performance indicators are defined applying a layered approach summarized by a specific impact tree, elaborated according to the methodology originally proposed by Tugnoli et al. (2011), including a stemming and pruning procedure to obtain a limited set of significant indicators. The procedure provides a set of environmental KPIs allowing a direct correlation between impacts and emissions and the evaluation of the shift in impacts from one category to another when considering different technological alternatives (Tugnoli et al., 2013). The specific pruning procedure conducted by Iannaccone et al. (2020) is applied, based on a shortcut comparative evaluation of the order of magnitude of the indicators in the framework of interest. Air and water are considered the environmental sub-domains mostly affected by emissions from fuel use. The environmental categories resulting from the customized impact tree are global warming, rain acidification and human toxicity for air and eutrophication for water (Iannaccone et al., 2020).

An activity-based approach is used to assess the annual emissions associated with the ship power system (Iannaccone et al., 2020; Nunes et al., 2017), as shown in Eq. (3).

$$E_i = \sum_j \left(ef_{i,j} \bullet P_j \bullet \int_0^{t_{act}} LF_j dt \right) \tag{3}$$

In Eq. (3), E_i is the amount of i-th pollutant emitted per unit time, $ef_{i,j}$ is the emission factor of the i-th pollutant, P_j is the nominal power associated with the propulsion unit of type j (e.g., main or auxiliary), LF_j is the load factor of the j-th power unit and t_{act} is the overall ship activity time (i.e., sea voyage duration). Based on the available operational data of the ship, the time interval and the level of detail of interest, different time resolutions can be considered to calculate the time integral of the load factor in Eq. (3). In the case study addressed in the following (see section 4), an approach based on the discretization among operational modes of the ship is assumed, and average values of the load factors are obtained for each operational mode.

The set of indicators quantifying the types of impact considered can then be calculated as in Eq. (4).

$$I_c = \sum_i E_i \bullet PF_{i,c} \tag{4}$$

In Eq. (4), I_c and $PF_{i,c}$ are respectively the environmental indicator and the potential factor of the i-th pollutant for the c-type impact category. Potential factors considered in Eq. (4) are retrieved from a reference operational guide (Guinèe, 2001) on standard LCA procedures and quantify the contributions of the pollutants to the types of impact considered. Clearly enough, alternative values may be considered for use.

Five critical pollutants are considered in the present study: carbon dioxide, methane, nitrogen oxides, sulfur oxides and particulate matter. Table 1 reports the values of potential factors adopted in the present study for each impact category. The above definition of the environmental performance indicator of ship power systems implies that a higher value of the indicator corresponds to a larger extent of the impact on the corresponding category.

3.2.4. Safety indicator

A set of consequence-based inherent safety KPIs (IS-KPIs) is adopted to assess the safety performance of ship power systems as a function of the hazards arising from fuel utilization on board (Iannaccone et al., 2019). Indeed, the IS-KPIs are suitable to introduce a quantitative safety metric in the framework of sustainability-oriented decision analysis among technological alternatives (Cipolletta et al., 2022; Crivellari et al., 2021). An overall inherent hazard index (*HI*) is defined in Eq. (5), where UHI_k is the unit inherent hazard index of the unit k in the ship power system considered, defined in Eq. (6).

$$HI = \sum_k UHI_k \tag{5}$$

$$UHI_k = \sum_i cf_{i,k} \bullet h_{i,k}^2 \tag{6}$$

In Eq. (6), $cf_{i,k}$ and $h_{i,k}$ are respectively the credit factor and the maximum damage distance evaluated for the i-th loss of containment (LOC) event considered for the unit k. Table 2 reports the set of release modes leading to loss of containment considered as a reference in the present study and derived from those originally proposed byUijt de Haag and Ale (2005)).

The applicable LOCs among those listed in Table 2 are determined for each unit, identifying the most hazardous factor among substance hold-up and process flow rates, as suggested by Zanobetti et al. (2023). Conventional consequence analysis models (Van Den Bosh and Weterings, 2005) are used to compute the damage distances, $h_{i,k}$ (see Eq. (6)), corresponding to specific threshold values. The threshold values adopted in the present study for the consequence analysis are reported in Table 3.

The credit factors evaluated for the set of LOCs adopted are intended to represent a measure of the likelihood of the occurrence of the alternative release modes considered, based on statistical data on equipment

Table 1
Potential factors considered for environmental impact assessment (CO_2, carbon dioxide; CH_4, methane; NO_x, nitrogen oxides; SO_x, sulfur oxides; PM, particulate matter). The potential factors are derived from Guinèe (2001). The categories of impact are derived from Iannaccone et al. (2020).

Substance	Global warming (GW)	Rain acidification (RA)	Human toxicity (HT)	Eutrophication (EU)
CO_2	1.00	–	–	–
CH_4	28.00	–	–	–
NO_x	–	0.50	1.20	0.13
SO_x	–	1.20	0.10	–
PM	–		0.82	–

Table 2
Loss of containment events (LOCs) considered for inherent safety assessment (Uijt de Haag and Ale, 2005).

LOC	Description
R1	Small leak, continuous release from a 10 mm equivalent diameter hole
R2	Catastrophic rupture, release of the entire inventory in 600 s
R3	Catastrophic rupture, instantaneous release of the entire inventory and release from the full-bore feed pipe
R4	Pipe leak, continuous release from a hole having 10% of pipe diameter
R5	Pipe rupture, continuous release from the full-bore pipe

Table 3
Threshold values considered for the quantification of damage distances (Iannaccone et al., 2019; Zanobetti et al., 2023).

Dangerous phenomenon	Threshold value (damage to human target)
Flash fire	½ LFL [a]
Fireball	7 kW/m^2
Jet fire	7 kW/m^2
Pool fire	7 kW/m^2
Vapor cloud explosion	14 kPa
Toxic dispersion	IDLH [b]

[a] LFL, lower flammability limit [% vol].

[b] IDLH, toxic concentration immediately dangerous to life and health [ppm vol].

leak frequency or fault tree analysis (Crivellari et al., 2021; Iannaccone et al., 2019; Zanobetti et al., 2023). Baseline release frequencies reported in previous technical studies (American Petroleum Institute, 2000; Uijt de Haag and Ale, 2005) are used as credit factors summarizing the safety score of standard equipment items.

The above-described safety assessment method ultimately allows ranking the inherent hazard level of each power system based on input data on the implemented equipment and operating parameters typically available during early design stages. It is important to remark that, based on the definition of the inherent hazard index (see Eq. (5)), a higher score of HI corresponds to a higher inherent hazard level and thus to a lower overall safety performance of the ship power system considered.

3.3. Normalization of indicators

In step 3 of Fig. 1, the KPIs are normalized to allow for the comparative assessment of the contribution of different categories of impact to the overall sustainability performance of the alternative ship power systems considered. The normalization procedure is conducted by measuring each key performance indicator with respect to a given reference value, as defined in Eq. (7).

$$NI_i = \frac{I_i}{NF_i} \tag{7}$$

In Eq. (7), NI_i, I_i and NF_i are respectively the normalized indicator, the value of the KPI and the normalization factor addressing the i-th impact category. The latter, applying a standard internal normalization route (Ahmad et al., 2019; Illahi and Mir, 2020), is assumed equal to the maximum value of the indicator obtained considering all the alternative power systems analyzed.

3.4. Aggregation of indicators

A two-stage multi-criteria weighted summation is adopted to perform the aggregation of level 1 key performance indicators (see step 4 of Fig. 1). The first step yields level 2 indices scoring the overall impact of the power system on each sustainability pillar. More specifically, no aggregation is required within the technological, economic and safety domains, being their corresponding impacts assessed by a single key performance indicator. Conversely, the fixed weighting approach adopted to aggregate the environmental KPIs in a single index (Iannaccone et al., 2020) is reported in Eq. (8).

$$EI = 0.3 \bullet NI_{GW} + 0.3 \bullet NI_{RA} + 0.2 \bullet NI_{HT} + 0.2 \bullet NI_{EU} \tag{8}$$

In Eq. (8), EI, NI_{GW} and NI_{RA} are respectively the environmental index and the normalized indicators referring to global warming and rain acidification, while NI_{HT} and NI_{EU} are the normalized indicators addressing impacts due to human toxicity and eutrophication.

Finally, the level 3 techno-economic sustainability index (TESI) and the overall sustainability index (OSI) are defined based on level 2 indices. The OSI index provides an overall sustainability fingerprint of ship power systems, while the TESI index is introduced to compare alternative technologies only considering the conventional techno-economic point of view.

Four alternative aggregation modes are applied to merge in a single index the performance indices defined in the different sustainability domains considered. More specifically, the individualist, egalitarian, hierarchist, and equal weighting approaches are considered in the present study. Table 4 reports the multi-criteria weighting approaches corresponding to the different archetypes of decision-makers considered for the assessment of level 3 indices. As shown in the table, the four different aggregation modes differ in the weighting coefficients used in the aggregation of the sustainability aspects considered. The selected coefficients can be intended as representative of the relative importance attributed by decision-makers to the specific sustainability domain. Additional insights on the available aggregation modes and their implications are reported in the literature (Crivellari et al., 2021; Dincer et al., 2021).

3.5. Comparative assessment

The alternative ship power systems considered are comparatively assessed in step 5 of the procedure (see Fig. 1) by ranking their performance according to the normalized level 2 and aggregated level 3 indices. The robustness of the performance-based rankings obtained is evaluated by an uncertainty analysis, considering the most influential input variables in the study. The parameters are preliminarily screened by a brute force sensitivity analysis accounting for the effects produced by alterations of the input data on the calculated indicators. More specifically, a modification factor between 0.9 and 1.1 is considered for each input variable. The differences between the resulting indicators and their corresponding base values are calculated with respect to each variable and expressed as percentage of variation. Any input parameter causing a percent variation larger than ±3% in the final indicator is considered influential in the study and thus included in the uncertainty analysis of the results.

A Monte Carlo technique is then used to simulate the effects of

Table 4
Weight factor attributed to each sustainability pillar in the computation of TESI and OSI indices according to the different aggregation perspectives adopted (Crivellari et al., 2021; Dincer et al., 2021).

	Weight factors			
Decision-making perspective	Technological performance	Economy	Environment	Safety
Techno-economic sustainability index (TESI)				
Individualist	0.23	0.77	0.00	0.00
Egalitarian	0.82	0.18	0.00	0.00
Hierarchist	0.69	0.31	0.00	0.00
Equal weighting	0.50	0.50	0.00	0.00
Overall sustainability index (OSI)				
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

uncertainty of the most influential input parameters identified by the sensitivity analysis on the performance rankings of the alternative power systems considered. A confidence interval is defined for each of the influential variables assessed. The uncertain parameters are considered sampled in their corresponding confidence range according to a uniform probability distribution function, the latter being able to yield conservative results based on limited initial assumptions (Crivellari et al., 2021). A total of 10^6 Monte Carlo runs are used since a higher number of simulations was proved not to affect the outcome of the analysis (Zanobetti et al., 2023). Cumulative probabilities of inversion in the performance-based rankings of the alternative power systems are finally obtained as a result of the above-described sensitivity and uncertainty assessment approach: the lower the probability of alterations in the rankings of power systems, the higher the robustness of the comparative sustainability assessment procedure adopted.

4. Alternative ship power systems

The methodology described in section 3 was applied to the assessment of alternative ship power systems considered to reduce the environmental impact of maritime transportation. Results were compared with the traditional system based on marine gas oil. A case study concerning a Hyperion-class cruise ship (The Maritime Executive, 2016) was defined to exemplify the practical application of the methodology.

The ship power systems considered in the present study are listed in Table 5.

Hydrogen, ammonia and natural gas were selected since they are considered promising clean fuels for the decarbonization of maritime transport (Al-Enazi et al., 2021). Liquid hydrogen (LH_2), compressed gaseous hydrogen (CGH_2) and cryo-compressed liquid hydrogen ($CcLH_2$) were considered as alternative storage concepts for pure hydrogen (Baetcke and Kaltschmitt, 2018). Storage of liquid ammonia (LNH_3) under pressure at 8.6 bar and ambient temperature is the concept mostly considered for application to ship propulsion (ABS, 2020; Zincir, 2020). Conversely, cryogenic liquid storage at 6 bar and subsequent vaporization before final utilization is the most frequent solution adopted for the use of liquefied natural gas (LNG) as a marine fuel (Iannaccone et al., 2019, 2020).

Conventional ship power systems are based on the storage and use of marine gas oil (MGO): hence, MGO was considered a benchmark to assess the performance of alternative clean fuel technologies.

Concerning ship propulsion, proton exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs) represent the most effective solutions for the utilization of hydrogen and ammonia, respectively (ABS, 2020; Fan et al., 2021). A lean burn spark ignition (LBSI) system and an internal combustion engine (ICE) were considered respectively for natural gas and MGO (Iannaccone et al., 2020).

The technical requirements of a Hyperion-class cruise ship (The Maritime Executive, 2016) were selected as a common reference basis for the conceptual design of the alternative ship power systems considered. The time-space resolution adopted for the specification of the above input data was defined based on the level of detail of interest for an early design phase of ship power systems. In this study, the temporal distribution of power demand during the voyage is expressed in a discretized form, wherein constant values of power demand and time duration are attributed to standard shipping operational modes (i.e., maneuvering, at berth, navigation), as shown in Table 6. Spatial-averaged values were used, and spatial variations were considered negligible for any input, in order to obtain baseline reference results suitable for the characterization of the early phase of the design lifecycle of ship power systems. The power demand is divided into auxiliary and main power. Additional characteristics and operational features considered for the shipping category assessed in the present study are reported elsewhere (Iannaccone et al., 2020; The Maritime Executive, 2016).

Fig. 2 shows the flowsheets developed for the alternative ship power systems. The total fuel storage capacity was calculated considering 10 days of overall activity time per voyage and the operational profile reported in Table 6. The efficiency of fuel utilization associated with each ship power system, η_{system} (see Eq. (1)), was gathered by a survey of dedicated technical databases and literature works (Ballard Power, 2023; Iannaccone et al., 2019, 2020). When multiple storage units were required, an equal nominal volume was assumed for each tank. The geometric features and the operating conditions of the equipment items implemented in each reference flowsheet are reported in Table 7. A detailed description of each reference power system is reported in the Supplementary Material.

For the sake of simplicity, the capital costs (CAPEX, see Eq. (2)) considered in the economic assessment of reference ship power systems only include the investments required for fuel storage and utilization on board. Investments related to auxiliaries (e.g., pumps, compressors, heat exchangers) are not considered, since these are strongly dependent on the specific assumptions made during detailed design and could introduce biases in the analysis when addressing the comparison of alternatives during early and conceptual design. Fuel consumption, maintenance and taxation on CO_2 emissions are considered in the overall operating expenditure (OPEX, see Eq. (2)). Specific cost data gathered for the alternative ship power systems considered, actualized to the year 2022, are reported in the Supplementary Material.

The assessment of exhaust gas emissions due to the operativity of ship power systems represents the starting point to quantify

Table 6
Breakdown of power load factor, power demand and activity time per operational mode of the ship under analysis. Data adapted from Iannaccone et al. (2020).

Operational mode	Activity time (h/yr)	Auxiliary power load factor (%)	Main power load factor (%)	Auxiliary power (MW)	Main power (MW)
Maneuvering	188	75	20	13.5	3.6
At berth	2756	60	0	10.8	0.0
Navigation	3320	30	80	5.4	14.4

Table 5
Summary of the characteristics of the alternative ship power systems considered (PEMFC, proton exchange membrane fuel cell; SOFC, solid oxide fuel cell; LBSI, lean burn spark ignition; ICE, internal combustion engine). Fuel storage parameters adapted from dedicated technical contributions (ABS, 2021, 2020; Gomez Trillos et al., 2019; Hassan et al., 2021; Hyde and Ellis, 2020; Iannaccone et al., 2020; Usman, 2022).

			Fuel storage conditions			
Power system	Designation	Fuel	Physical state	Pressure (bar)	Temperature (°C)	Propulsion
PS 1	LH_2-PEMFC	Hydrogen, liquid (LH_2)	Liquid	1.0	−252.8	PEMFC
PS 2	CGH_2-PEMFC	Hydrogen, compressed gas (CGH_2)	Gas	350.0	20.0	PEMFC
PS 3	$CcLH_2$-PEMFC	Hydrogen, cryo-compressed liquid ($CcLH_2$)	Liquid	350.0	−252.8	PEMFC
PS 4	LNH_3-SOFC	Ammonia, liquid (LNH_3)	Liquid	8.6	20.0	SOFC
PS 5	LNG-LBSI	Liquefied natural gas (LNG)	Liquid	6.0	−133.2	LBSI
PS 6	MGO-ICE	Marine gas oil (MGO)	Liquid	1.2	44.9	ICE

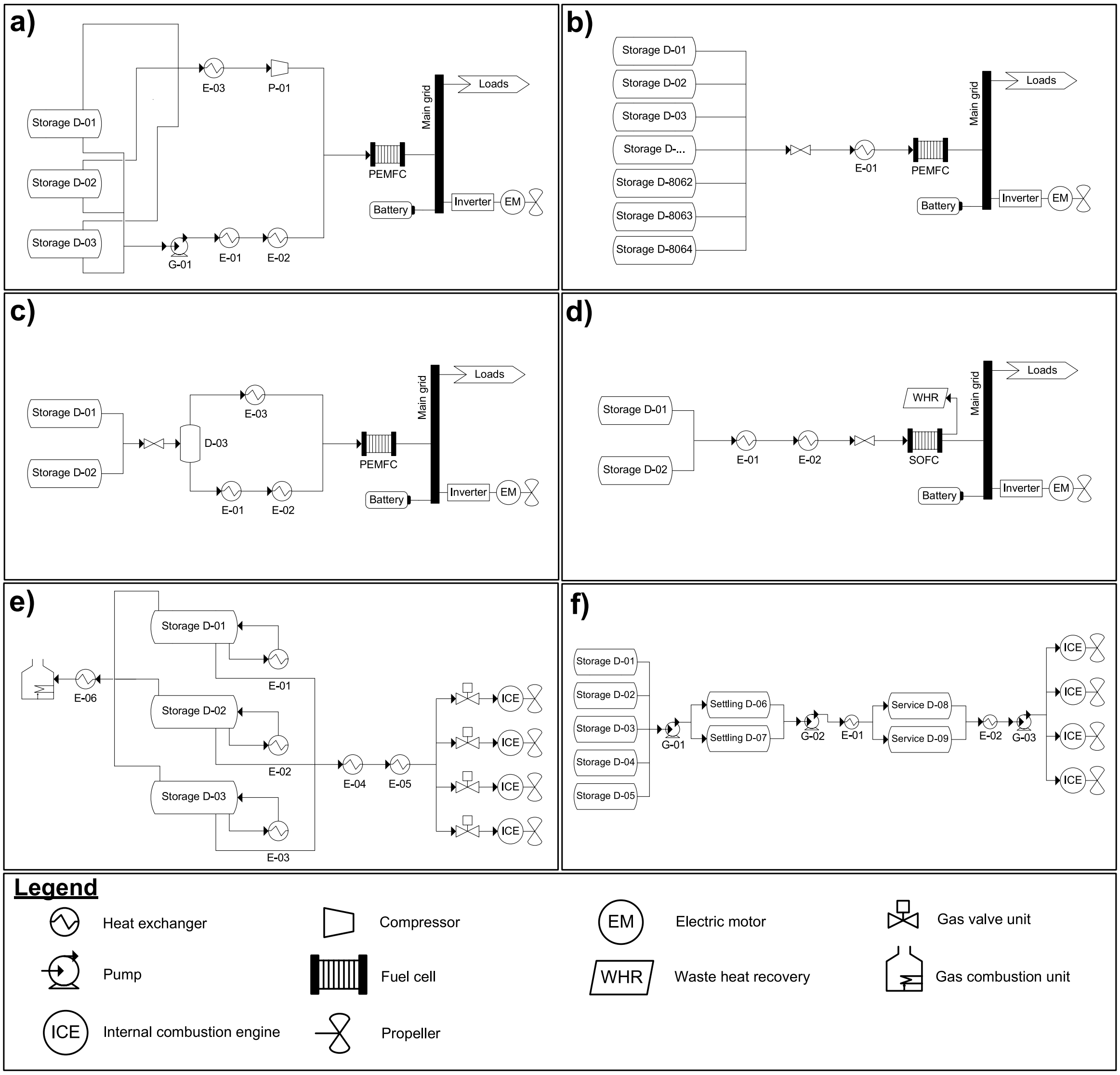

Fig. 2. Reference flowsheets of the alternative ship power systems considered in the analysis: a) PS 1 – Liquid hydrogen-based proton exchange membrane fuel cell (LH_2-PEMFC); b) PS 2 – Compressed gaseous hydrogen-based proton exchange membrane fuel cell (CGH_2-PEMFC); c) PS 3 – Cryo-compressed liquid hydrogen-based proton exchange membrane fuel cell ($CcLH_2$-PEMFC); d) PS 4 – Liquid ammonia-based solid oxide fuel cell (LNH_3-SOFC); e) PS 5 – Liquefied natural gas-based lean burn spark ignition (LNG-LBSI); PS 6 – Marine gas oil-based internal combustion engine (MGO-ICE). Table 5 reports the main features of Power Systems (PSs). Table 7 reports the key features of the equipment.

environmental impacts (see Eq. (4)). To evaluate the emissions by the activity-based method described in Eq. (3), pollutant emission factors were specified for each power unit (i.e., main and auxiliary). In particular, the utilization of ammonia and hydrogen by fuel cell systems was assumed to yield a condition of zero-emission propulsion (i.e., null emission factors) (McKinlay et al., 2021), being electricity, water and heat the only expected products (Xing et al., 2021b). The emission factors considered for the quantification of the set of environmental impact indicators are reported in the Supplementary Material.

5. Results

5.1. Sustainability KPIs (level 1 and level 2)

The flowsheets for the alternative power systems considered for a Hyperion-class cruise ship (see section 4) were assessed by applying the methodology developed in this study (Step 2 in Fig. 1, see section 3). Table 8 reports the highest value of each level 1 KPI obtained in the analysis of the alternative reference flowsheets (i.e., the normalization factors, NFs), together with the corresponding power system. The values of all the level 1 indicators calculated for the case study are reported in the Supplementary Material.

The NFs values reported in Table 8 were assumed as a reference for the internal normalization procedure (Step 3 in Fig. 1). The level 2 KPIs were obtained by implementing the above normalization approach and the aggregation procedure described in section 3.4 (Step 4 in Fig. 1).

Fig. 3 reports the values calculated for the level 2 KPIs, which provide a performance-based ranking of the alternative ship power systems per each sustainability domain considered.

As shown in Fig. 3, PS 2 (CGH_2-PEMFC) results in the least effective alternative from a combined techno-economic point of view, scoring the highest impacts for both the technological index, TI, and the economic index, PrI. This can be attributed to the massive volume of hydrogen storage required on board, which leads to the installation of several pressurized storage tanks, and to the significant cost of compressed hydrogen. When considering the technological performance, Fig. 3a shows that PS 4 (LNH_3-SOFC) scores the lowest value of the corresponding KPI, TI, thus resulting in the best-performing solution.

Table 7

Operating conditions and key features resulting from the conceptual process design performed in the present study for the reference ship power systems reported in Fig. 2. See Table 5 for the main features of Power Systems (PSs).

PS 1: Liquid hydrogen-based proton exchange membrane fuel cell (LH$_2$-PEMFC)

Parameter	Storage tank (D01-D03)	Pump (G01)	Vaporizer (E01)	Heater (E02)	BOG heater (E03)	BOG compressor (P01)
Nominal volume (m^3)	1,200	–	–	–	–	–
Fuel inventory (t)	63.03	–	–	–	–	–
Fuel flow rate (kg/s)	–	0.24	0.24	0.24	4.0×10^{-5}	4.0×10^{-5}
Pressure (bar)	1.0	3.5	3.5	3.5	1.01	3.5
Temperature (°C)	−252.8	−252.4	−247.8	70	−50.6	70
Fuel state	Liquid	Liquid	Vapor	Vapor	Vapor	Vapor

PS 2: Compressed gaseous hydrogen-based proton exchange membrane fuel cell (CGH$_2$-PEMFC)

Parameter	Storage tank (D01-D8064)	Heater (E01)
Nominal volume (m^3)	0,99	–
Fuel inventory (t)	0.02	–
Fuel flow rate (kg/s)	–	0.25
Pressure (bar)	350.0	3.5
Temperature (°C)	20.0	70.0
Fuel state	Vapor	Vapor

PS 3: Cryo-compressed liquid hydrogen-based proton exchange membrane fuel cell (CcLH$_2$-PEMFC)

Parameter	Storage tank (D01-D02)	Separator (D03)	Vaporizer (E01)	Heater (E02)	Gas heater (E03)
Nominal volume (m^3)	1,200	–	–	–	–
Fuel inventory (t)	93.61	–	–	–	–
Fuel flow rate (kg/s)	–	0.25	0.14	0.14	0.10
Pressure (bar)	350.0	3.5	3.5	3.5	3.5
Temperature (°C)	−252.8	−247.8	−247.8	−247.8	−247.8
Fuel state	Liquid	Vapor-Liquid	Liquid	Vapor	Vapor

PS 4: Liquid ammonia-based solid oxide fuel cell (LNH$_3$-SOFC)

Parameter	Storage tank (D01-D02)	Vaporizer (E01)	Heater (E02)
Nominal volume (m^3)	1,200	–	–
Fuel inventory (t)	558.47	–	–
Fuel flow rate (kg/s)	–	1.46	1.46
Pressure (bar)	8.6	8.6	8.6
Temperature (°C)	20.0	20.3	601.0
Fuel state	Liquid	Vapor	Vapor

PS 5: Liquefied natural gas-based lean burn spark ignition (LNG-LBSI)

Parameter	Storage tank (D01-D03)	Pressure build-up unit (E01-E03)	Vaporizer (E04)	Fuel gas heater (E05)	BOG heater (E06)
Nominal volume (m^3)	1,200	–	–	–	–
Fuel inventory (t)	495	–	–	–	–
Fuel flow rate (kg/s)	–	0.20	1.62	1.62	6.96×10^{-3}
Pressure (bar)	6.0	6.0	6.0	6.0	6.0
Temperature (°C)	−133.0	−130.0	−123.0	20.0	20.0
Fuel state	Liquid	Vapor	Vapor	Vapor	Vapor

PS 6: Marine gas oil-based internal combustion engine (MGO-ICE)

Parameter	Storage tank (D01-D05)	Transfer pump (G01)	Settling tank (D06-D07)	Feed pump (G02)	Heater (E01)	Service tank (D08-D09)	Heater (E02)	Booster pump (G03)
Nominal volume (m^3)	400	–	25	–	–	25	–	–
Fuel inventory (t)	293.4	–	20.0	–	–	20.0	–	–
Fuel flow rate (kg/s)	–	1.78	–	1.78	1.78	–	1.78	1.78
Pressure (bar)	1.2	3.5	3.5	5.0	5.0	5.0	5.0	8.0
Temperature (°C)	45.0	45.0	45.0	45.0	60.0	60.0	100.0	100.0
Fuel state	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid

However, limited differences are present in the TI values of PSs 3, 4, and 6. The relatively low values of the TI obtained for these power systems are due to the high energy content per unit volume associated with MGO, cryo-compressed liquid hydrogen and liquid ammonia, together with the high efficiency in energy conversion obtained when using fuel cells. Also in the case of the aggregated environmental index, EI, a single power system scores the worst performance. Not surprisingly, PS 6 (MGO-ICE), based on the use of MGO as a fuel, presents the highest environmental impact, due to the significant amounts of greenhouse gases and harmful pollutants emitted (see Table 8). The comparative assessment of the environmental performance of the alternative power systems considered, expressed by the EI index shown in Fig. 3c, clearly points out the significant advantage in the adoption of carbon-free energy vectors (i.e., ammonia, hydrogen) as marine fuels. Actually, both PSs 5 (LNG-LBSI) and 6 (MGO-ICE) show relevant impacts with respect to all the power systems based on clean fuels, even if the LNG-based solution scores an EI value that is about half of that of MGO. When the hazard index, HI, is considered as a proxy of the societal pillar of sustainability, Fig. 3d highlights that power systems based on fossil fuels result in general inherently safer solutions. This is due to the higher inherent hazard level generated by the accident scenarios involving gaseous hydrogen and ammonia, respectively extremely flammable and toxic. Indeed, the NH$_3$-based power system (PS 4) results in the highest value of the HI index, and thus in the lowest safety performance, due to

Table 8
Internal normalization factors adopted for the level 1 KPIs calculated for the case study. Table 5 reports the main features of the Power Systems (PSs) considered.

Indicator	Impact	Least performant option	Normalization factor (NF)	Unit
TI	Technological	PS 2	8015.00	m^3
I_{GW}	Global warming	PS 6	5.70×10^7	kg_{eq}/yr
I_{RA}	Rain acidification	PS 6	1.98×10^5	kg_{eq}/yr
I_{HT}	Human toxicity	PS 6	4.19×10^5	kg_{eq}/yr
I_{EU}	Eutrophication	PS 6	4.36×10^4	kg_{eq}/yr
PrI	Economic	PS 2	1046.56	M€ [a]
HI	Safety	PS 4	1232.89	m^2/yr

[a] PrI indicator is based on costs actualized to the year 2022.

the wide impact area associated with possible toxic releases of ammonia. Among the fuel cell-based power systems considered, only PS 3 (CcLH_2-PEMFC) presents a safety performance comparable to those of LNG and MGO. The lower inherent hazard of PS 3 is caused by the reduced criticality of credible LOCs involving hydrogen stored as a subcooled liquid. Indeed, a significantly wider area may be impacted by releases of high-pressure gaseous hydrogen in PS 2, generating an inherent hazard index about 1.6 times higher than in PS 3. Similarly, the lower safety performance of PS 1 (LH_2-PEMFC) compared to that of PS 3 may be attributed to the greater proneness of hydrogen stored as an atmospheric boiling liquid to cause the formation of flammable vapor clouds.

As shown in Fig. 3b, PS 6 (MGO-ICE) emerges as the alternative scoring the best economic performance, due to the overall lowest capital and operating expenditures estimated based on the currently available cost figures. Differently, PS 5 (LNG-LBSI) and PS 3 (CcLH_2-PEMFC) score respectively the second and third highest values of the economic index. The significant capital expenditure related to the implementation of pressurized cryogenic storage vessels limits the economic performance of both power systems, with the high cost of supply of LNG further penalizing PS 5. However, the results concerning the profitability index may be analyzed more in detail if the breakdown into capital and operating costs per reference power system is considered, as reported in Fig. 4. As shown in the figure, the profitability of the examined alternative power systems appears to be mostly determined by OPEX. The above consideration suggests that a careful evaluation of operating costs considering the variability of fuel prices and the time value of money (i.e., discount rate) is paramount to improve confidence in the results obtained from the economic comparison of alternative ship power systems.

5.2. Techno-economic and overall sustainability aggregations (level 3)

The level 2 technological and economic KPIs reported in Fig. 3 were used to assess the level 3 techno-economic sustainability index (TESI) by the aggregation procedure described in section 3.4 (Step 4 in Fig. 1). Fig. 5 shows the TESI values obtained for the alternative power systems considered, calculated according to the different decision-making perspectives implemented.

Fig. 5 clearly shows that PS 2 (CGH_2-PEMFC) exhibits the worst techno-economic performance, regardless of the perspective adopted for the analysis. This confirms the significant drawbacks deriving from the voluminous and costly pressurized tanks needed for the storage of compressed gaseous hydrogen. Nevertheless, the techno-economic assessment provided by the TESI index seems not to be sufficient to identify unambiguously the best-performing ship power system. The aggregation of the indices representing the system's performances with respect to all the four sustainability dimensions considered in this study,

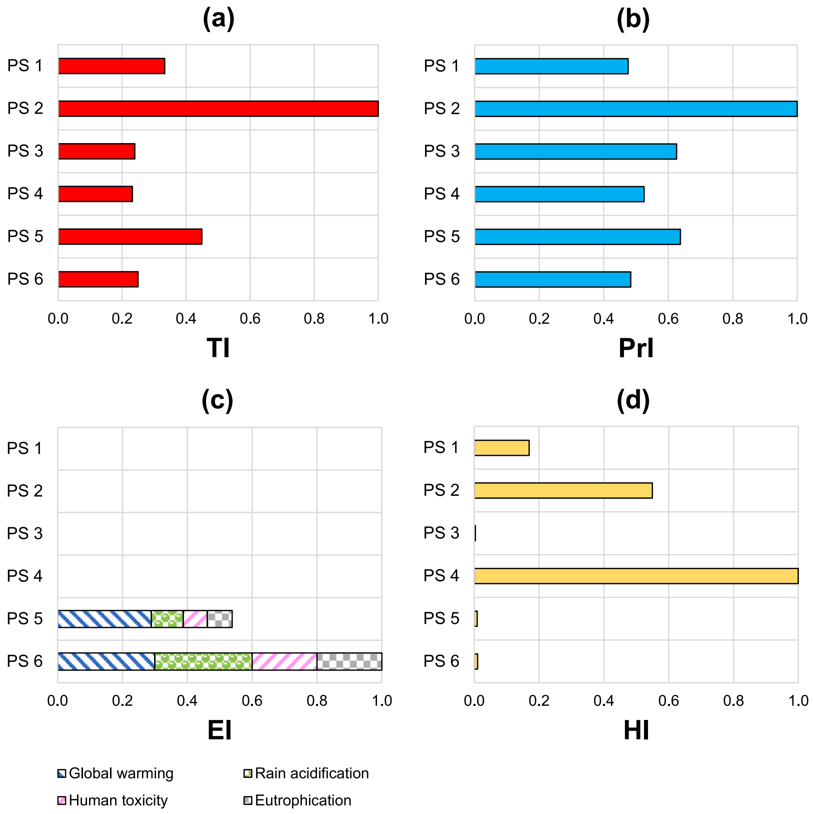

Fig. 3. Values of level 2 KPIs computed for each alternative ship power system: a) technological index (TI); b) profitability index (PrI); c) environmental index (EI); d) inherent hazard index (HI). Table 5 summarized the features of Power Systems (PSs).

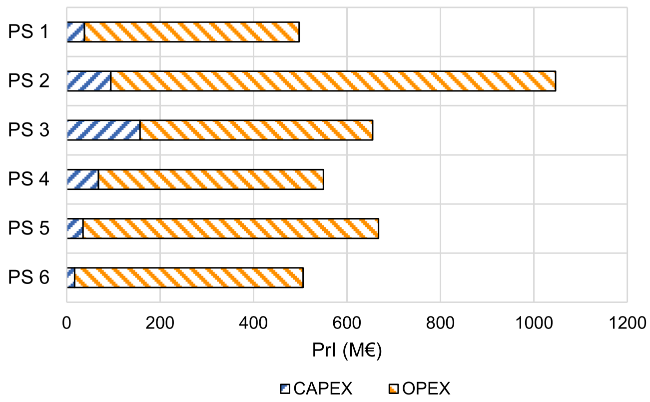

Fig. 4. Contributions of capital expenditure (CAPEX) and operating expenditure (OPEX) to the PrI values calculated for the alternative ship power systems. PS: Power System (see Table 5).

therefore, represents an important option to further support decision-making.

Fig. 6 shows the results obtained considering different archetypes of decision-makers to calculate the level 3 OSI (Step 4 in Fig. 1). As shown in the figure, PS 3 (CcLH$_2$-PEMFC) scores the best overall sustainability performance with respect to all the aggregation modes considered. This suggests that the benefits given by a compact zero-emission power system with a low inherent hazard level tend to overcome the limitation related to its lower profitability in determining the overall sustainability profile of PS 3. The individualist perspective, which aims to enhance short-term social sustainability, identifies the NH$_3$-based ship power system (PS 4) as the least effective option, mainly due to the high toxicity of ammonia processed on board. Moreover, the sustainability performance of PS 5 (LNG-LBSI) and PS 6 (MGO-ICE) appears to drastically worsen when aggregation perspectives prioritizing long-term benefits on the ecosystem (i.e., egalitarian, hierarchist) are adopted. Such penalization on the overall sustainability fingerprints of fossil fuel-based systems can be attributed to the depletion of environmental performance due to the emissions of greenhouse gases and polluting substances.

5.3. Sensitivity and uncertainty analysis

The robustness of the results obtained with respect to possible uncertainties present in the study is dealt with by a sensitivity and uncertainty analysis, following the approach described in section 3.5.

As shown in Fig. 3, when comparing clean fuel alternatives to the environmental performance of the conventional fossil fuel-based power systems, a robust ranking of alternatives is obtained. This is due to the drastic reduction of impacts on the environment obtained by switching from the use of MGO to cleaner fuels (e.g., LNG, hydrogen, ammonia). Similarly, the inherent safety key performance indicators approach adopted is reported to be robust with respect to the uncertainty affecting the evaluation of input parameters (i.e., credit factors and damage distances) (Zanobetti et al., 2023).

Therefore, the sensitivity and uncertainty analysis focused on the techno-economic performances, since several alternative solutions result in similar values of the TESI values, as shown in Fig. 5. Hence, the outcome provided by the presented methodology can be reasonably affected by the uncertainty deriving from technological and economic input variables.

Fig. 7 reports the results obtained for the sensitivity analysis of the technological and economic KPIs assessed for power systems based on carbon-free fuels (i.e., PSs 1 to 4). Similar figures were obtained for the other fossil fuel-based power systems investigated, and are reported in the Supplementary Material. The density of the fuel and the efficiency of the fuel utilization system were identified as the main sources of uncertainty in the technological performance assessment of alternative ship power systems, whereas the discount rate and the operating cost related to fuel consumption emerged as the most influential input variables in the economic assessment.

Based on the results of the sensitivity analysis, the Monte Carlo probabilistic method described in section 3.5 was applied to verify the extent to which technological and economic performance-based rankings are affected by the propagation of uncertainties characterizing the evaluation of the previously identified critical input variables. The confidence intervals adopted to simulate uncertain variations of critical variables are detailed in the Supplementary Material. Fig. 8 shows the results obtained from the analysis, expressed in terms of distribution curves of cumulative probability evaluated for the differences in technological, TI, and profitability, PrI, indices among the reference ship

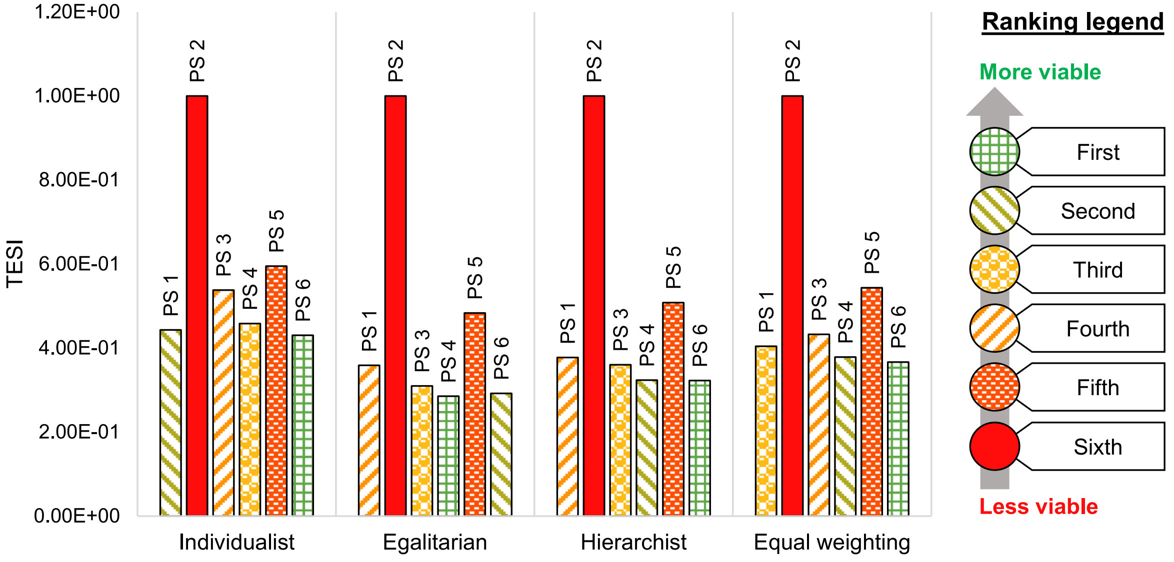

Fig. 5. Values of the techno-economic sustainability index (TESI) of the alternative ship power systems computed based on the different aggregation modes considered (the color of the TESI bar shifts from red to green for power systems progressively more viable according to the indicator). PS: Power System (see Table 5). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

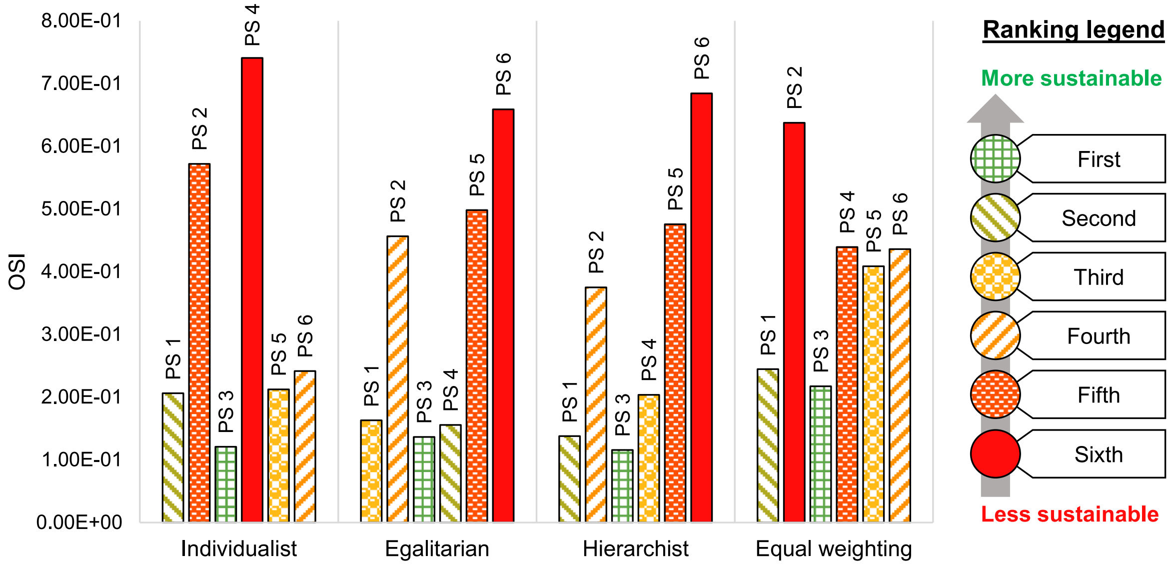

Fig. 6. Values of the overall sustainability index (OSI) of the alternative reference ship power systems calculated according to different decision-making perspectives (color of the OSI bar shifts from red to green for power systems with a higher overall sustainability performance according to the indicator). PS: Power System (see Table 5). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

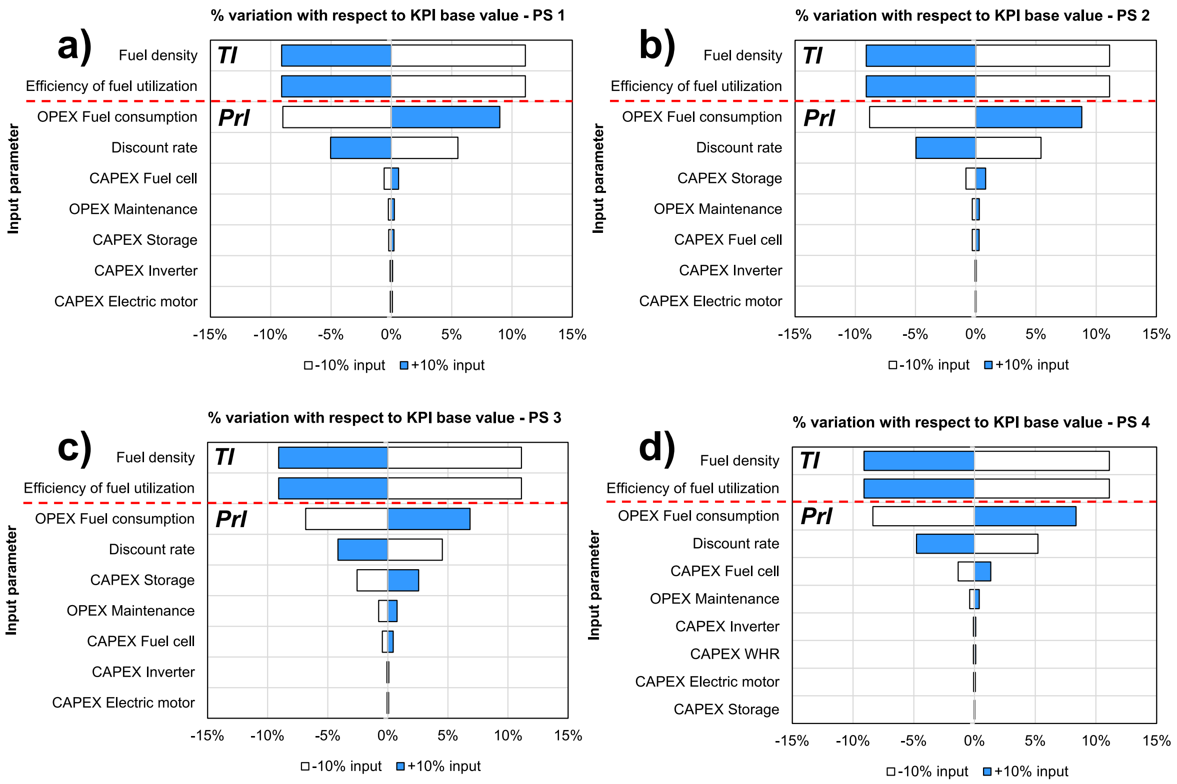

Fig. 7. Tornado charts obtained from the sensitivity analysis of the technological index (TI) and profitability index (PrI) calculated for the alternative carbon-free ship power systems considered in the analysis: a) PS 1 – Liquid hydrogen-based; b) PS 2 – Compressed gaseous hydrogen-based; c) PS 3 – Cryo-compressed liquid hydrogen-based; d) PS 4 – Liquid ammonia-based. PS: Power System (see Table 5).

power systems considered.

The results confirm that the technological performance of PS 2 (compressed hydrogen) is expected to be by far the lowest with respect to all the other alternatives considered, being the values of the difference calculated with respect to PS 5 always positive. Moreover, even in the case of PSs 1 and 5, the uncertainties are not expected to influence the ranking obtained, since only a limited probability (i.e., *ca* 10%) of ranking modification is calculated. Differently, relevant probabilities of obtaining a different ranking among PSs 3, 4 and 6 due to uncertainties resulted from the analysis.

Concerning the economic dimension, the ranking based on the profitability index may be strongly affected by uncertain variations of fuel prices and discount rate. Considering reasonable modifications in the prices of NH_3 and MGO may lead to a probability of changes in the

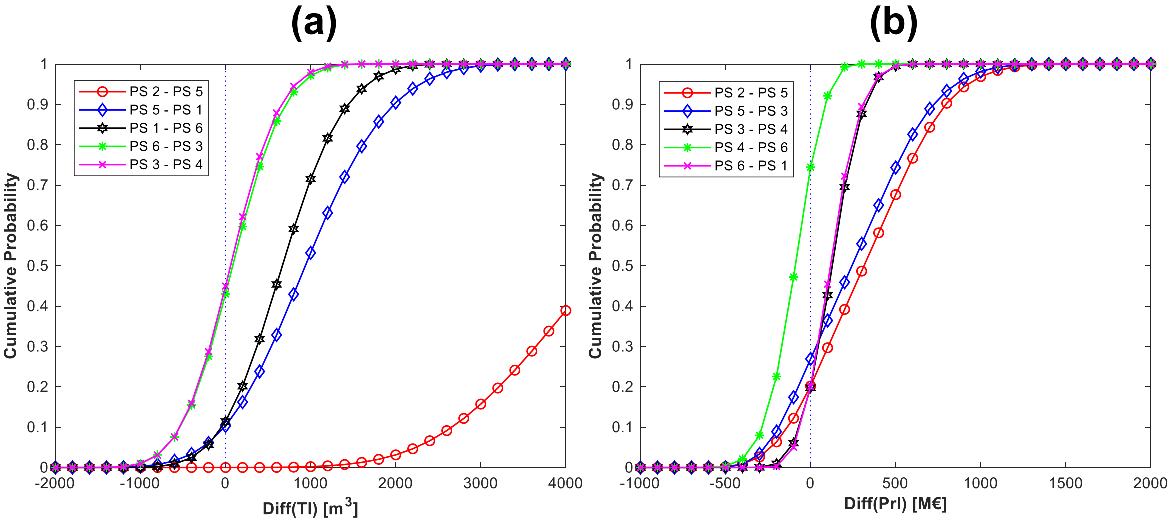

Fig. 8. Cumulative probability of the differences of (a) the technological index (TI) and (b) the profitability index (PrI) among reference ship PSs. See Table 5 for the main features of the Power Systems (PSs) considered.

ranking of the alternatives as high as 70%.

6. Discussion

The methodology developed for the comparative sustainability assessment of alternative technological concepts proved to be effective in supporting early decision-making among alternative ship power systems. The approach integrates techno-economic assessment criteria with the evaluation of environmental and safety impacts.

However, it is worth noting that the assessment of the most effective ship power systems yields contrasting outcomes when considering techno-economic, environmental and safety performances one at a time. Both the data concerning the TESI index (see Fig. 5) and the results of the uncertainty analysis (see Fig. 8) show that the comparison of alternative solutions for maritime propulsion based exclusively on techno-economic aspects can lead to decisions strongly affected by contingencies. Indeed, the time span within which the operating costs (e.g., fuel price) can change significantly (i.e., in the order of months) is much smaller than the expected operating time or payback time (i.e., in the order of years) of a ship power system. Thus, the inclusion of additional criteria in decision-making is advised to consider further elements in the selection of alternatives, consolidating the results of the assessment. In particular, environmental and safety aspects represent key factors to guarantee the long-term sustainability of technological solutions.

When considering the environmental and inherent hazard indices, shown respectively in Fig. 3c and d, it is evident that a duality is present between the environmental and safety performances of power systems: the inherently safer alternatives are those less environment-friendly, whereas the environmentally sustainable technologies score a higher inherent hazard index. The utilization of ammonia and hydrogen (i.e., PSs 1 to 4) appears favorable to minimize impacts on the environment due to the zero-emission condition achieved by fuel cell-based power systems. Conversely, the pattern of safety performances obtained in Fig. 3 highlights a significant increase in the risk of major accidents if carbon-free energy vectors (i.e., ammonia, hydrogen) are used as marine fuels, mainly due to the high inherent hazard level determined by credible releases of such substances. A risk trade-off needs therefore to be considered in the optimization of the overall sustainability performance of ship propulsion when shifting from the utilization of conventional fossil fuels to clean energy vectors.

Thus, multi-criteria decision-making should be based on specific policies, prioritizing the impacts that need to be reduced. Moreover, it should be remarked that specific design solutions may mitigate or reduce the impacts associated with a given power system. As an example, the inherent safety assessment performed is based on representative accident scenarios and generic credit factors: thus, the design and implementation of specific safety systems may modify and reduce the actual risk. Therefore, the results obtained should be considered as a support to identify criticalities to be prioritized when evaluating the detailed design of alternative solutions for sustainable ship propulsion.

A final remark is that in the present study only a limited number of level 1 indicators was considered in each sustainability domain, seeking a compromise among the complexity and significance of the set of indicators defined. Moreover, the set of indicators is conceived to be used to support and orient early and conceptual design, when limited technical details on the power system are available. Depending on the aim of the study, further indicators may be considered to capture specific aspects of the sustainability performance of alternative power systems. In particular, future research efforts should be oriented towards the development and integration of quantitative metrics addressing other key criteria of social sustainability in the maritime sector, e.g., regulatory compliance, social acceptability, ethics and social responsibility (Andersson et al., 2020; Ashrafi et al., 2022). Actually, as evident from the workflow shown in Fig. 1, the methodology allows for the introduction of further indicators in the analysis. This may also be of particular interest for the assessment of specific technological options progressing through the design lifecycle (e.g., to basic and detailed design steps), when further information becomes available concerning the performance and the features of the power systems considered. An additional pathway to extend the proposed methodology could be the assessment of the upstream fuel supply chain, thus quantifying and aggregating multi-criteria KPIs addressing fuel production and bunkering processes and including Scope 2 and Scope 3 (Trivyza et al., 2022; WRI, 2015) emissions in the assessment of environmental impacts.

7. Conclusions

A methodology based on the integrated evaluation of technological, economic, environmental and safety performances was proposed to compare alternative ship power systems from the perspective of decarbonized maritime transport. In order to highlight the potentialities of the proposed multi-criteria sustainability assessment approach, the alternative ship power systems were compared by adopting both a conventional techno-economic assessment route and a methodology based on four sustainability domains. A set of KPIs was defined to quantify the impacts on each sustainability aspect. The KPI values were then normalized and aggregated to produce an overall performance index. Reference ship power systems based on the utilization of liquid hydrogen (i.e., PSs 1 and 3) are the most performant according to both a short-term (i.e., individualist) and long-term (i.e., egalitarian, hierarchist) overall sustainability performance assessment of alternative options. The adoption of different multi-criteria aggregation modes succeeded in identifying the most critical type of impact as a function of the relative weights attributed to the four sustainability aspects considered. Indeed, the scarce environmental performance emerged as the leading factor limiting the sustainability of MGO-based ship propulsion in the long-term. When prioritizing the short-term well-being of human mankind, PS 4 (LNH_3-SOFC) appeared as the least sustainable option due to the significant inherent hazard posed by credible loss of containment events of pressurized liquid ammonia.

Compared to a conventional techno-economic assessment, the proposed approach demonstrated that the inclusion of safety and environmental impacts during early design stages can successfully orient the selection of the most sustainable power system with respect to various archetypes of decision-makers. However, the computed values of level 2 indices evidence that trade-offs may arise when simultaneously optimizing multi-criteria impacts associated with the shipping activity. Indeed, the study highlighted that the environmental benefit deriving from the substitution of fossil fuels with clean energy vectors may come with an increased inherent hazard profile of the ship power system.

Sensitivity and uncertainty analyses were performed to evaluate the effect of the erroneous quantification of critical input data used in the comparison of alternative ship power systems. Alterations of the obtained sustainability-based ranking were found to be most likely triggered by the uncertainty affecting the evaluation of key technological and economic input parameters. The results from the technological KPIs quantification proved to be moderately robust with respect to the uncertainty affecting its identified key input variables. On the other hand, the aleatory characteristic of the fuel prices and the discount rate appear as critical factors to be carefully assessed in order to strengthen the comparative evaluation of profitability among the alternative reference ship power systems considered.

CRediT authorship contribution statement

Francesco Zanobetti: Conceptualization, Investigation, Methodology, Writing – original draft. **Gianmaria Pio:** Conceptualization, Methodology, Validation, Writing – review & editing. **Sepideh Jafarzadeh:** Conceptualization, Investigation. **Miguel Muñoz Ortiz:** Conceptualization, Investigation. **Valerio Cozzani:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.137989.

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