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Onboard carbon capture and storage (OCCS) for fossil fuel-based shipping: A sustainability assessment

Francesco Zanobetti [a], Gianmaria Pio [a], Marta Bucelli [b], Laura Miani [a], Sepideh Jafarzadeh [c], Valerio Cozzani [a,*]

[a] LISES – Laboratory of Industrial Safety and Environmental Sustainability, Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Via Terracini 28, 40131, Bologna, Italy
[b] SINTEF Energy Research AS, Sem Sælandsvei 11, 7034, Trondheim, Norway
[c] SINTEF Ocean, Postboks 4762 Torgarden, NO-7465, Trondheim, Norway

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ABSTRACT

Limiting the carbon intensity of maritime transport is crucial to meet 2050 net-zero targets. Onboard carbon capture and storage (OCCS) offers a practical short-term solution for reducing shipping-related CO_2 emissions until cleaner technologies are ready for large-scale adoption. This study introduces an innovative multi-objective approach to integrate sustainability into the conceptual design and decision-making phases of OCCS. A systematic technology screening identified possible OCCS solutions, which were then assessed for onboard feasibility. Specific indicators were defined to evaluate OCCS performance based on technological, economic, environmental, and social criteria, and aggregated sustainability perspectives. Using a fossil fuel-powered cruise ship as a case study, results were benchmarked against zero-carbon alternatives. Among the alternatives considered, chemical absorption by amine scrubbing (AS) and advanced cryogenic carbon capture (A3C) appeared as the only feasible solutions considering onboard energy requirements. The emerging cryogenic A3C concept resulted in being outperformed by benchmark AS, primarily due to an environmental impact 1.5 times higher. All alternative technologies, whether OCCS- or cleaner fuel-based, were found to be more sustainable than the baseline fossil fuel-based engine, lowering the environmental impact by at least 61%. Hydrogen as a marine fuel leads to the most promising scenario for future cleaner shipping operations, reducing the sustainability footprint by up to 76%. The robustness of the proposed method was confirmed by a probabilistic Monte Carlo sensitivity analysis. Overall, the results obtained can guide toward more informed solutions and policies promoting the sustainability of ship propulsion systems.

1. Introduction

The maritime industry represents a major contributor to global warming, accounting in 2018 for about 2.89% of worldwide CO_2 emissions (IMO, 2021). In addition, CO_2 emitted from shipping can increase by up to 250% if mitigation strategies are not implemented (IMO, 2023). Therefore, a drastic reduction of the carbon intensity of maritime technologies is paramount for the transition towards a net-zero economy. To this aim, decarbonization strategies have been recently outlined for the maritime sector, setting GHG emission reduction targets respectively of at least 20% and 70% by 2030 and 2040 compared to 2008 (IMO, 2023). The implementation of cleaner solutions is widely regarded as the key to enable future carbon-neutral shipping (Ampah et al., 2021). Nevertheless, their large-scale implementation is currently hampered by many technical and economic factors (Lloyd's Register and UMAS, 2017), and they are expected to be successful only in a long-term perspective (IMO, 2021). Carbon capture, utilization, and storage (CCUS) is widely regarded as an effective solution to address point-source anthropogenic carbon emissions in the short to medium term until cleaner technologies are ready for large-scale adoption. For on-land applications, this strategy is expected to significantly reduce CO_2 emissions from carbon-intensive power generation when combined with biomass-fossil fuel co-firing systems, appropriate carbon pricing and policy incentives, and optimized CO_2 source-sink matching (Fan et al., 2023a, 2023b). Additionally, the reliability and resilience of energy systems were found to benefit from widespread CCUS, as

* Corresponding author.
E-mail address: valerio.cozzani@unibo.it (V. Cozzani).

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demonstrated also by specific studies on the resilience to extreme conditions of China's power sector (Fan et al., 2023c). The proved advantages discussed for the onshore applications have been increasing the interest in applying CO_2 emissions capture strategies in the maritime sector, as well. Onboard carbon capture and storage (OCCS) involves applying post-combustion carbon capture to the exhaust gas, storing the separated CO_2 onboard, and unloading it at ports for final geological storage or utilization (Lee et al., 2021). Various post-combustion carbon capture technologies, including chemical absorption, adsorption, membrane and cryogenic separations, have demonstrated a significant potential for commercial applications (Leonzio and Shah, 2024; Zhang et al., 2020). Besides, each technology presents several alternatives for the selection of layout, conditions, and materials involved in CO_2 separation (Bui et al., 2018). Carbon emission reductions from fossil fuel-based shipping as high as 50% could be achieved with OCCS systems, considering typical energy penalties and CO_2 capture efficiencies associated with their onboard implementation (DNV, 2024). Recent figures on future shipping decarbonization scenarios (DNV, 2023) highlight OCCS as one of the key technologies for achieving net-zero emissions, with a greenhouse gas (GHG) reduction potential of up to 90%. OCCS was found to potentially achieve zero or even negative shipping-related lifecycle GHG emissions when capturing 70% of onboard CO_2 emissions and blending combusted fossil fuels with at least 30% renewable fuels (DNV, 2023).

Despite the clear environmental advantages, the technical feasibility and overall sustainability of implementing OCCS solutions onboard ships, including economic and social criteria, have been poorly evaluated. Maritime stakeholders have been mostly focusing on addressing the technical and economic challenges of OCCS using conventional solvent-based CO_2 separation methods (Bureau Veritas, 2023; DNV, 2024; Sustainable Ships, 2023). The techno-economic feasibility of solvent-based OCCS was demonstrated to be deeply linked to solvent selection, space requirements and process configuration (Feenstra et al., 2019; Luo and Wang, 2017; Ros et al., 2022). From an environmental sustainability perspective, this technology resulted as the most effective short-term decarbonization solution for shipping, proving also highly viable by displacing only 4% of ship volume with minimal capture costs (Negri et al., 2022). The adoption of additional specific auxiliary equipment into solvent-based OCCS, such as gas turbines and electric heat pumps, was found to further boost its performance, increasing CO_2 abatement by at least 5% without exceeding a total capture cost of about 160 €/ton of CO_2 (Luo and Wang, 2017; Visonà et al., 2024). Capture costs as well as space requirements of solvent-based OCCS could also be significantly reduced by properly optimizing the design of the system to cope with varying ship engine loads (Oh et al., 2024). A novel approach was proposed to account for OCCS in the evaluation of the energy efficiency design index (EEDI) for existing ships (Lee et al., 2021). It was found that ships could become up to 50% more energy-efficient when *ca* 70% of the CO_2 from exhaust gases is captured onboard. More recently, innovative OCCS systems have been designed to minimize energy consumption and space requirements, as well as to avoid the use of hazardous solvents onboard. It was estimated that membrane-based processes could reduce OCCS volume occupation by at least 46%, with an almost unvaried energy demand compared to solvent-based technologies if membrane selectivity is optimized properly (Oh et al., 2022). Analogously, OCCS cost by cryogenic separation can be up to 70% lower than conventional CO_2 absorption processes (PMW Technology, 2019), depending on the availability and cost of utilities onboard as well as on the amount and composition of treated exhaust gases (Willson et al., 2019). The literature analysis evidenced that an assessment of the implications of OCCS installations from a holistic sustainability perspective, including environmental and societal aspects, is still missing. Moreover, to the best of the authors' knowledge, none of the previous studies addressed a systematic procedure for OCCS design, considering different possible alternative technologies.

The present study aims to fill these gaps, proposing a structured workflow integrating a novel rigorous procedure for an *a-priori* identification of the most effective OCCS solutions. Multi-criteria sustainability principles were applied to the conceptual design of OCCS systems to identify better-performing solutions. Alternative conceptual schemes for OCCS were defined as a case study. Their integration with the onboard power system was assessed to identify feasible OCCS alternatives. An original set of key performance indicators (KPIs) was proposed to rank the selected OCCS alternatives concerning multiple sustainability criteria. Ultimately, a two-level approach for the computation of an aggregated sustainability performance measure was developed to support the selection of a single best option within conceptual OCCS design phases. The selected OCCS solutions were then benchmarked to zero-carbon alternatives. Considering the nature of the study and the possible oscillations in the boundary conditions, the robustness of the technology ranking obtained was assessed. More specifically, a dedicated sensitivity and uncertainty analysis based on a probabilistic approach was applied to assess the extent to which the uncertainty in the calculation of KPIs may influence the sustainability-based comparison of the OCCS alternatives.

2. Methodology

An innovative method based on the integration of multi-criteria KPIs in conceptual process design phases was developed to address the sustainability assessment of emerging OCCS concepts. The KPIs considered are intended to capture the performance of alternative OCCS strategies for four different dimensions of sustainability (Crivellari et al., 2021), namely technological performance, economy, environment and society. The approach is developed starting from that originally developed by (Zanobetti et al., 2023a), including several elements of novelty, in particular concerning the identification of the best design among alternative technology concepts and the footprinting of sustainability. Fig. 1 schematizes the workflow of the approach developed in the present study.

Step 1 consists of the definition and identification of possible OCCS design alternatives suitable for the system under consideration based on a technology scouting supported by the analysis of literature data. The aim of this step is the definition and the development of a reference scheme for each OCCS technology analysed. In Step 2, starting from the alternative solutions identified in Step 1, plausible OCCS design configurations are selected by a technology feasibility screening, considering the technological requirements for the onboard storage of CO_2. The calculation of multi-criteria KPIs (Step 3) for the plausible OCCS concepts allows the evaluation of probable design alternatives according to the different sustainability dimensions considered. Ultimately, aggregated indices are defined in Step 4 to assess the best OCCS design options from an overall sustainability viewpoint. A detailed description of each step of the procedure highlighted above is provided in the following sections.

2.1. Possible design identification

The final goal of this step (Step 1 in Fig. 1) is the identification of alternative technologies for a possible design of OCCS. To this aim, the definition of the target power system and the design specifications are first required. Then, alternative technologies potentially suitable for the proposed aims shall be defined, also based on indications reported within technical literature.

A systematic procedure was developed to define possible technological concepts for CO_2 capture processes applicable to OCCS. The checklist below was developed to univocally specify each carbon capture process further considered in the application of the methodology.

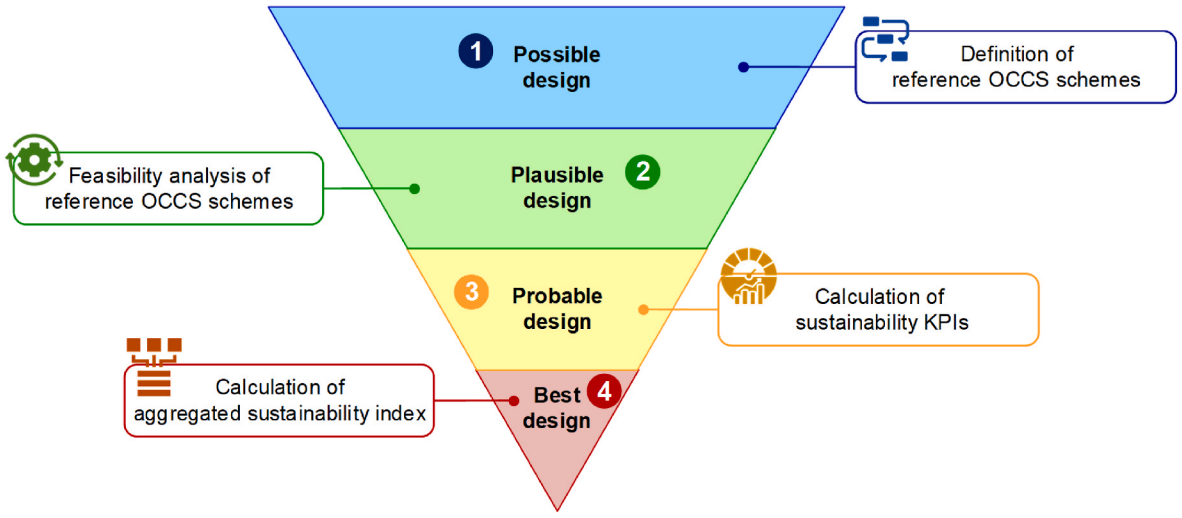

Fig. 1. Flowchart of the approach developed for sustainability assessment of OCCS concepts.

- Selection of carbon capture strategy (e.g., membrane-based, absorption, adsorption, cryogenic)
- Definition of process configuration
- Selection of separating agent
- Collection of main operating parameters

A reference OCCS scheme is specified in this step for each carbon capture strategy identified. The OCCS schemes include the units required for carbon capture and subsequent CO_2 conditioning (e.g., compression, liquefaction), as well as storage equipment and utilities (e.g., electricity, cooling water) needed onboard for OCCS operation. Ultimately, the output of the possible design identification step consists of defining a flowsheet for each reference OCCS concept, where suitable unit operations are specified to model process steps and interconnected by material streams.

2.2. Plausible design identification

In Step 2 of the method (see Fig. 1), the feasibility of the possible OCCS design alternatives defined in Step 1 is assessed, based on the reference process schemes defined, the specification of the main OCCS operating parameters, and mass and energy balances. Process simulation software may be used to model steady-state conditions of OCCS systems (e.g., Aspen Plus).

To provide a robust comparison of the sustainability performance, each reference OCCS scheme is simulated considering a convenient CO_2 capture efficiency from the inlet exhaust gas as a common reference basis. More specifically, the definition of a benchmark case is necessary at this stage to specify the target for the CO_2 capture efficiency. The selection of the OCCS concept having a higher technology readiness level (TRL) as the baseline for benchmarking is recommended.

The possibility of integrating fossil fuel-based ship power systems and OCCS schemes in terms of heating and cooling services was analysed. The exploitation of waste heat (e.g., associated with exhaust flue gases from fuel combustion) and the heat sinks available onboard (e.g., provided by low-temperature material streams in LNG-based fuel systems) needs to be maximized to obtain enhanced technological viability of OCCS solutions. Process integration feasibility assessment of OCCS schemes is performed using a specific generalized block flow diagram (BFD) for OCCS retrofit to the power system as a reference. The specific BFD developed in the present study for OCCS implementation is discussed in Section 3, where the case study is described. Therefore, a reference OCCS scheme is deemed feasible and is, thus, considered in the following steps of the procedure only if its energy integration with the retrofitted power system is deemed possible according to the defined BFD for OCCS implementation.

2.3. Probable design identification

Identification of probable design alternatives (Step 3 in Fig. 1) is performed by ranking the plausible OCCS schemes according to specific technological, economic, environmental, and societal sustainability impact KPIs. The indicators considered in the present study are detailed in the following and defined so that higher KPIs correspond to lower performances.

2.3.1. Technological KPI

The volume occupied onboard (VOO) is proposed as a quantitative metric addressing the technological viability of OCCS processes. Indeed, designing OCCS systems with limited space requirements represents a key technical challenge for their widespread implementation onboard fossil fuel-powered ships (Tavakoli et al., 2024). The VOO KPI is defined as follows:

$$VOO = \sum_i V_{ST,i} + \sum_j V_{PV,j} + \sum_k V_{HE,k} + \sum_p V_{PCU,p} \quad (1)$$

where $V_{ST,i}$ is the volume occupied by the i-th storage tank, $V_{PV,j}$ is the volume occupied by the j-th process vessel, $V_{HE,k}$ is the volume occupied by the k-th heat exchanger, and $V_{PCU,p}$ is the volume occupied by the p-th pressure change unit (e.g., pump, compressor). The types of process and storage units considered for VOO KPI assessment (see Eq. (1)) were defined according to the categorisation proposed in previous studies on the multi-criteria sustainability assessment of cleaner maritime systems (Iannaccone et al., 2020; Zanobetti et al., 2023a). On the one hand, conventional basic design procedures (e.g., Perry and Green (2008)) are applied to assess the geometrical features of storage tanks, process vessels and heat exchangers constituting reference OCCS schemes. On the other hand, the sizing of pressure change units may be neglected due to their relatively low volume compared to the other equipment categories considered. Table 1 summarises the input parameters estimated for VOO KPI assessment.

2.3.2. Economic KPI

The economic impact related to the implementation of a given OCCS scheme is quantified by its net present cost (NPC). This index measures the overall expenditure originating over the entire OCCS system lifetime discounted to the current time value of money (Hopkinson, 2017). The NPC index introduced in the analysis can be expressed as follows:

Table 1
Summary of input parameters considered for VOO KPI assessment.

Input parameter	Assessment
Volume occupied by storage tank, V_{ST} (m^3)	Sizing not to exceed 90% filling of the tank and considering tanks available on the market
Volume occupied by process vessel, V_{PV} (m^3)	Sizing of the unit following reference design procedures (e.g., Perry and Green (2008))
Volume occupied by heat exchanger, V_{HE} (m^3)	Sizing of the unit following reference design procedures (e.g., Perry and Green (2008))
Volume occupied by pressure change unit, V_{PCU} (m^3)	Neglected

$$NPC = CAPEX + OPEX \bullet \left[\frac{(1+i)^n - 1}{i \bullet (1+i)^n}\right] \quad (2)$$

where *CAPEX*, *OPEX* and *n* are respectively the initial capital expenditure, the annual operating expenditure and the economic lifetime in years of the OCCS installation. On the other hand, *i* represents the discount rate. The *i* and *n* parameters assumed in the analysis are equal to 8% and 25 years respectively (Sridhar et al., 2024). CAPEX was computed by the following set of equations, proposed by Feenstra et al. (2019) for OCCS economic assessment:

$$CAPEX = \frac{FCI}{0.8} \quad (3)$$

$$FCI = TDPC + TIPC \quad (4)$$

$$TIPC = 0.14 \bullet TDPC \quad (5)$$

$$TDPC = 2.01 \bullet TEC \quad (6)$$

$$TEC = \sum_i EC_i \quad (7)$$

where *FCI*, *TDPC*, and *TIPC* represent the fixed capital investment, the total direct plant cost, and the total indirect plant cost, respectively. On the other hand, *TEC* and EC_i are respectively the total equipment cost and the cost of the *i*-th equipment item. In the present study, the Aspen process economic analyzer (APEA) was used to evaluate equipment cost components, although alternative tools or vendor data may be used as well.

Operating expenditures were modelled as the sum of fixed OPEX (FOPEX) and variable OPEX (VOPEX). FOPEX includes operating and maintenance expenses, overhead costs and long-term service agreement (Feenstra et al., 2019) and may be calculated by Eq. (8):

$$FOPEX = 0.03 \bullet CAPEX \bullet \left[\frac{i \bullet (1+i)^n}{(1+i)^n - 1}\right] \quad (8)$$

VOPEX may be assessed by summing the costs deriving from the onboard supply of utilities and raw materials. For the sake of conciseness, specific VOPEX cost elements assumed for economic KPI quantification are reported in the Supplementary Material for the OCCS schemes analysed in the case study described in Section 3, as deriving from the literature (Gardarsdottir et al., 2019; Seo et al., 2016; Towler and Sinnott, 2013). Table 2 summarises the input parameters evaluated for economic KPI assessment.

Table 2
Summary of input parameters for economic KPI assessment.

Input parameter	Assessment
Discount rate, *i* (%)	8 (Sridhar et al., 2024)
Economic lifetime, *n* (yr)	25 (Sridhar et al., 2024)
Equipment cost, *EC* (€)	Aspen process economic analyzer (APEA)
Variable operating expenditures, *VOPEX* (€/yr)	Sum of the consumption of utility/raw material multiplied by the corresponding unitary cost (see Section 2 of the Supplementary Material)

2.3.3. Environmental KPI

A global warming index (GWI) was defined as follows to quantify the environmental benefit provided by OCCS implementation:

$$GWI = PIF_{GW} \bullet e_{net} \quad (9)$$

where PIF_{GW} and e_{net} are respectively the potential impact factor for global warming and the net emissions flowrate, both related to carbon dioxide. PIF_{GW} was set equal to 1 (Zanobetti et al., 2023a), whilst e_{net} can be computed as follows:

$$e_{net} = e_{EG} - e_{capt} + e_{dir} \quad (10)$$

where e_{EG}, e_{capt} and e_{dir} are respectively the CO_2 emissions flowrate associated with the exhaust gas, CO_2 emissions flowrate captured by OCCS and direct CO_2 emissions flowrate due to OCCS electric power demand. The e_{capt} variable was determined considering the CO_2 capture efficiency assumed as a reference in the analysis, whereas e_{dir} can be computed as follows:

$$e_{dir} = EF \bullet \sum_i W_{el,i} \quad (11)$$

where *EF* and W_{el} represent respectively the CO_2 emission factor due to onboard electricity consumption and the electric power requirement associated with the *i*-th equipment item. In this study, a value of 0.413 kg_{CO2}/kWh was considered for EF (Feenstra et al., 2019). Table 3 summarises the input parameters evaluated for environmental KPI assessment.

2.3.4. Social KPI

Social sustainability assessment may cover several different aspects, such as public acceptability, health and safety, and regulatory compliance (Ashrafi et al., 2022), difficult to quantify based solely on technical data on the OCCS design considered. In the approach developed, an inherent safety indicator was proposed to obtain an objective and systematic quantification of OCCS social performance (Tugnoli et al., 2013). This approach can be applied even with only the limited technical information resulting from early design phases and used to reflect the social acceptability of new technologies in the context of sustainability analyses (Zanobetti et al., 2023a). The output of the method consists of an inherent hazard index (HI) for the considered OCCS scheme, calculated as follows:

$$HI = \sum_k \pi \sum_i cf_{i,k} \bullet \max_j d_{i,j,k}^2 \quad (12)$$

where $cf_{i,k}$ and $d_{i,j,k}$ are respectively the credit factor (in 1/yr) related to the *i*-th loss of containment event (LOC) of the *k*-th equipment item, and the damage distance (in m) associated with the *j*-th accident scenario originating from the *i*-th loss of containment event (LOC) of the *k*-th equipment item.

A set of loss of containment events was assigned to each equipment item based on reference guidelines derived from the technical literature (Uijt de Haag and Ale, 2005). Credit factors assessment allows considering the credibility of LOC occurrence in the analysis and was based on

Table 3
Summary of input parameters for environmental KPI assessment.

Input parameter	Assessment
Emissions associated with the exhaust gas, e_{EG} (t_{CO2}/yr)	Ship-specific (see Section 5 of the Supplementary Material)
Emissions captured by OCCS, e_{capt} (t_{CO2}/yr)	CO_2 capture efficiency × e_{EG} (see Section 2.2 for CO_2 capture efficiency specification)
CO_2 emission factor related to onboard electricity supply, *EF* (kg_{CO2}/kWh)	0.413 (Feenstra et al., 2019)
Onboard electric power consumption, W_{el} (kW)	Energy-flow balances embedded with Aspen Plus (Aspen Technology, 2023)

baseline release frequency data for conventional process and storage equipment retrieved in the literature (American Petroleum Institute, 2008; Uijt de Haag and Ale, 2005). Conventional models for consequence analysis (e.g., van den Bosch and Weterings, 1997) can be applied to estimate damage distances $d_{i,j,k}$ in Eq. (12). Specifically, $d_{i,j,k}$ represents the distance from the release source and the location where a physical effect of the j-th scenario equals a defined threshold. LOCs, credit factors and threshold values specified for OCCS inherent safety assessment are reported in the Supplementary Material, based on the values reported in the dedicated literature (Zanobetti et al., 2023b). The methodology defined above allows the ranking of social sustainability of reference OCCS schemes based on their inherent safety performance. Table 4 summarises the input parameters evaluated for safety KPI assessment.

2.3.5. Evaluation of probable designs

Based on the definition of KPIs, an OCCS solution is deemed probable if the corresponding KPI is lower than the alternative concepts considered. Thus, a set including a maximum of four probable design options (namely the best performing per each of the sustainability domains considered in this study) is obtained as the output of Step 3 of the proposed method (see Fig. 1). Specifically, less than four probable design options are obtained if a single plausible OCCS alternative scores the best performance within more than one of the sustainability pillars considered. The probable design identification allows therefore to evaluate the most sustainable OCCS design when focusing separately on each sustainability criterion. This is the starting point to identify the best design (see Step 4, Fig. 1), as described in the following.

2.4. Best design identification

In the last step of the methodology (Step 4 in Fig. 1), the best OCCS design option is selected based on the assessment of specific aggregated sustainability indices (ASIs). In this study, a two-level approach was developed to quantify the overall sustainability of OCCS.

The Level 1 ASI, named overall sustainability index (OSI), defined as in Eq. (13), yields a performance-based ranking of OCCS reference schemes according to different decision-making perspectives introduced to weigh the different sustainability-related aspects considered:

$$OSI = \sum_i W_i \bullet NI_i \tag{13}$$

where W_i and NI_i represent respectively the weight factor and the normalised KPI values for the OCCS scheme of interest, related to the i-th sustainability dimension considered in the study. The values of the NI indices may be calculated by applying an internal KPIs normalisation, considering their corresponding maximum value calculated in the analysis as a reference (Zanobetti et al., 2023a). The W_i coefficients in Eq. (13) represent the relative importance of each sustainability pillar in determining the overall performance level. These coefficients are defined using literature-based approaches, considering different factors, including time (e.g., intergenerational equity), space (e.g., intragenerational equity), and receptor (e.g., human, ecosystem) considerations (Dincer et al., 2021; Hacatoglu, 2014). Weight factors may be assigned considering four alternative representative aggregation perspectives, accounting for the subjectivity of the involved decision-makers in considering multiple sustainability criteria simultaneously (Crivellari et al., 2021). The weight factors related to the aggregation perspectives considered in the analysis are reported in the Supplementary Material. Alternative normalisation methods and tailored weighing factors may be introduced in the analysis to implement company-specific or site-specific criteria (Pollesch and Dale, 2016).

Based on the expression of the OSI aggregated indicator, provided in Eq. (13), the lower its value, the higher the sustainability performance of the OCCS scheme regarding the considered aggregation perspective.

A sustainability footprint (SF) was then introduced as a Level 2 ASI. The SF results from the Level 1 OSI values were obtained considering the four different aggregation perspectives introduced in the study. As shown in Fig. 2, the SF is computed as the ratio between the internal surface area of the our OSIs ($Area_{OCCS}$) and the overall orthogonal radar chart ($Area_{CHART}$). An internal division-by-maximum approach (Norris, 2001) was applied to normalise OSIs on a scale of 0–1. By this procedure, the SF value is always between 0 and 1, and a lower value of SF implies a higher sustainability performance.

Alternative probable designs can be ranked based on aggregated sustainability metrics, to univocally identify a single best OCCS design option. The obtained ranking may differ based on the calculated values of multi-criteria KPIs as well as on the weight factors adopted for index aggregation (Zanobetti et al., 2023a). A Monte Carlo probabilistic approach was applied to verify the sensitivity of the results to the above-mentioned variables. A confidence interval of ±20% of the baseline value computed in the analysis was assumed for all the KPIs. A random sampling based on a uniform probability distribution function was considered, in agreement with the literature (Crivellari et al., 2021). A total of 10^6 Monte Carlo simulations was found to be sufficient to yield robust results in a reasonable computational time. To account for the sensitivity to the multi-criteria weighted summation step, aggregated KPIs were also calculated for 10^6 quaterns of weighting factors, homogeneously distributed among the acceptable values in confidence intervals ranging from 0 to 1. The outcome of the probabilistic approach

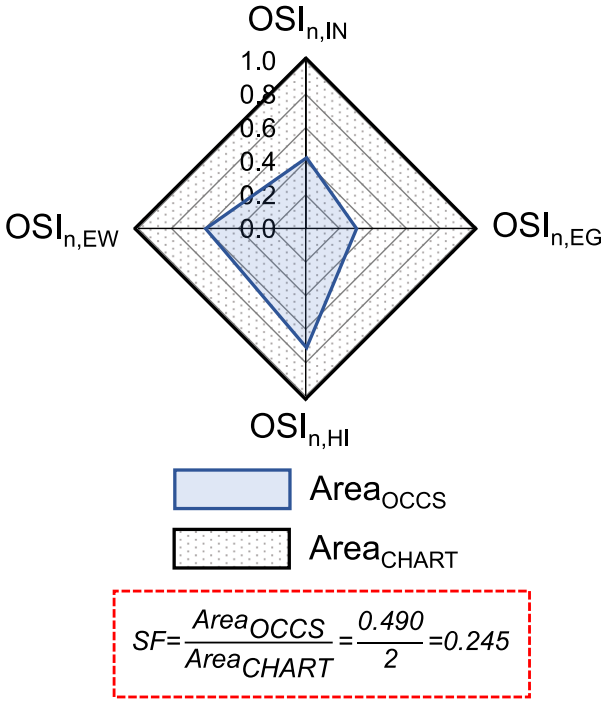

Fig. 2. Example of the SF ASI graphical representation and corresponding numerical values ($OSI_{n,IN}$: Normalised Individualist OSI; $OSI_{n,EG}$: Normalised Egalitarian OSI; $OSI_{n,HI}$: Normalised Hierarchist OSI; $OSI_{n,EW}$: Normalised Equal Weighting OSI).

Table 4
Summary of input parameters for safety KPI assessment.

Input parameter	Assessment
Credit factor, cf (1/yr)	Reference guidelines from literature (e.g., Uijt de Haag and Ale (2005))
Damage distance, d (m^2)	Consequence analysis models provided by van den Bosch and Weterings (1997)

was expressed in terms of the cumulative probability of a modification in the initial sustainability ranking. The lower the probability of an inversion in the ranking examined, the higher the robustness of the sustainability ranking obtained.

3. Case study

3.1. OCCS systems

A Hyperion-class cruise ship was considered as a case study for OCCS implementation. This passenger vessel features a 36 MW power system with an expected trip time per year of 6264 h and 10 days per single voyage. A LNG-fuelled lean burn spark ignition (LNG-LBSI) engine was considered as the prime mover, because of its attractiveness for retrofitting and possible integration opportunities with CO_2 capture. Additional technical and geometrical details relevant to the definition and characterization of the main equipment items and streams involved in the reference ship category investigated are reported elsewhere (Iannaccone et al., 2020). More specifically, the exhaust gas composition referring to a 100% engine load was calculated, as reported in Supplementary Material, providing a conservative design approach to OCCS (Feenstra et al., 2019). Such assumption ensures that energy requirements for OCCS integration onboard the ship are met throughout the entire sea voyage duration, regardless of the navigation phase considered (e.g., at berth, manoeuvring, etc.)

In this study, the captured CO_2 was considered to be compressed and totally condensed for cost-effective storage as a liquid, offering the possibility of integrating the conditioning system with the LNG preheating facilities. Fig. 3 shows the generalized block flow diagram defined to design the OCCS integrated with the LNG-based power system.

In this scheme, the hot exhaust gas deriving from LNG pre-treatment and utilization can be exploited for heat recovery before being sent to the main carbon capture section. Chemical absorption, cryogenic separation, membrane-based separation and physical adsorption were considered as possible alternative strategies for onboard CO_2 abatement (Zincir, 2020). Further details on the investigated OCCS technologies are reported in Sections 4.1 and 4.2. The identification of the typical process layout from the available literature allowed for the design of the main equipment items as well as the quantification of the flow rates and compositions of the main process streams and utilities, in agreement with the method described in the previous sections. The captured CO_2 is then compressed and sent to liquefaction, with vaporizing LNG serving as a cold sink. CO_2 was assumed to be in the condensed phase at a reference pressure corresponding to the OCCS design with the higher TRL, and to be ultimately stored as a saturated liquid.

3.2. Benchmarks

The convenience of retrofitting OCCS to the reference LNG-fuelled ship was further analysed considering the sustainability performance of alternative carbon-neutral power systems as a baseline. Indeed, the exploitation of cleaner marine fuels is increasingly considered a key long-term strategy for the achievement of 2050 net-zero emission targets (Xing et al., 2021). Thus, OCCS was benchmarked to green hydrogen and ammonia, given their attractiveness as zero-carbon energy vectors. The baseline ship power system using a LNG-fuelled engine without OCCS implementation was also considered as a further benchmark. Table 5 reports the technological concepts defined for OCCS sustainability benchmarking, based on the recommendations reported in the literature (ABS, 2021) and detailed in Supplementary Material.

The three benchmarks summarised in Table 5 underwent process design and sustainability assessment for their application to the reference ship category using the same procedures proposed in the present study for OCCS systems. To this scope, the required input data were retrieved from the literature (Zanobetti et al., 2023a). For the comparison with cleaner technologies, a multi-criteria performance assessment of OCCS-equipped systems was conducted by combining KPIs figures of the baseline LNG-fuelled engine with those previously evaluated for the considered OCCS concepts.

Table 5
Benchmarks considered for comparative sustainability assessment with the OCCS concepts evaluated in this study.

Benchmark ID	Fuel	Utilization
LNG – LBSI	Liquefied natural gas	Lean burn spark ignited engine
LH_2 - PEMFC	Cryogenic liquid hydrogen	Proton exchange membrane fuel cell
LNH_3 – SOFC	Pressurised liquid ammonia	Solid oxide fuel cell

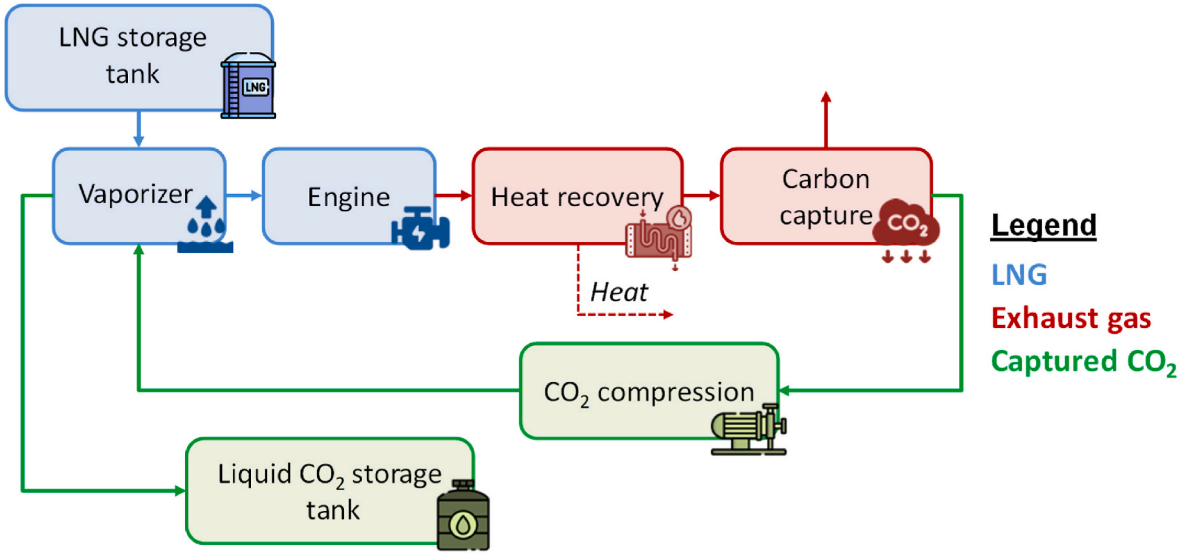

Fig. 3. Generalized BFD adopted for integration of OCCS and LNG systems.

4. Results and discussion

4.1. Identification of possible design alternatives

Table 6 summarises the main features of the OCCS process obtained in the analysis for each technology addressed. Monoethanolamine (MEA) was selected for CO_2 separation by chemical absorption, as recommended in the literature (Luo and Wang, 2017). Onboard solvent regeneration allows ship-based carbon capture to operate continuously also with a limited footprint (Feenstra et al., 2019). Concerning the cryogenic capture strategy, the CO_2 desublimation-sublimation technology selected is based on the removal of CO_2 as a solid frost on the surface of moving cold metallic beads (Font-Palma, 2021). This solution can separate a highly pure dry CO_2 stream from the exhaust gases of ship engines (Font-Palma, 2021). A two-stage CO_2 separation concept with polymeric membranes was introduced for the reference ship-based application, due to its compactness and energy requirements comparable to conventional amine-based processes (Oh et al., 2022). Ultimately, Zeolite 13X was tested as a separating physical adsorbent for a conventional post-combustion pressure swing adsorption (PSA) process (Riboldi and Bolland, 2017). The main operating parameters collected to simulate a steady-state operation of the considered carbon capture technologies are reported in the Supplementary Material.

A reference OCCS process scheme was then developed for each technology concept defined in Table 6, obtained the possible design alternatives for OCCS considered in the study. Fig. 4 illustrates the possible design alternatives identified, reporting for each concept the reference scheme obtained. For the sake of clarity, a detailed description of each scheme is provided in Supplementary Material together with the corresponding main operating parameters assumed in the present study, derived from the literature (Di Martino et al., 2021; Dutta et al., 2017; Konduru et al., 2007; Madeddu et al., 2019; Roussanaly et al., 2013; Voldsund et al., 2017, 2019; Won et al., 2012; Xu et al., 2019).

4.2. Identification of plausible design alternatives

To identify plausible designs (Step 2 in Fig. 1), each reference scheme in Fig. 4 was analysed following the described methodologies.

The CO_2 capture efficiency and storage conditions adopted for process simulations were derived from the performance assessment of the amine-based carbon capture process. This is the most technologically mature OCCS alternative and was thus considered as a benchmark in the following, given the carbon capture technology readiness for commercial service (Global CCS Institute, 2021).

The CO_2 capture efficiency was calculated from process simulation assuming that the stripper reboiler duty for CO_2 capture by AS was fully supplied through waste heat recovery from the exhaust gas. This assumption is consistent with previous investigations on OCCS integration onboard LNG-fuelled ships (Feenstra et al., 2019; Ros et al., 2022). The design CO_2 capture efficiency should be maximized considering the heat available in the exhaust gas (Feenstra et al., 2019). Based on this assumption, CO_2 capture efficiencies even higher than 90% could be obtained for MEA-based OCCS (Feenstra et al., 2019; Ros et al., 2022). A CO_2 capture efficiency of 95% was computed and was considered as a reference to assess other OCCS alternatives. While this value exceeds the typically recommended 90% for absorption-based CO_2 capture (Brandl et al., 2021), the cost increase originating from the larger CO_2 absorber size necessary to achieve the higher capture efficiency is expected to be marginal within the specific scenario under consideration.

LNG vaporization and pre-heating required by the power system occur in the temperature range between 139 K and 293 K (Zanobetti et al., 2023a). The corresponding total cold duty available is *ca* 1.28 MW. In the case of the AS scheme, liquefaction of the captured CO_2 stream by exploitation of the above-mentioned cold duty is possible only at an operating pressure of at least 22.6 bar. Therefore, a reference storage condition of saturated liquid at 22.6 bar was established for all the OCCS processes considered in the case study. A minimum approach temperature of 5 K was adopted in the heat exchange between compressed CO_2 and LNG, as suggested for cryogenic applications (Baccanelli et al., 2016).

Table 7 summarises the main process features evaluated for the alternative reference OCCS schemes (see Fig. 4), considering the above-mentioned assumptions for CO_2 capture and storage conditions. In this table, CO_2 avoidance was calculated as follows:

$$CO_2\ avoidance\ (\%) = \frac{e_{EG,BAU} + e_{dir,BAU} - e_{EG} - e_{dir}}{\left(e_{EG,BAU} + e_{dir,BAU}\right)} \quad (14)$$

where $e_{EG,BAU}$ and $e_{dir,BAU}$ are respectively the CO_2 emissions flowrate associated with the exhaust gas and the direct CO_2 emissions flowrate due to electric power demand of the business-as-usual LNG-based power system. Conversely, e_{EG} and e_{dir} are respectively the CO_2 emissions flowrate associated with the exhaust gas and the direct CO_2 emissions flowrate due to electric power demand of the alternative cleaner concept considered (e.g., OCCS retrofitted to LNG-based engine, carbon-free ship power system).

MS and PSA exhibited no CO_2 avoidance, primarily due to the substantial carbon emissions associated with the electric power requirements of the refrigeration cycle.

Table 8 summarises the results of the energy integration analysis for the alternative OCCS schemes considered in the case study.

AS and A3C emerge as the only feasible OCCS design concepts when considering the driving force and cold duty available onboard to liquefy CO_2. Indeed, CO_2 conditioning in MS and PSA would require an excessively low operating temperature based on the temperature approach and a cold duty at least 6 times higher than that provided by LNG. This can be justified considering the relatively large amounts of volatiles present in the separated CO_2 stream, which result in lower liquefaction temperatures and increased cold duty required. Therefore, to apply such technology concepts, advanced chemical or physical separation processes as well as multiple combined CO_2 capture approaches need to be developed to enhance CO_2 purity (Song et al., 2018). However, the development of new technology options falls out of the scope of the present study, which focuses on the early conceptual design of mature

Table 6
Specifications of the technologies for OCCS analysed in this work (AS: Amine scrubbing; A3C: Advanced cryogenic carbon capture; MS: Membrane separation; PSA: Pressure swing adsorption).

OCCS ID	Selection of carbon capture strategy	Definition of process configuration	Selection of separating agent	Collection of main operating parameters
AS	Chemical absorption	Absorption and onboard solvent regeneration (Feenstra et al., 2019)	Monoethanolamine (MEA) (Luo and Wang, 2017)	See Section S.1.1 of Supplementary Material
A3C	Cryogenic separation	Desublimation-sublimation (Font-Palma, 2021; PMW Technology, 2019)	Chilled stainless steel beads (Font-Palma, 2021)	See Section S.1.2 of Supplementary Material
MS	Membrane separation	Two-stage process (Oh et al., 2022)	Polymeric membrane (Merkel et al., 2016; Oh et al., 2022)	See Section S.1.3 of Supplementary Material
PSA	Physical adsorption	Pressure swing adsorption (Ho et al., 2008)	Zeolite 13X (Ho et al., 2008)	See Section S.1.4 of Supplementary Material

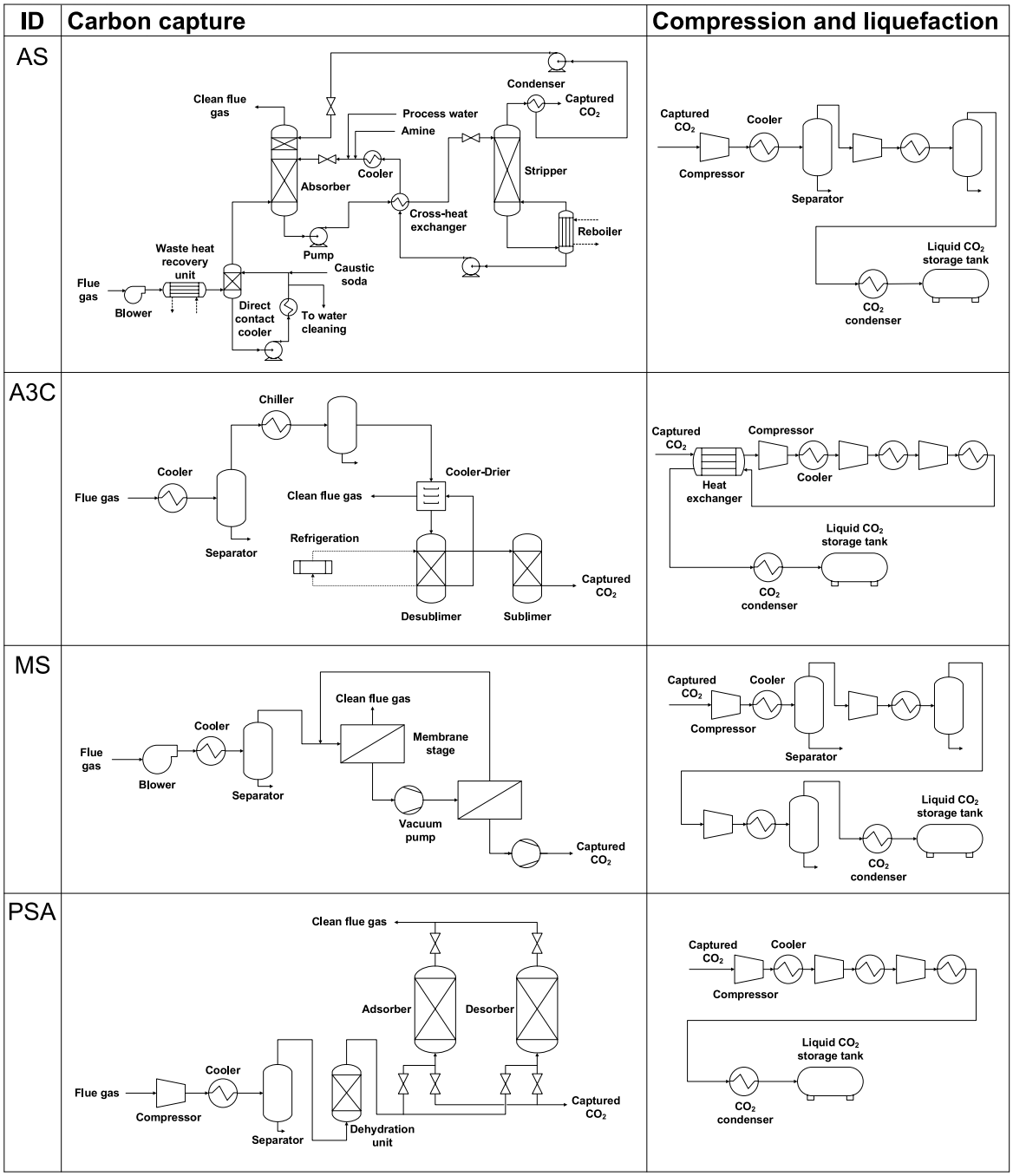

Fig. 4. Reference process schemes defined for OCCS based on the different technologies selected in the case study (AS: Amine scrubbing; A3C: Advanced cryogenic carbon capture; MS: Membrane separation; PSA: Pressure swing adsorption).

Table 7
Summary of the main operating and technical parameters evaluated for the alternative reference OCCS schemes considered in the analysis (n.a., not applicable) (AS: Amine scrubbing; A3C: Advanced cryogenic carbon capture; MS: Membrane separation; PSA: Pressure swing adsorption).

OCCS ID	CO_2 separation pressure, P_{sep} (bar)	CO_2 separating agent regeneration pressure, P_{reg} (bar)	CO_2 capture efficiency (%)	CO_2 avoidance (%)	Specific thermal duty ($MJ/kg_{CO2\ avoided}$)	Specific electric power consumption ($MJ/kg_{CO2\ avoided}$)
AS	1.2	1.8	95.0	85.7	3.55	0.95
A3C	1.0	1.0	95.0	77.5	12.14	1.98
MS	0.95[a]	*n.a.*	95.0	0.0	*n.a.*	*n.a.*
PSA	6.0	1.0	95.0	0.0	*n.a.*	*n.a.*

[a] Transmembrane pressure (TMP) = P_{feed} - $P_{permeate}$.

Table 8
Energy integration assessment of the alternative reference OCCS schemes with the LNG engine. Green cells refer to feasible solutions based on the LNG vaporizer, whereas red cells indicate that additional energy sources are needed.

OCCS ID	Liquefaction temperature (K)	Required cold duty (MW)	Feasibility
AS	255.9	1.28	✓
A3C	257.9	0.92	✓
MS	118.8	11.90	
PSA	116.0	8.22	

OCCS systems. Therefore, AS and A3C are the only possible design options further considered in the study.

4.3. Identification of probable design alternatives

To identify the probable design options (Step 3 in Fig. 1), the KPIs addressing the expected performance in each of the four sustainability domains considered were assessed for the plausible design options obtained in the case-study.

Fig. 5 shows the KPI values calculated for the selected OCCS options, providing a ranking of the performance of the OCCS alternatives for each of the selected sustainability domains.

As shown in Fig. 5a, all the OCCS schemes considered share a similar VOO. The A3C is the option with the worst performance, due to ~2.2% increased space requirement compared to AS. This can be justified considering the significant volume occupied by the set of process vessels required for exhaust gas drying and subsequent CO_2 capture by the A3C technology.

Fig. 5b evidences that the A3C concept scores a NPC almost 16% lower than that of the AS concept. The limited consumption of raw materials for CO_2 capture and the enhanced energy efficiency of the dedicated refrigeration system strongly contribute to the overall cost-effectiveness of A3C.

The environmental performance assessment results in A3C being the least effective design alternative (see Fig. 5c), given a GWI almost 1.6 times higher than AS. This can be attributed to the increased amount of LNG burned onboard and consequently to the direct carbon emissions due to the high electricity demand of the cryogenic A3C process.

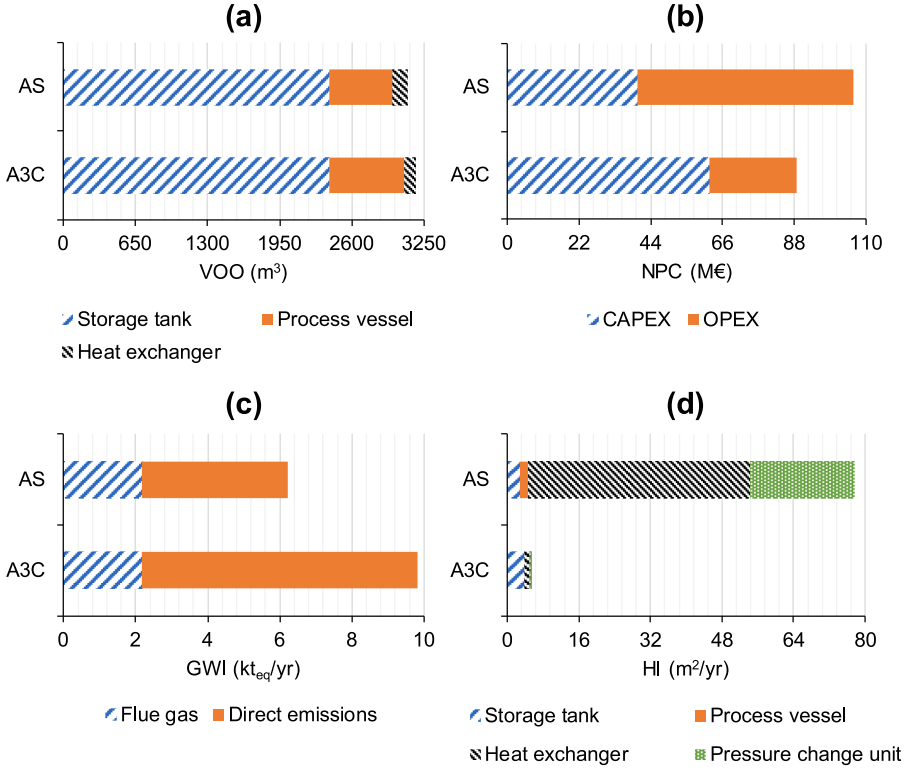

Fig. 5. KPIs calculated for the plausible OCCS concepts identified in the case-study. a) Technological: Volume occupied onboard (VOO); b) Economic: Net present cost (NPC); c) Environmental: Global warming index (GWI); Social: Hazard index (HI).

When focusing on social impacts, the implementation of the AS results in a hazard KPI *ca* 15 times higher than the alternative OCCS option. The lower safety performance of the AS is mainly due to the consequences of credible releases possibly occurring from process units handling toxic and flammable amine solutions.

According to the procedure implemented, AS is the probable design when focusing on both the technological and environmental sustainability perspective. Conversely, the prioritisation of safety and economic aspects indicates A3C as the probable design option.

4.4. Identification of best design alternatives

Based on the results discussed, the best-performing design alternative was identified. The Level 1 OSI was computed for all the probable OCCS design alternatives identified (Table 9), applying the normalisation and multi-perspective aggregation approach described in Section 2.4.

AS-based OCCS resulted in scoring a *ca* 2.5 times higher OSI value (i.e., lower sustainability performance) compared to A3C when aiming at minimizing impacts on individuals. Indeed, the significant hazard level for onboard human targets greatly contributes to penalize the adoption of amine scrubbing as OCCS technology. A3C, on the contrary, tends to be significantly outperformed when switching to sustainability evaluations more prone to environmental preservation (e.g., egalitarian, hierarchist). This can be justified considering the increased global warming contribution related to carbon emissions from A3C operations. Ultimately, even weighing sustainability domains equally, the significant safety-related impacts tend to dominate the overall sustainability performance of AS, which emerges as the least-performing option. It is possible to conclude that the identification of the most sustainable solution for OCCS can be significantly affected by the aggregation perspective adopted.

Fig. 6 shows the cumulative probability of differences in the overall sustainability index (ΔOSI) between A3C- and AS-based OCCS design options according to the four different decision-making perspectives introduced in the analysis (IN: Individualist; EG: Egalitarian; HI: Hierarchist; EW: Equal Weighting).

The individualist and equal weighing sustainability performance rankings result not affected by the uncertainty considered for the values of KPIs, being the OSI of A3C always lower than that of the more technologically mature AS option. Similarly, a marginal cumulative probability of ranking inversion is present in the case of the other two decision-making perspectives considered, being equal to about 5% and 3% respectively for the hierarchist and egalitarian approaches, confirming the robustness of the proposed overall sustainability assessment method. Ultimately, a cumulative probability of *ca* 18.5% was calculated for A3C having a higher OSI than AS for the variations considered in the set of weight factors.

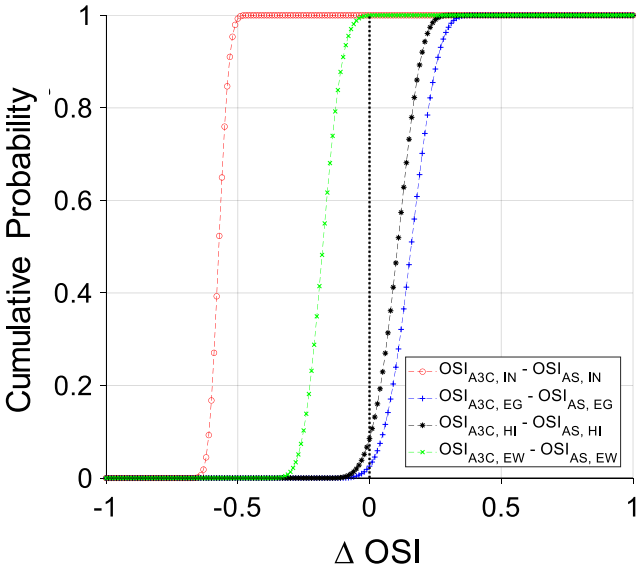

Fig. 6. Results of the Monte Carlo analysis on the investigated OCCS schemes.

4.5. Benchmarking of OCCS concepts

The main process features of the clean fuel-based power systems considered as benchmarks for the OCCS (see Section 3.2) are summarised in Table 10.

Multi-criteria KPIs (see Sections 2.3.1-2.3.4) were computed to compare the sustainability performance of clean fuel power systems, used as a benchmark, with that of OCCS.

Fig. 7 shows a comparison of the sustainability KPIs calculated for the OCCS schemes to those obtained for the benchmarking concepts.

The considered OCCS systems present an increased technological complexity for onboard implementation, with a volumetric occupation up to *ca* 1.9 and 2.8 times higher than that of respectively LH_2 – PEMFC and LNH_3 – SOFC. Minimizing the number and size of additional equipment items for post-combustion CO_2 capture and storage is a key to fully unlocking OCCS technological viability. Focusing on the economic pillar of sustainability, the baseline LNG-fuelled power system without OCCS still results in the most effective option. A higher value of the economic KPI is computed for the green fuel and OCCS concepts, with

Table 9
Overall sustainability indices calculated for the AS and A3C concepts considered in the case-study. Green and red colours indicate respectively the most and least sustainable alternatives.

Decision-making perspective	Overall sustainability index	
	AS	*A3C*
Individualist	0.95	0.38
Egalitarian	0.80	0.96
Hierarchist	0.78	0.89
Equal weighting	0.90	0.73

Table 10
Summary of the main operating and technical parameters evaluated for the benchmarking cleaner fuel-based power systems (n.a., not applicable) (see Section 3.2).

Cleaner fuel-based system ID	Fuel storage pressure, P_{stor} (bar)	Fuel utilization pressure, P_{util} (bar)	CO_2 avoidance (see Eq. (14)) (%)	Specific thermal duty (MJ/$kg_{CO2\ avoided}$)	Specific electric power consumption (MJ/$kg_{CO2\ avoided}$)
LNG – LBSI	6.0	6.0	0.0	*n.a.*	*n.a.*
LH_2 – PEMFC	1.0	3.5	100.0	3.1×10^{-1}	3.1×10^{-4}
LNH_3 – SOFC	8.6	1.0	100.0	1.0	0.0

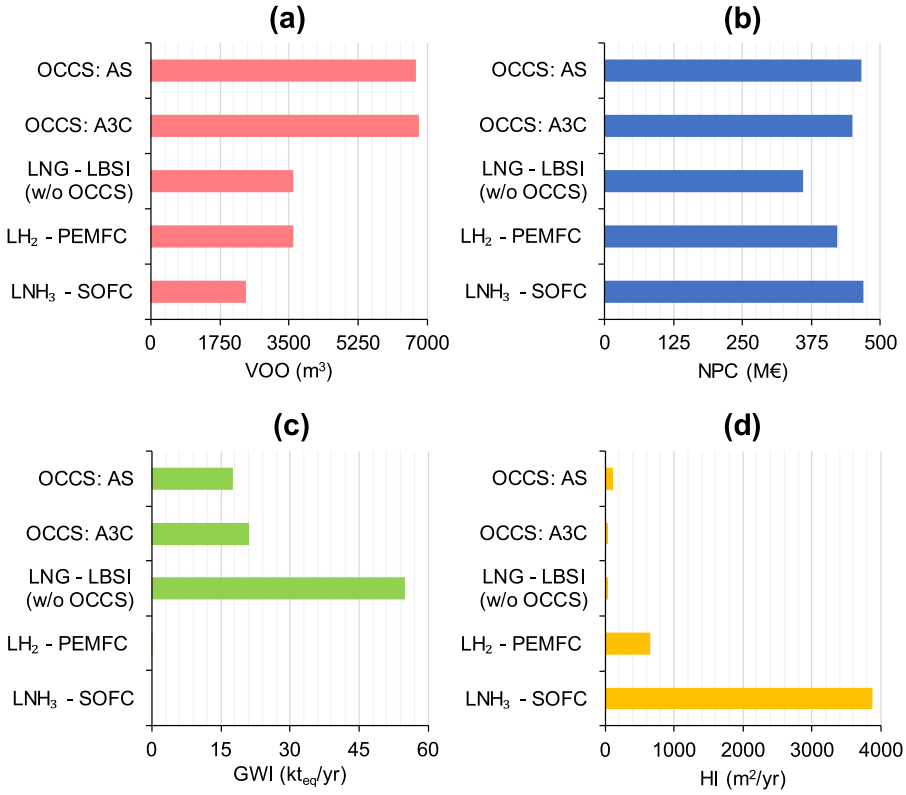

Fig. 7. Comparison of the sustainability KPIs calculated for the alternative probable OCCS concepts and benchmark technologies. a) Technological: Volume occupied onboard (VOO); b) Economic: Net present cost (NPC); c) Environmental: Global warming index (GWI); Social: Hazard index (HI).

LH_2 – PEMFC predicted to be at least 6% more cost-effective. However, it should be remarked that such results may be affected by variations depending on fluctuations in fuel prices, as previously highlighted by Zanobetti et al. (2023), as well as by the costs of utilities and raw materials required for the OCCS systems. The environmental benefit provided by either OCCS implementation or the usage of zero-carbon marine fuels appears evident. Carbon emissions are almost fully abated in the case of LH_2 – PEMFC and LNH_3 – SOFC, whilst a reduction in the GWI of up to 68% is observed for OCCS systems. Conversely, the social acceptability of marine technologies based on hydrogen and ammonia results affected by their poor onboard safety performance. LNH_3 – SOFC presents an inherent hazard level of more than one order of magnitude higher than OCCS systems. Similarly, the HI value of LH_2 – PEMFC, despite accounting for only *ca* one-fifth of the ammonia-based system, is more than 6 times higher than that of the AS OCCS. Such results shed light on the possible criticalities of toxic and flammable carbon-neutral energy vectors as marine fuels and highlight that OCCS systems should be considered inherently safer alternatives in the short term.

Fig. 8a reports the normalised indicators in terms of Level 1 OSI, whereas Fig. 8b reports the calculated sustainability footprint expressed as Level 2 SF for the alternative OCCS concepts and the benchmarking alternatives considered. For the sake of clarity, it is worth mentioning that, based on the definition of the ASIs provided above, a high value of the index indicates a poor sustainable performance of the technological solution analysed.

Except for the OCCS systems, which share an almost equal surface area, the alternative technologies considered differ significantly in their sustainability profile. The SF values of the alternative technologies were then comparatively assessed based on the data from the radar plot, showing that the fossil LNG-powered ship always represents the least sustainable alternative. The ranking obtained confirms the relatively similar performance of OCCS schemes, with AS scoring ~6% reduced SF value compared to A3C. This leads to infer that, in an overall sustainability framework, the reduced environmental performance of cryogenic-based OCCS tends to be more detrimental than the higher hazard level associated with amine scrubbing technologies.

When considering the zero-carbon concepts, LH_2 – PEMFC greatly outperforms all the alternative technological concepts considered, with a SF value at least 2.7 times lower. Conversely, the significant inherent hazards related to onboard ammonia handling result in a SF value of LNH_3 – SOFC comparable to that of the OCCS alternative concepts.

Fig. 9 shows the distributions of the cumulative probability of SF differences for the OCCS and green fuel-based benchmarking technologies with respect to the baseline LNG-fuelled ship without CO_2 capture.

Since none of the curves intersects the vertical dotted line (i.e., the 0 value), each clean power system in the study shows an improved

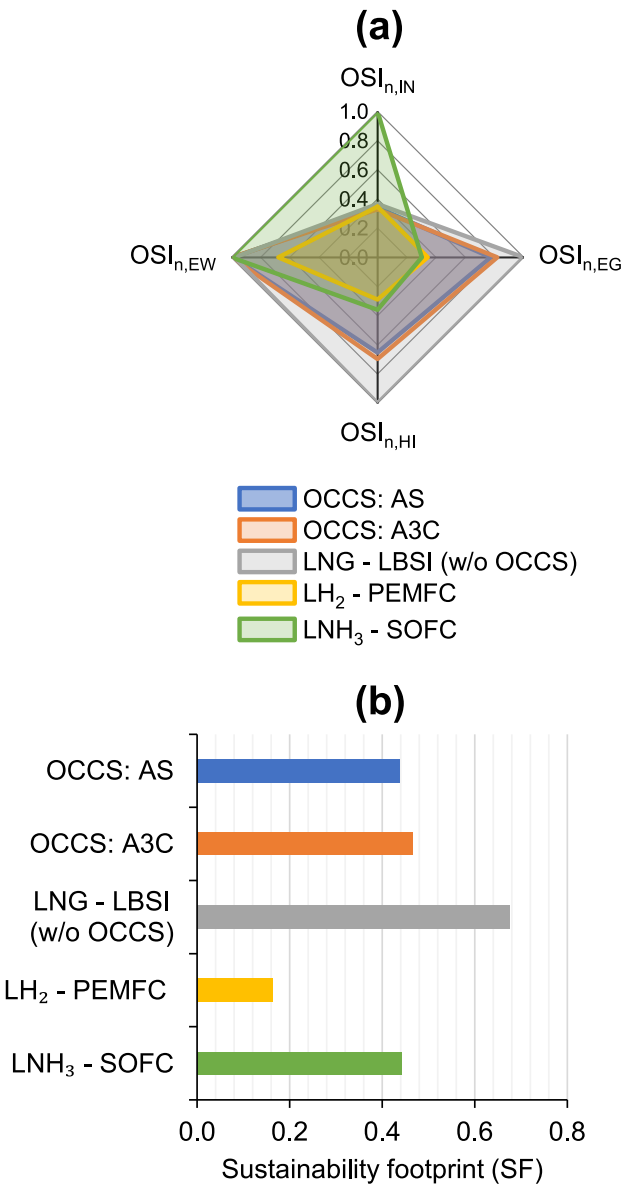

Fig. 8. SF values for the reference LNG-based (without and with the integration of OCCS systems), hydrogen- and ammonia-fuelled ship power systems. a) Radar plot of Level 1 OSI used as the input for SF assessment; b) SF-based ranking.

sustainability footprint compared to the baseline scenario, considering the uncertainty in KPIs within the confidence intervals. Moreover, LH_2 – PEMFC is confirmed as the best-performing alternative, presenting the curve with the highest SF differences with respect to the baseline LNG propulsion system considered. Similarly to the OSI sensitivity analysis, no SF-based ranking inversion between the OCCS-based concepts is encountered under the investigated conditions, since their corresponding curves of cumulative probability do not result in intersecting each other. Conversely, the ranking with respect to benchmarking technologies presents a significant level of uncertainty when focusing on OCCS concepts and the ammonia-based power system. Indeed, there is a probability of ranking inversion as high as 30%, mainly due to AS and LNH_3 – SOFC sharing a nearly equal sustainability footprint.

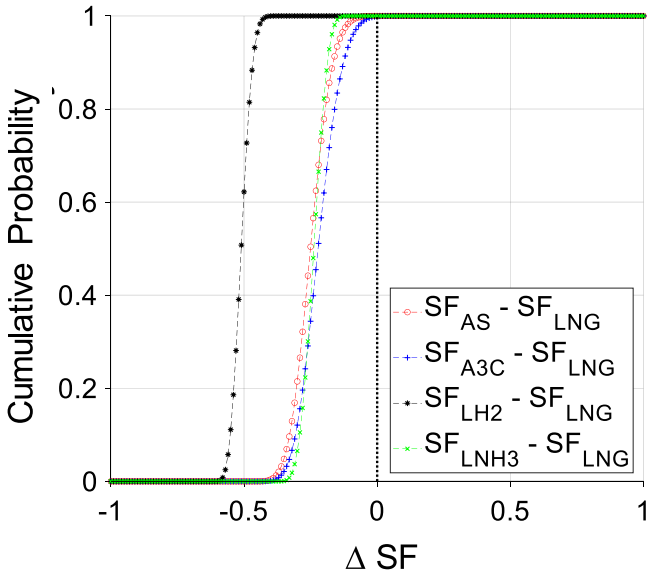

Fig. 9. Distributions of cumulative probability of SF differences (ΔSF) amongst the OCCS, the clean fuel benchmarking technologies and the baseline LNG-based power system (without OCCS) considered.

4.6. Discussion

4.6.1. Alternative decarbonization solutions

Different possible OCCS technologies were analysed for onboard implementation. For the sake of clarity, Table 11 summarises the main strengths and limitations of each reference OCCS solution, considering both the findings from the present analysis and information derived from the literature.

The analysis of the alternative OCCS systems evidenced that only amine-based and cryogenic-based concepts can be successfully integrated with the LNG-based power system considered in the case-study analysed. The present multi-criteria sustainability assessment shows that, while the amine scrubbing (AS) technology results in both a high purity of the captured CO_2 and a mature technology, it faces increased safety and operational cost challenges due to the handling of hazardous solvents and higher consumption of raw materials for carbon capture. Conversely, the advanced cryogenic carbon capture (A3C) system shows a lower environmental performance, primarily due to the significant carbon emissions related to electricity consumption, and proved to be more cost-effective and inherently safer than AS. The Level 1 overall sustainability index suggests that the emerging A3C concept may be the best choice for OCCS design in the near future, according to an individualist perspective prioritising minimized short-term social impacts. However, when considering environmental impacts over the medium to the long term (e.g., from egalitarian and hierarchist perspectives), the analysis indicates that significant technological enhancements of A3C are still needed to achieve a better sustainability performance level than conventional AS.

The benchmarking of feasible OCCS solutions against business-as-usual LNG-powered shipping identified the techno-economic aspects as the main limitation for sustainable large-scale implementation of OCCS. The significant space requirements needed to allocate CO_2 storage tanks appears as the most critical technological factor to be addressed for OCCS to become widely attractive to maritime stakeholders. Concerning economics, limiting the OCCS capital costs proved to be key in improving the economic viability of OCCS. In this context, efforts should focus on minimizing the size of process and storage units, e.g. by optimizing separating agents used for CO_2 capture, improving internal mass and heat transfer, and developing systems and materials that limit the volume of stored CO_2 per unit mass. The analysis also

Table 11
Main strengths and limitations of the OCCS solutions examined in the present study (AS: Amine scrubbing; A3C: Advanced cryogenic carbon capture; MS: Membrane separation; PSA: Pressure swing adsorption).

OCCS ID	Strengths	Limitations
AS	• Mature technology (Global CCS Institute, 2021; Leonzio and Shah, 2024) • High captured CO_2 purity • Feasible application considering onboard energy requirements	• Increased inherent hazard level onboard the ship • Significant operating costs due to raw materials consumption
A3C	• High captured CO_2 purity • Simultaneous CO_2 and water removal •Feasible application considering onboard energy requirements • More cost-effective than benchmark AS • Inherently safer than benchmark AS	• Substantial environmental impact due to electricity consumption-related carbon emissions • High capital costs
MS	• Simpler system to operate than benchmark AS (Leonzio and Shah, 2024) • No regeneration energy required	• Low CO_2 purity for the target CO_2 capture efficiency (trade-off between CO_2 purity and CO_2 capture efficiency) • Elevated sensitivity to the impurities present in the feed gas stream (Leonzio and Shah, 2024) • Unfeasible without external energy sources for CO_2 liquefaction
PSA	• Simpler system than benchmark AS (Leonzio and Shah, 2024) • Lower energy requirement to regenerate separating agent than benchmark AS (Leonzio and Shah, 2024)	• Low CO_2 purity for the target CO_2 capture efficiency (trade-off between CO_2 purity and CO_2 capture efficiency) • Elevated sensitivity to impurities present in the feed gas (Leonzio and Shah, 2024) • Unfeasible without external energy sources for CO_2 liquefaction

included benchmarking against alternative zero-carbon fuels such as liquid hydrogen (LH_2) and liquid ammonia (LNH_3). The Level 2 sustainability footprint (SF) indicates that all decarbonization strategies, whether using OCCS or cleaner fuels, lead to significant improvements in shipping sustainability. However, the SF figures show that the adoption of ammonia and hydrogen as alternative marine fuels is currently hindered by critical safety issues, which are not present in the OCCS concepts. Specifically, the hydrogen-based concept emerged as the most promising option for future sustainable shipping operations, significantly reducing the environmental impact due to zero carbon emissions upon use. However, it poses substantial safety concerns due to the highly flammable nature of hydrogen. Similarly, ammonia-fuelled power systems offer a substantial reduction in carbon emissions but are hampered by the significant inherent hazards related to the large volumes of toxic ammonia handled and stored onboard. These observations support the possible consideration of OCCS technologies as a sustainable short-term solution for low-carbon shipping, while tailored risk management and safer design strategies are developed and standardized for zero-carbon fuel-based ship power systems.

Overall, the study highlights that the implementation of different solutions for shipping-related CO_2 emissions abatement may significantly impact the sustainability profile of ship operations. Critical trade-offs between different sustainability dimensions, namely technological, economic, environmental, and social, are present when considering OCCS concepts and benchmarking them to cleaner zero-carbon technologies. These findings emphasize the necessity of a tailored approach in the decision-making processes, ensuring that the chosen solutions align with system-specific sustainability goals and operational contexts.

4.6.2. Limitations and future work

The proposed approach aims to support sustainability-oriented design and decision-making activities, especially during the early stages of the lifecycle of OCCS technology concepts. Its systematicity and auditability make it suitable for extension to different ship types as well as to other propulsion systems (e.g., diesel oil-fuelled internal combustion engines). In this study, the application of the proposed methodology has been performed assuming an early design stage. Hence, although robust and systematic, the analysis presented has some inherent limitations due to the lack of detailed data on ship layout as well as the type and time distribution of secondary loads. Nevertheless, the assumptions posed for the realization of the procedure allow also the applicability of the method to later design stages, when additional data relevant to the analysis become available. For example, the space available onboard for OCCS equipment varies significantly depending on the ship's design and purpose, necessitating to customize the OCCS designs once more details on the ship's volume and layout are defined. Similarly, different levels of detail may be used to describe the logistics of CO_2 storage onboard, with varying operational patterns impacting the size and number of storage tanks required. At this stage, only the duration of a single voyage was defined, to determine a proper size for fuel and captured CO_2 storage systems. Capturing and storing CO_2 onboard increases the ship's overall mass, with possible limitations concerning the maximum permissible tonnage. This may e.g. affect process sizing and economic evaluations as provided by the application of the present tool. Different optimal OCCS design configurations may therefore be obtained at a later design stage, integrating the present method with ship design procedures. Future enhancements of the present approach should focus on incorporating more detailed data on ship layout and tonnage, developing advanced models to simulate varying conditions onboard, and optimizing the integration of OCCS systems with existing ship systems. Eventually, based on the detailed layout, the identification and positioning of suitable risk mitigation systems can be conducted. This task may significantly improve the accuracy of the results concerning the safety domain. Addressing these limitations enhances the practical applicability of the method in orienting effective design and operation throughout the entire lifecycle of OCCS systems.

4.6.3. Recommendations for maritime stakeholders

To promote sustainability in shipping operations by OCCS technologies, policymakers and industry stakeholders may consider several strategic actions. The introduction of economic incentives such as subsidies, tax breaks, or carbon pricing mechanisms makes investing in OCCS solutions more attractive for shipping companies by offsetting the increased capital and operational costs. Rising funding for research into more efficient OCCS strategies, prioritising the development of advanced capture agents and capture and storage systems with reduced costs and size and enhanced energy efficiency, would also benefit sustainability all-round, from safety-related social issues to environmental ones. In this context, collaborative efforts between academia, industry, and government can drive significant innovation for sustainable OCCS applications. Making the public aware of the benefits of OCCS is also paramount to drive market demand for these solutions in the near term. From a regulatory perspective, establishing clear frameworks for the gradual integration of onboard carbon capture and storage is crucial, including standardised procedures to deal with CO_2 unloading and storage operations at ports. The latter may need drastic and costly modifications to handle offloading and transporting captured CO_2, including facilities for temporary storage and transportation to permanent geological storage sites. A cohesive supply chain integrating OCCS technology providers, shipping companies, and storage facilities can streamline this process. Establishing green shipping corridors with the necessary infrastructure along key maritime routes is expected to further boost the widespread OCCS adoption. By adopting these measures, shipping-related CO_2 emissions abatement by OCCS technologies may be greatly advanced, paving the way for more sustainable shipping operations in the short-term.

5. Conclusions

The methodology developed in this study includes a multi-objective approach combining different tools aimed at the identification of the possible, plausible, probable, and best design in terms of sustainability performance, accounting for technical constraints affecting the implementation of the alternative technology concepts considered. The methodology is systematic, auditable and based on the adaptation of step-by-step procedures typically applied in the basic design of conventional process engineering systems. The potential outcomes of the methodology were demonstrated considering a case-study concerning the onboard carbon capture and storage (OCCS) on a large-size ship implementing a LNG-based power system. The results were benchmarked to both zero-carbon options (i.e., hydrogen- and ammonia-based) and the baseline fossil fuel-based LNG power system without OCCS. These highlight on the one hand the improved environmental performance of OCCS and zero-carbon options. On the other hand, the appropriate management of critical safety issues is a required step for the large-scale adoption of zero-carbon ship power systems, in particular when considering passenger and cruise ships. In the shorter term, OCCS solutions appear as sustainable options for the reduction of the environmental impact of maritime transport. Among all the sustainability dimensions examined, the competitiveness of large-scale OCCS implementation compared to a business-as-usual shipping scenario was found to be primarily limited by techno-economic challenges, such as the minimization of the space requirements and of the installation costs. Under these premises, it is possible to infer that the adoption of OCCS strategies in small and medium scale ships represents a challenging task. In addition, the increased complexity and high level of integration between propulsion and OCCS systems require a dedicated assessment, aiming at the production of guidelines and protocols for safe and optimized operations when dealing with hazardous materials, especially during the load and unloading stages at berth. A probabilistic Monte Carlo sensitivity analysis confirmed the robustness of the approach developed for sustainability footprint assessment, showing a limited probability of alterations in the ranking among the alternative technologies assessed for decarbonization of maritime transport. Overall, the case-study analysed demonstrated the applicability of the methodology and the usefulness of the results, providing a holistic assessment of the technological, economic, environmental, and social performances of alternative cleaner maritime technology concepts from a sustainability perspective.

CRediT authorship contribution statement

Francesco Zanobetti: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Gianmaria Pio:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Marta Bucelli:** Writing – review & editing, Validation, Methodology, Conceptualization. **Laura Miani:** Methodology, Investigation, Data curation. **Sepideh Jafarzadeh:** Writing – review & editing, Validation, Conceptualization. **Valerio Cozzani:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.143343.

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