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The Role of Inherent Safety in the Selection of Sustainable CO_2 Capture Options

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Decarbonising hard-to-abate sectors such as energy-intensive industries and maritime transport is essential to mitigating climate change. While carbon capture technologies are critical to this effort, social sustainability, particularly process safety, is often overlooked in the evaluation of their suitability at an early design stage. This study integrates inherent safety into a four-pillar sustainability framework, encompassing technological, economic, environmental, and social criteria, to enable a more comprehensive assessment. Case studies focused on an industrial cement plant and a cruise ship explored three carbon capture technologies: solvent-based absorption, adsorption, and calcium looping for the industrial case, and solvent-based absorption, adsorption, and cryogenic separation for the maritime case study. The inherent safety assessment revealed significant performance differences, with amine scrubbing demonstrating a hazard level at least 15 times higher than alternative catpure technologies. Trade-offs between safety and environmental performance were evident in both case studies, highlighting the necessity of incorporating inherent safety into decision-making to ensure sustainable carbon capture strategies.

1. Introduction

In order to mitigate the impact of anthropogenic greenhouse gas (GHG) emissions, rapid and widespread decarbonisation of the global economy is essential. Carbon capture technologies are critical to achieving this goal, particularly in hard-to-decarbonise sectors such as energy-intensive industries and maritime transport, where alternative solutions remain at low technological readiness levels (DNV, 2024; IEA, 2019). A wide variety of carbon capture technologies is being developed, each presenting specific features such as CO_2 separation mechanism, energy requirements, and product purity (Leonzio and Shah, 2024). The selection of the most convenient technology should balance various technical, economic, environmental, and societal criteria (Moktadir et al., 2024; Zanobetti et al., 2023a) while accounting for the specific boundary conditions of the hard-to-decarbonise context considered. For instance, industrial emitters often exhibit significant heterogeneity in flue gas composition and emission scale, which complicates the assessment of CO_2 abatement performance and applicability of carbon capture strategies (IEA, 2021, 2019). In the maritime sector, implementing carbon capture strategies poses significant challenges due to limited onboard space and increased energy demands, often necessitating substantial ship modifications (Gray et al., 2021; Tavakoli et al., 2024). While techno-economic and environmental aspects of carbon capture strategies in energy-intensive industrial and maritime applications have been extensively investigated (Kim et al., 2015; Kuramochi et al., 2012; Visonà et al., 2024), their implications for social sustainability have received limited attention. In this context, process safety is often neglected, despite its critical role in ensuring sustainable and socially acceptable solutions (Park et al., 2020; Zanobetti et al., 2023d). This study investigates the role of process safety in sustainability-oriented decision-making for CO_2 capture strategies, targeting hard-to-decarbonise applications. Inherent safety was adopted as an objective and comparative approach, enabling the quantitative screening of technologies at the early stages of their lifecycle (Zanobetti et al., 2023b, 2023d). A methodology based on the quantification of Key Performance Indicators (KPIs) was developed to evaluate the inherent safety levels of the considered carbon capture technologies. This inherent safety metric was subsequently employed as a proxy for the social sustainability of

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carbon capture technologies within a four-pillar sustainability assessment framework, encompassing technological, economic, environmental, and social dimensions (Dincer et al., 2021). Case studies involving different hard-to-decarbonise settings were conducted to enable a comparative discussion. Specifically, in the context of energy-intensive industries, a cement manufacturing plant was examined, while for maritime transport, the focus was on onboard CO_2 capture systems designed for large-scale cruise ships.

2. Case studies

Post-combustion carbon capture technologies were considered in this study for their proven effectiveness in achieving CO_2 separation with minimal modifications to core processes, making them a practical solution for addressing existing emission sources (Chao et al., 2021; DNV, 2024; IEA, 2019). Figure 1 illustrates the emission sources and alternative carbon capture strategies examined in case studies. The characteristics of the emission sources and the selected carbon capture technologies are detailed below for both hard-to-abate industrial and maritime applications. A 90% carbon capture efficiency was assumed for all technologies in the analysis.

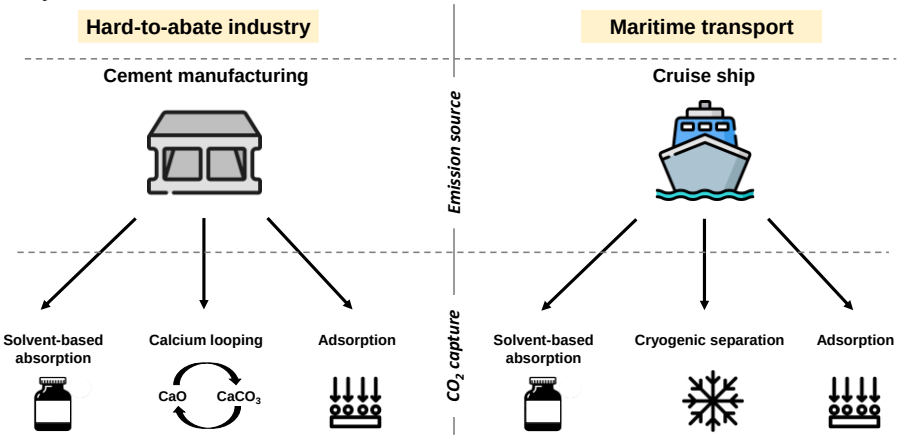

Figure 1: Schematic representation of emission sources and carbon capture technologies evaluated for the hard-to-abate industrial and maritime sectors.

2.1 CO_2 capture technologies for hard-to-abate industries

A cement manufacturing plant designed according to the European Best Available Technique (BAT) recommendations (Voldsund et al., 2019) was considered as a representative hard-to-abate industrial emission source for the analysis. Table 1 summarises the key characteristics of the exhaust flue gas from the evaluated cement plant.

Table 1: Flue gas characteristics for the evaluated cement manufacturing plant (Voldsund et al., 2019).

Parameter	Unit	Value
Flow rate	kg/s	107.8
Temperature	°C	110
Pressure	bar	1.01
CO_2 concentration	mol.%	18
N_2 concentration	mol.%	63
O_2 concentration	mol.%	10
H_2O concentration	mol.%	9

Three different carbon capture strategies were selected, based on their technology readiness level (TRL) (Kearns et al., 2021), to retrofit the industrial emission source: solvent-based absorption, calcium looping, and adsorption. For solvent-based absorption, the amine scrubbing concept proposed by Madeddu et al. (2019), which employs monoethanolamine (MEA) within a reactive CO_2 absorption-amine solvent regeneration process, was adopted. The calcium looping strategy, in which CO_2 is captured via cyclic carbonation and calcination reactions using a solid calcium-based sorbent, was modelled using the process simulation approach developed by Moore & Kulay (2019). A pressure swing adsorption (PSA) process utilising commercial Zeolite 13X as the adsorbent was considered for modelling the CO_2 adsorption strategy, as described by Ho et al. (2008).

2.2 CO_2 capture technologies for maritime transport

The analysis of CO_2 capture technologies within the maritime transport sector considered a Hyperion-class cruise ship as the reference emission source. This is characterised by a 36 MW nominal power capacity installed onboard and operates 6264 hours per year with an autonomy per trip equal to 10 days (Iannaccone et al., 2020). More technical and operational details on the ship under analysis can be found elsewhere (Iannaccone et al., 2020; The Maritime Executive, 2016). Table 2 summarises the key data for the exhaust stream originating from the cruise ship under operative considerations.

Table 2: Flue gas characteristics associated with the considered passenger vessel (Zanobetti et al., 2024).

Parameter	Unit	Value
Flow rate	kg/s	51.88
Temperature	°C	380
Pressure	bar	1.01
CO_2 concentration	mol.%	4.9
N_2 concentration	mol.%	75.0
O_2 concentration	mol.%	10.2
H_2O concentration	mol.%	9.7

Analogous to the hard-to-abate industry case study, three alternative CO_2 capture technologies were selected for comparative analysis. Solvent-based absorption and adsorption were chosen due to their established maturity in commercial carbon capture applications (Leonzio and Shah, 2024). Cryogenic separation was included as a third option, given its growing prominence as a promising alternative to conventional solvent-based technologies, particularly in maritime applications (Font-Palma et al., 2021). The process modelling approaches outlined by Madeddu et al. (2019) and Ho et al. (2008) were utilised to simulate amine scrubbing for solvent-based absorption and PSA for the adsorption strategy, respectively. Additionally, the Advanced Cryogenic Carbon Capture (A3C) process, employing CO_2 separation as a solid frost, was analysed because of its techno-economic viability for LNG ships (Font-Palma, 2021).

3. Methodology

A structured approach is proposed to quantify the inherent safety performance of reference CO_2 capture technologies and integrate these evaluations into a comprehensive multi-criteria sustainability assessment framework. The flowchart of the developed approach is schematically presented in Figure 2.

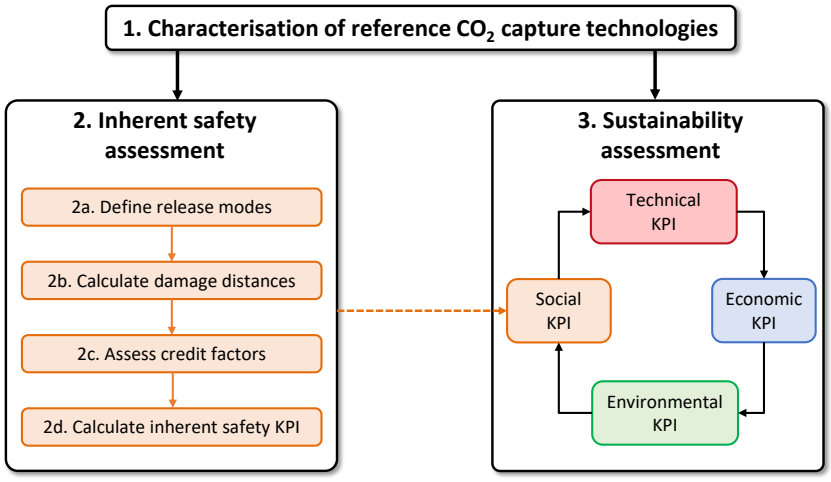

Figure 2: Flowchart illustrating the approach developed for evaluating the inherent safety of CO_2 capture technologies and integrating the results into a multi-criteria sustainability assessment framework.

Step 1 involves characterising the reference CO_2 capture technologies through a process flow sheet, where operating parameters are analysed, energy and material balances are solved, and process units are subjected to preliminary design. These technical input data are used for conducting the inherent safety assessment in Step 2. Additional details on this procedure are provided in Section 3.1. The approach in Figure 2 leverages a four-pillar sustainability assessment framework (Zanobetti et al., 2023c), where the inherent safety metric is

considered as an objective measure of social sustainability and integrated with other technical, economic, and environmental Key Performance Indicators (KPIs) (Step 3). The KPIs defined for addressing technological, economic, and environmental sustainability assessments are detailed in Section 3.2.

3.1 The safety domain

An inherent Hazard Index (HI) was proposed to evaluate the inherent safety performance of CO_2 capture technologies, as follows:

$$HI = \sum_k \pi \sum_i cf_{i,k} \cdot \max_j d_{i,j,k}^2 \quad (1)$$

where $cf_{i,k}$ and $d_{i,j,k}$ represent the credit factor (in 1/y) associated with the *i*-th release mode of the *k*-th process unit and the damage distance (in m) related to the *j*-th accident scenario originating from the *i*-th release mode of the *k*-th process unit, respectively. The assessment of release modes, credit factors, and damage distances is conducted within Steps 2a, 2b, and 2c of Figure 2, using the inherent safety assessment approach outlined by Tugnoli et al. (2007). As expressed in Equation (1), a higher *HI* value indicates a greater hazard level associated with the carbon capture technology, ultimately reflecting a lower inherent safety performance.

3.2 Indicators for the other sustainability domains

A tailored set of KPIs for technological, economic, and environmental sustainability was defined for both case studies to appropriately account for their respective boundary conditions.
For application to the industrial hard-to-abate point source, CO_2 purity was considered as the key technological index, objectively measuring the separation performance (Riboldi and Bolland, 2017) of carbon capture technologies as a function of the characteristics of the treated industrial flue gas. The economic viability was considered measured by a CO_2 Avoidance Cost (CAC) metric, calculated as outlined by Gardarsdottir et al. (2019). Ultimately, a Cumulative Specific Primary Energy Consumption per CO_2 Avoided (CSPECCA), including the primary energy consumption associated with heat and electricity supply, as well as the cumulative contribution due to raw material usage, was considered, being representative of the environmental impact associated with commodity production (Huijbregts et al., 2010; Steinmann et al., 2016). The procedure proposed by Voldsund et al. (2019) was used to calculate CSPECCA, with input data for calculating primary energy demand contribution for raw materials supply retrieved from the ecoinvent (Frischknecht et al., 2005) Life Cycle Inventory (LCI) database. In this context, CO_2 avoided (in t/y) represents the net amount of CO_2 abated through carbon capture, considering the direct emissions due to heat supply and indirect emissions due to electricity supply (Voldsund et al., 2019). For the maritime carbon capture, the KPIs for the other dimensions were defined as recommended by Zanobetti et al. (2024): Volume Occupied Onboard (VOO) for technological sustainability, Net Present Cost (NPC) for economic sustainability, and Global Warming Index (GWI) for environmental sustainability.

4. Results and discussion

The inherent safety KPI was evaluated for each carbon capture technology across the investigated case studies, following the methodology described in Section 3.1. According to the procedure proposed by Zanobetti et al. (2024), PSA was deemed not feasible for use onboard the cruise ship under analysis. This was due to the energy required for CO_2 liquefaction exceeding the available energy onboard, and therefore, PSA was excluded from further evaluation in the present study. For the hard-to-abate industry case, the calculated HI index values were adjusted by dividing them by the amount of CO_2 avoided, ensuring consistency with the CAC and CSPECCA indices, which are expressed per unit of CO_2 avoided. All KPIs, including the inherent safety KPI and those described in Section 3.2, were visualised on a radar plot. An internal normalisation approach was employed to scale each KPI value from 0 to 1, using the highest value within the dataset as the normalisation factor (Norris, 2001). Figure 3 illustrates the normalised technological, economic, environmental, and inherent safety KPIs for the carbon capture technologies considered in the two case studies: hard-to-abate industry and maritime transport.The figure highlights inherent safety as the sustainability subdomain with the most significant performance divergence among carbon capture technologies across both case studies. Notably, amine scrubbing (AS) achieves a normalised inherent safety KPI at least 15 times higher than those of alternative technologies, reflecting a substantially greater hazard level. Relying solely on techno-economic and environmental impact assessments, without considering safety implications, may therefore result in suboptimal decision-making. Incorporating an inherent safety metric into the early-stage evaluation of carbon capture technologies helps address this gap by providing insights into social sustainability that often result in being uncorrelated with techno-economic and environmental figures. This is evident in both the hard-to-abate industrial and maritime case studies considered, where trade-offs between environmental performance and

inherent safety are observed. Technologies with relatively low environmental impacts, such as AS (refer to Figure 3), may exhibit significantly lower inherent safety levels, potentially introducing emerging risks that must be addressed during decision-making. Overall, the proposed approach allowed for a more comprehensive sustainability assessment, reducing the possibility of favouring solutions that may be economically or environmentally advantageous but socially suboptimal.

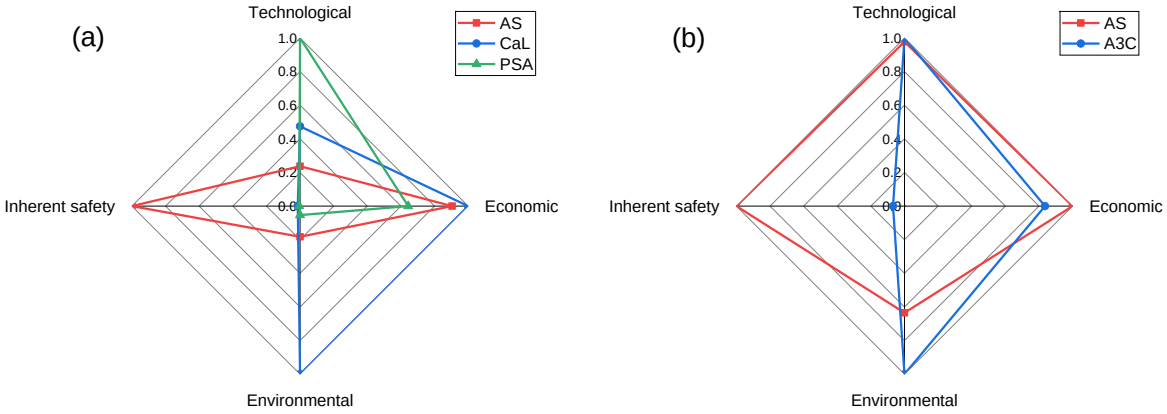

Figure 3: Normalised sustainability KPIs for carbon capture technologies applied to: (a) cement manufacturing plant (hard-to-abate industry); (b) cruise ship (maritime transport).

5. Conclusions

This study highlights the critical role of inherent safety in assessing the sustainability of carbon capture technologies for hard-to-decarbonise applications. By integrating inherent safety into a multi-criteria sustainability framework alongside technological, economic, and environmental dimensions, the analysis reveals performance trade-offs that would otherwise remain unaddressed. Notably, the significant variation in inherent safety performance among technologies underscores the importance of including safety metrics in decision-making processes. The results demonstrate that relying solely on techno-economic and environmental assessments risks favouring solutions that may be economically or environmentally viable but socially sub-optimal. This is especially evident comparing the safety and environmental domains. The implemented approach enables a more comprehensive sustainability evaluation, fostering informed decision-making that balances all sustainability dimensions. By addressing these complexities, the approach presented here contributes to advancing carbon capture strategies that are socially sustainable, ultimately supporting the broader goal of global decarbonisation.

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