



Sustainability assessment of CO₂ capture across different scales of hard-to-abate emission sources

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ABSTRACT

Carbon capture, utilization and storage (CCUS) can support the decarbonization of hard-to-abate industries, where carbon-containing raw materials are integral to core processes. Given the vast portfolio of carbon capture technologies and the specificity of each industry, comprehensive decision-making frameworks are essential for identifying the most suitable option in each case. A quantitative approach to the early-stage sustainability assessment of industrial carbon capture (CC) technologies is proposed, incorporating inherent safety quantification as a proxy for social sustainability. Two case studies were defined to test the method, considering industrial plants with varying emission scales and flue gas compositions in the ceramic and cement sectors. Considering 590,000 t/y of avoided CO₂ emissions achieved by applying CC to multiple ceramic plants, CO₂ avoidance costs resulted in the range of 369–509 €/tCO₂, with an increase up to 300 % when compared to the costs of CC application to a single cement plant, which has a 45 times higher emission rate. Regarding the safety domain, results suggest that the increased likelihood of potential accidents when carbon capture is applied to multiple distributed sources rather than a single large emitter is a point of attention. Notably, safety-related impacts increase as much as 87 %, while environmental impacts are less affected by the scale. In comparing technologies, safety-related impacts appear uncorrelated with other sustainability indicators, underscoring the importance of their inclusion for a comprehensive sustainability assessment. When inherent safety is considered, amine scrubbing emerged as the least sustainable option, with a hazard index at least 25 times higher than alternative CC technologies not involving the use of solvents.

1. Introduction

A drastic reduction of anthropogenic carbon dioxide (CO₂) emissions is a global imperative to limit temperature rise to 1.5°C by the end of the century. In the decarbonization pathways envisaged by national governments and international institutions [1,2], carbon capture and sequestration (CCS), the portfolio of technologies directly addressing CO₂ emissions at source, is expected to play a role as a bridge solution to facilitate and accelerate the transition from the current fossil-fuel based economy to a renewable energy future [3].

To date, carbon capture has been proposed mainly for the application to large stationary sources of CO₂ emissions. Most of the mature CO₂ capture processes available have been developed for application in large power plants [4]. In recent years, CCS application in the power generation sector has been declining in interest [5], both from the standpoint of financial viability, as cost reductions in renewable energy sources can

substantially erode CCS economic competitiveness [6,7], and from the perspective of social acceptance, as there are increasing concerns that CCS can determine a “carbon lock-in” effect [8], reinforcing a long-term dependence on fossil fuels and inhibiting greener alternatives [9,10]. Differently, interest in deploying CCS for industrial emission sources is gaining momentum, particularly when considering the so-called “hard-to-abate” (HTA) sectors [11]. HTA industries include sectors such as iron and steel, cement, glass, ceramics, and chemicals, where CO₂ emissions are mainly: i) “combustion” emissions related to the demand of high-temperature heat (e.g., for kilns and furnaces) [12,13], and ii) “process” emissions related to the transformation of the feedstocks (e.g., the decomposition of carbonates in raw materials) [14]. To date, there is a wide recognition that, in the short and medium term, alternatives for a deep decarbonization of HTA industries are limited in terms of technological readiness and financial sustainability and, in contrast to electricity generation, carbon neutrality in these sectors appears unlikely to

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be met without the use of CCS [15–17]. Recent social research also suggests a more favorable public perception for CCS application to industrial CO₂ sources compared to the power sector [18,19].

Nevertheless, the application of CCS to industrial CO₂ sources is technically challenging, due to the heterogeneity of industrial plants in terms of sizes and flue gas composition. Given the variety of available CO₂ capture technologies that could in principle realize the same CO₂ capture efficiency from the industrial flue gas stream, there is the need to investigate their expected performance and the suitability of application considering a wide range of case-specific constraints. Actually, when considering the financial viability of CO₂ capture projects, the cost per unit of CO₂ captured can be significantly affected by the scale of the application and the CO₂ concentration in the flue gas stream [20]. More generally speaking, the selection of the optimal technological alternative for each industrial application should go through a holistic assessment of the sustainability of the project, encompassing technical, economic, environmental and societal performances [21,22].

Several recent studies focused on the sustainability assessment of CO₂ capture technologies. Romero-García et al. [23] discussed the optimization of the design of a post-combustion CO₂ absorption unit for a power plant having as objective functions the minimization of environmental impacts, expressed using the Eco-indicator 99, and the maximization of the return on investment. Araújo et al. [24] proposed the use of a set of sustainability metrics considering the environmental and economic domains for assessing alternatives of post-combustion CO₂ abatement in a natural gas combined cycle power plant. Zhao et al. [25] compared different approaches for CO₂ capture in coal-fired power plants, considering resource depletion, life cycle costs and energy payback ratio as sustainability metrics.

Two major knowledge gaps have been identified in evaluating the sustainability of CO₂ capture in industrial installations. First, the influence of emission scale on the sustainability of industrial carbon capture applications has been largely overlooked. Pérez-Calvo and Mazzotti [26] compared the economics of a piperazine-based CO₂ capture unit at different scales, showing that the total costs per unit of CO₂ captured more than double when changing the scale of the process from 10⁴ t/d to 10² t/d of flue gas treated. To the best of the authors' knowledge, no other studies explored how the sustainability of CO₂ capture technologies varies with the scale of application.

Second, the current literature lacks an objective approach to quantify the social sustainability of CO₂ capture strategies. In the frame of the “just transition”, different authors have discussed the potential role of the CCS value chain in facilitating the energy transition of regions relying on carbon-intensive industry [27,28], but a systematic incorporation of societal aspects in the assessment of process alternatives has not been proposed yet. Indeed, evaluating societal criteria often relies on subjective elements that are difficult to estimate based only on the technical data of the CO₂ capture process that are available during design.

Within the societal domain, process safety represents a relevant measure of social sustainability, since it correlates with the societal acceptability of innovative technologies and can be quantified since the early stages of the life cycle [29]. In retrofitting applications, carbon capture processes are typically “end-of-pipe” treatments that add complexity to existing plants, thus it is important to quantify the additional risks introduced. Only a few studies considered safety within sustainability metrics in the carbon capture context. Li et al. [30] defined a multi-criteria assessment framework for the evaluation of CCS technologies, including 8 metrics in the domains of environment, economy and society. The societal dimension included the evaluation of public acceptance, determined by expert judgment, and of safety implications, approximated by the calculation of the human toxicity potential indicator, as defined by the widely adopted CML-IA method for life cycle impact assessment [31]. Quader et al. [32] discussed the selection of evaluation criteria of CCS technologies in the iron and steel industry, considering the human toxicity potential as a proxy for process

safety aspects in the social domain. Badr et al. [33] and Shavaliya et al. [34] presented a sustainability assessment of, respectively, various amine-based solvents and alternative phase-change solvents for CO₂ chemisorption, compared to conventional mono-ethanolamine as benchmark solvent, combining environmental life cycle analysis (LCA) with environmental, health and safety (EHS) assessment. In both studies, the simplified hazard assessment framework proposed by Koller et al. [35] was used to identify the main hazards. Nevertheless, previous safety analyses appear to rely on empirical factors, built-in assumptions, and numerical scoring methods, which may introduce biases and undermine the robustness of the results.

The present study aims at providing a methodology for the sustainability assessment of alternative CO₂ capture technologies at their early design stage, specifically addressing the aforementioned gaps. The proposed approach, specifically tailored to address CO₂ capture processes, enables a comprehensive evaluation of the sustainability of industrial carbon capture processes from the conceptual design phase by incorporating objective metrics that encompass all four pillars of sustainability [36] and can be quantified using limited technical data, available since the conceptual design phase. To demonstrate the applicability of the method across varying industrial emission scales, two case studies concerning CO₂ capture in HTA installations were analyzed: a cement manufacturing plant, representative of a large-scale HTA plant, and a ceramic tile production plant, representative of a medium-scale HTA facility. Well-established carbon capture technologies, proposed in the literature for commercial or near-commercial applications, were considered as reference process options. The effect of scale on the technological, economic, environmental and safety performance of alternative CO₂ capture processes was investigated.

2. Methodology

2.1. Overview

An innovative method based on multi-criteria key performance indicators was developed to address the quantitative assessment of the sustainability of CO₂ capture processes. The methodology builds on the approach proposed by Zanobetti et al. [37] to address the systematic evaluation of the sustainability profile of maritime transport technologies. The novel approach proposed addresses the knowledge gaps identified in Section 1 by the following contributions: (i) quantification of social sustainability for CO₂ capture processes, using a newly developed safety metric as a proxy for societal acceptability; (ii) integration of this approach into a systematic holistic sustainability assessment framework, incorporating a concise yet representative set of multi-criteria performance metrics for industrial carbon capture applications, suitable for application in the early design phases where available technical information is still limited; (iii) investigation of the impact of emission scale on the sustainability of CO₂ capture technologies, allowed by the specific metrics introduced to quantify the different impacts on sustainability.

Fig. 1 illustrates the flowchart of the novel method developed for the quantitative sustainability assessment of alternative CO₂ capture technologies.

First, a reference process scheme is defined and characterized in terms of operating conditions and material/energy balances for each CO₂ capture option considered in the analysis (Step 1). Step 2 consists in the calculation of sustainability indicators. The specific set of indicators introduced in the study is meant to describe the performance of CO₂ capture solutions across four key sustainability pillars identified in the literature [38–40]: technological (described by the CO₂ purity index, CPI – see Section 2.3.1), economic (represented by the CO₂ avoided cost, CAC – see Section 2.3.2), environmental (measured by the cumulative specific primary energy consumption per CO₂ avoided, CSPECCA – see Section 2.3.3), and societal (quantified by the CO₂ avoided inherent hazard index, CAHI – see Section 2.3.4). The multi-

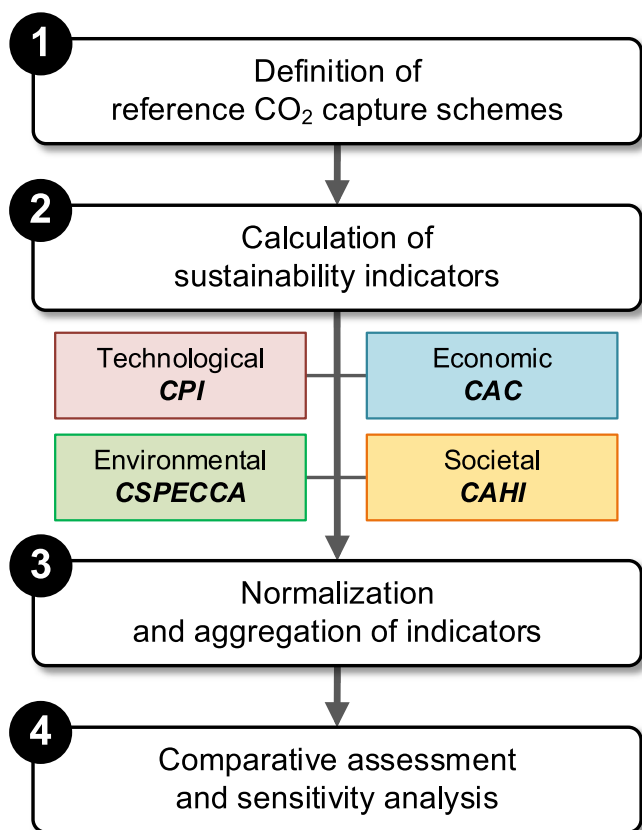


Fig. 1. Flowchart of the methodology developed for CO₂ capture quantitative sustainability assessment.

criteria indicators proposed in this analysis, one for each domain, are intended to provide an objective and quantitative evaluation of the performance of carbon capture technologies across all four pillars of sustainability, while being based on limited input data usually available also during conceptual design and early design phases. The specific rationale for selecting each indicator in the analysis is detailed in Sections 2.3.1-2.3.4, with reference to the four sustainability dimensions considered. It is relevant to point out that economic, environmental and societal indicators are calculated per unit of CO₂ avoided, thus inherently producing a comparative assessment of CO₂ capture options at equal net CO₂ capture performance. Normalization and aggregation procedures are then adopted to produce an overall sustainability performance measure of CO₂ capture (Step 3). Lastly, in Step 4, the reference CO₂ capture schemes are compared according to the computed overall sustainability performance level, and the results obtained are screened by a sensitivity analysis aimed at verifying their robustness with respect to possible uncertainties. A detailed step-by-step description of the quantitative sustainability assessment procedure developed is provided in the following (see Sections 2.2-2.5).

2.2. Definition of reference CO₂ capture schemes

A consistent assessment of the sustainability performance among different CO₂ capture schemes requires the specification of a common reference basis and of the boundaries for the analysis. In this study, the raw flue gas flow rate and the CO₂ capture efficiency were set as the common reference basis. The process boundaries considered in the present study include all the installed process units and the fuels, raw materials, and process utilities consumed on-site to obtain a CO₂-enriched captured stream at the imposed reference basis.

Based on the above assumptions, the specification of reference alternative CO₂ capture process schemes is carried out. This entails the

identification of technologically mature CO₂ capture solutions for the application of interest and the collection of data on their main operating conditions. For each identified CO₂ capture concept, process units are defined and interconnected to each other, obtaining a set of reference process schemes input for the analysis. The calculation of material and energy flow balances needs then to be carried out to snapshot the flow rates and compositions of all the material streams along with thermal/mechanical power exchanges within the reference schemes. Following the above quantification, basic process equipment design procedures (e.g., [41,42] for conventional chemical process units) are applied in order to evaluate the key geometric features of the equipment and the number of units required per each unit operation.

2.3. Calculation of sustainability indicators

2.3.1. Technological dimension

A CO₂ purity index (CPI) is defined as the metric to quantify the technological component of sustainability for CO₂ capture processes:

$$CPI = 1 - y_{CO_2} \quad (1)$$

where y_{CO_2} is the CO₂ purity, expressed as CO₂ molar fraction, in the captured product stream.

The rationale for selecting CPI as the technological key performance indicator is twofold. Firstly, it is derived from CO₂ purity, a widely recognized technical metric for the early-stage evaluation of carbon capture technologies based on their separation efficiency [43,44]. Secondly, CPI reflects the residual level of impurities in the captured stream, which may significantly influence the number and type of equipment required on-site for CO₂ compression and purification prior to downstream stages of the carbon capture, utilization and storage (CCUS) value chain [45–48]. In this context, minimizing the spatial footprint of carbon capture and conditioning installations is particularly important for industrial sites, where space availability is often limited [49]. CPI thus addresses separation performance while also serving as a proxy for the technological complexity of downstream CO₂ compression and purification units.

The above-defined indicator can be computed once the given reference CO₂ capture scheme is defined and quantified by material and energy flow balances, i.e., at the end of the first step of the proposed method (Step 1 in Fig. 1, see Section 2.2). By definition, the higher the value of the indicator, the lower the technological performance of CO₂ capture.

2.3.2. Economic dimension

The CO₂ avoided cost (CAC) [50–52] is proposed to quantify the economic viability of carbon capture technologies:

$$CAC = \frac{CRF \times C_{cap} + C_{op}}{m_{ref} - m_{eq}} \quad (2)$$

where CRF , C_{cap} and C_{op} are the capital recovery factor, capital and operating costs of CO₂ capture, respectively. The values of m_{ref} and m_{eq} represent respectively the CO₂ mass flow rate from the reference emission source and the mass flow rate of equivalent CO₂ from the reference emission source equipped with carbon capture.

This indicator was selected for its ability to provide a well-established measure of the economic performance of industrial carbon capture processes, incorporating the time value of money through the CRF and eventually facilitating comparisons with carbon pricing mechanisms [53,54].

The capital recovery factor in Eq. (2) can be computed as follows:

$$CRF = \frac{r}{1 - (1+r)^{-n}} \quad (3)$$

where r and n are the discount rate and the project lifespan, respectively. A value of 8 % was assumed for the discount rate whilst the project

lifespan was set equal to 25 years [55].

The costing procedure proposed by Gardarsdottir et al. (2019) [56] is adopted to estimate the overall capital and operating costs (C_{cap} and C_{op} respectively, see Eq. (2)) of CO₂ capture technologies. A detailed description of the method is reported in the [Supplementary Material](#) with reference to the specific CO₂ capture schemes considered in the case study (see [Section 3.2](#)).

The equivalent CO₂ emissions (m_{eq}) comprise direct emissions from the outlet CO₂-lean flue gas and on-site steam generation by natural gas-fired boilers, along with indirect emissions from electricity demand/generation. Specifically, direct emissions with CO₂-lean flue gas represent the unabated emissions based on the CO₂ capture efficiency specified as a reference common basis for analyzing carbon capture schemes. Indirect emissions due to electricity demand/generation ($m_{eq,indir}$) are computed by the following expression:

$$m_{eq,indir} = EF_{el} \times P_{el} \times OH \quad (4)$$

where EF_{el} , P_{el} and OH represent respectively the CO₂ emission factor for electricity production, the net power consumption/generation in the process and the total operating hours per year. OH is considered equal to 8766 hr/yr in the framework of a preliminary costing analysis [54], whilst EF_{el} is set equal to an average value of 238 kg/MWh related to the European Union in the reference year (i.e., 2021) in the case study analyzed [57]. Considering the definition of CAC (see Eq. (2)), it follows that the higher the value of the indicator, the lower the economic performance of CO₂ capture.

2.3.3. Environmental dimension

A cumulative specific primary energy consumption per unit of CO₂ emission avoided (*CSPECCA*), in MJ/kg, is defined to quantify the environmental performance of carbon capture technologies:

$$CSPECCA = \frac{Q_{fuel} + Q_{el} + Q_{RM}}{m_{ref} - m_{eq}} \quad (5)$$

where Q_{fuel} , Q_{el} and Q_{RM} are respectively the primary energy consumptions related to the demand of fuel (e.g., coal, natural gas), electricity, and raw materials in the capture process.

The definition of *CSPECCA* as the KPI to address the environmental impact of the capture processes derives from its ability to serve as a simplified, yet representative proxy for the cross-media environmental impacts of capturing CO₂, which, as it is the case for any emission control system [58], typically result from the supply of reactants and energy for process operation. Such environmental trade-offs can be systematically identified through the conduction of a complete life cycle assessment (LCA) study [59], requiring detailed data on the value chain considered. Considering that the cumulative energy demand of a system is recognized as a reliable predictor of the overall environmental burden of commodity production [60,61], *CSPECCA* reasonably approximates the environmental impact of implementing carbon capture to the primary energy consumption associated with the additional supply of resources, i.e., fuels, electricity, raw materials. Unlike comprehensive LCA studies, which require extensive data and are time-intensive, *CSPECCA* can be calculated efficiently using preliminary process data. This characteristic makes *CSPECCA* particularly suitable for use in this study, as timely and practical evaluations are essential during early design and decision-making phases [62].

In Eq. (5), the primary energy requirement due to fuel consumption (Q_{fuel}) can be calculated as follows:

$$Q_{fuel} = m_{fuel} \times LHV_{fuel} \quad (6)$$

where m_{fuel} and LHV_{fuel} are respectively the mass flow rate and the lower heating value of the fuel consumed for CO₂ capture.

Similarly, the electricity demand of the process yields a primary energy consumption (Q_{el}) that can be estimated using the following

expression:

$$Q_{el} = \frac{P_{el}}{\eta_{el}} \quad (7)$$

where η_{el} is the electricity generation efficiency. An average value of 60.9 % was computed for η_{el} considering the 2021 EU energy mix [63].

The primary energy consumption associated with the supply of raw materials (e.g., solvents and solid adsorbents for CO₂ abatement) to the carbon capture system (Q_{RM}) can be calculated as follows:

$$Q_{RM} = \sum_i m_i \times SCED_i \quad (8)$$

where m_i and $SCED_i$ are respectively the mass flow rate and the specific cumulative energy demand (i.e., per unit mass) related to the i -th raw material utilized in the process. More specifically, the latter is a measure of the overall primary energy consumption due to the extraction, manufacturing, and disposal of a given raw material [60]. The procedure adopted for collecting $SCED$ data is described in the following (see [Section 3.2](#)) with reference to the specific CO₂ capture schemes considered in the case study. The amount of equivalent CO₂ emissions (m_{eq}) is evaluated as described in [Section 2.3.2](#). It is worth noting that, based on the definition of the *CSPECCA* indicator (see Eq. (5)), a higher value of the indicator corresponds to a lower environmental performance of CO₂ capture.

2.3.4. Societal dimension

A CO₂ avoided inherent hazard index (*CAHI*) is defined as the metric for assessing the social sustainability of carbon capture technologies:

$$CAHI = \frac{\sum_k \pi \sum_i [cf_{i,k} \times \max_j (d_{i,j,k}^2)]}{m_{ref} - m_{eq}} \quad (9)$$

where $cf_{i,k}$ and $d_{i,j,k}$ represent respectively the credit factor (in 1/yr) associated with the i -th release mode of the k -th process unit and the damage distance (in m) with reference to the human target computed for the j -th accident scenario following the i -th release mode of the k -th process unit.

The *CAHI* was selected as the social sustainability KPI as it directly quantifies the inherent safety of carbon capture technologies, a critical factor in early technology development to ensure societal acceptability and support widespread deployment [29,64,65]. Unlike most social sustainability criteria, which are typically qualitative and subjective, inherent safety offers a measurable and objective approach that relies solely on technical information [29]. This makes *CAHI* particularly suited as a proxy for social sustainability quantification in early design phases, where limited data availability can hinder the application of more detailed safety assessment methods [66,67].

[Table 1](#) presents the set of release modes and associated credit factors used in computing Eq. (9) for the various categories of process units considered in the case study. Reference approaches [68,69] in the technical literature were applied to derive the failure modes leading to loss of containment considered. Credit factors associated with the reference release events are meant to quantify the credibility of the various release modes to occur [67] and were assessed considering baseline equipment leak frequency data [69,70].

Damage distances, $d_{i,j,k}$ (see Eq. (9)), may be quantified by standard consequence analysis models [71] using the specific threshold values for humans reported in [Table 2](#).

The *CAHI* indicator allows the quantification of the overall area impacted per CO₂ avoided by credible releases of hazardous substances, based on limited input data on the equipment layout and operating conditions of the carbon capture process. Given the definition of *CAHI*, the higher the indicator value, the lower the safety performance and thus the societal sustainability of CO₂ capture.

Table 1

Release modes and corresponding credit factors relevant to the present analysis (n.a., not applicable; n.c., not considered).

Release mode	Pressurized vessel	Atmospheric vessel	Shell and tube heat exchanger	Compressor	Pump
R1: small leak, continuous release from a 10 mm equivalent diameter hole	1×10^{-5}	1×10^{-4}	1×10^{-3}	n.a.	n.a.
R2: large leak, continuous release from a 100 mm equivalent diameter hole	5×10^{-7}	5×10^{-6}	5×10^{-5}	n.a.	n.a.
R3: catastrophic rupture, instantaneous release of the inventory	5×10^{-7}	5×10^{-6}	5×10^{-5}	n.a.	n.a.
R4: pipe leak, continuous release from a hole having 10 % of pipe diameter	n.c.	n.c.	n.c.	1×10^{-3}	5×10^{-4}
R5: pipe rupture, continuous release from the full-bore pipe	n.c.	n.c.	n.c.	1×10^{-4}	1×10^{-4}

Table 2

Threshold values assumed for the quantification of damage distances with respect to the human target [67].

Accident scenario	Threshold value (human target)
Flash fire	$\frac{1}{2}$ LFL ^a
Fireball	7 kW/m ²
Jet fire	7 kW/m ²
Pool fire	7 kW/m ²
Vapor cloud explosion	14 kPa
Physical explosion	14 kPa
Toxic cloud	IDLH ^b

^a LFL, lower flammability limit [vol%].
^b IDLH, immediately dangerous to life and health concentration [ppm_v].

2.4. Normalization and aggregation of indicators

In Step 3 of Fig. 1, the key performance indicators are normalized and aggregated to produce a single-value index quantifying the overall sustainability performance of CO₂ capture.

A standard internal approach [72] was proposed for normalization, where each indicator is scaled to its corresponding maximum value determined in the analysis. The aggregation of normalized indicators was then performed as follows:

$$OSI = \sum_i W_i I_{i,n} \quad (10)$$

where *OSI*, *W_i* and *I_{i,n}* are respectively the overall sustainability index, the weight factor for the *i*-th sustainability domain and the normalized key performance indicator related to the *i*-th sustainability domain, respectively.

The formulation in Eq. (10) corresponds to the weighted arithmetic mean (WAM) aggregation method [22,73], which is the method most commonly used in sustainability analysis due to its transparency and practicality in combining indicators of different types [74]. The calculation of *OSI* is influenced by the selection of the weight factors, *W_i*, in Eq. (10). These coefficients define the relative importance of each sustainability domain and reflect the specific preferences of the decision-maker conducting the analysis [75]. For instance, industrial stakeholders often prioritize technological efficiency and economic benefits, whereas public authorities are more inclined to favor technologies that minimize environmental impacts and align with regulatory requirements [76]. In order to capture the variability in *OSI* calculation across a limited, yet representative range of decision-making perspectives, the present approach incorporates four distinct weighting schemes based on well-established decision-maker archetypes: individualist, egalitarian, hierarchist, and equal weighting [75].

Table 3 presents the weight factors adopted in this study for each archetype. These coefficients were derived using a literature-based approach [22,36,75], which assigns the relative importance of each sustainability domain within a given decision-making archetype by evaluating criteria across three key dimensions: time (e.g., short-, medium-, and long-term effects), space (e.g., local, regional, and global equity), and receptor (e.g., humans, ecosystems or both). Further details on the approach used to determine the weighting schemes in Table 3 are available in the literature [36,75].

Table 3

Weight factors for overall sustainability assessment according to the different decision-making archetypes considered [22,36,37].

Decision-making archetype	Weight factors			
	Technological dimension	Economic dimension	Environmental dimension	Societal dimension
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

Ultimately, an internally normalized OSI (*OSI_n*) was defined to allow a straightforward comparison of the CO₂ capture alternatives considered from an overall sustainability standpoint (see Section 2.5).

2.5. Comparative assessment and sensitivity analysis

Lastly, in Step 4 of the methodology (see Fig. 1), the hierarchy of sustainability indicators defined in Sections 2.3-2.4 allows the ranking of the performance of reference CO₂ capture schemes with respect to the specific sustainability dimensions considered, as well as from an overall perspective. A sensitivity analysis considering key uncertain variables in the study may be carried out at this stage, in order to verify the robustness of the performance-based rankings obtained. In the case-studies analyzed, the effect of uncertainty sources on the sustainability indicators was investigated by sampling the input parameters considered in specifically defined confidence intervals. The variables and corresponding ranges of uncertainty defined in the present study are detailed in Section 4.5.

3. Case studies

3.1. Emission sources

Two distinct HTA industrial emission sources, namely ceramic and cement manufacturing plants, were considered as reference applications for testing the developed method. These HTA installations are relevant examples for the potential application of carbon capture, since a significant portion of their CO₂ emissions is process-related. Over half of the CO₂ emissions from cement production result from the calcination of limestone in the rotary kiln [15,77], whereas up to 17 % of CO₂ emissions from ceramic tile production are due to the decomposition of clays in tunnel furnaces [78].

Table 4 presents the flue gas conditions evaluated for the two reference HTA emission sources examined in this study. These correspond to ceramic and cement manufacturing plants designed in accordance with the respective European Best Available Techniques (BAT) recommendations [79,80]. Significant differences are present between the two plants in terms of both emission scale and CO₂ concentration in the flue gas. The emission scale of the cement plant, as indicated by the flue gas flow rate in the table, is approximately 14 times greater than that of the ceramic tile production facility. Furthermore, the flue gas

Table 4

Flue gas characteristics assumed for the reference systems considered in the two case studies.

Parameter	Ceramic manufacturing	Cement manufacturing
Flow rate (Nm ³ /h)	20,000	286,102
Temperature (°C)	180	110
Pressure (bar)	1.01	1.01
Flue gas composition		
CO ₂ (mol%)	6	18
N ₂ (mol%)	78	63
O ₂ (mol%)	9	10
H ₂ O (mol%)	7	9
SO _x (mg/Nm ³)	300	180
NO _x (mg/Nm ³)	200	450
HF (mg/Nm ³)	50	–

from the ceramic tile production has a CO₂ concentration that is roughly one-third that of the cement plant. Notably, the lower CO₂ concentration in the ceramic manufacturing flue gas is similar to values typically observed in natural gas-fired power plants [81]. Both the emission scale and the CO₂ concentration in the flue gas are critical factors influencing the application of carbon capture technologies in industrial installations [82].

3.2. CO₂ capture schemes

CO₂ capture is assumed to be performed by a post-combustion strategy, being the latter the more viable choice to retrofit existing facilities without causing substantial modifications to the core industrial process [83–86]. Amine scrubbing (AS), calcium looping (CaL) and pressure swing adsorption (PSA) were considered as alternative carbon capture solutions due to their technological readiness for near-commercial deployment [20,87]. Reference process schemes were defined for the CO₂ capture options considered, as detailed in Section 2.2, with the support of process simulation tools, i.e. Aspen Plus v11, Aspen Exchanger Design and Rating v11 [88].

Fig. 2 shows the reference CO₂ capture process schemes considered in the present study. A 90 % CO₂ capture efficiency from the inlet flue gas was assumed as a common reference basis. Case-specific process steps and material streams related to the pre-treatment of other contaminants (i.e., SO_x, NO_x, HF) are colored in red and blue for the retrofitting of ceramic and cement manufacturing, respectively.

Concerning CO₂ capture economic performance assessment, capital costs of conventional process units were assessed by the Aspen Process Economic Analyzer (APEA) [88]. Cost models provided by Cinti et al. [89] were adopted for non-standard pieces of equipment (e.g., DeSO_x and DeNO_x units, high temperature solid looping reactors, molecular sieve dehydration units). Capital and operating cost items in the analysis were ultimately expressed in euro on a 2021 basis. Specifically, capital expenditures were updated to €₂₀₂₁ by the Chemical Engineering Plant Cost Index (CEPCI) [90] when necessary.

The SCED values of raw materials (see Eq. (8)) used for environmental impact quantification were computed by dedicated Life Cycle Inventory (LCI) databases [91]. Consequence analysis models implemented in the Phast v.8.4 [92] software were applied for the calculation of the damage distances in Eq. (9) with respect to reference environmental conditions, i.e. average wind speed of 2 m/s and Pasquill stability class F. Additional details concerning process modelling and related key input data, cost assumptions and LCI databases specifically adopted for the analysis of the reference CO₂ capture schemes are reported in the Supplementary Material. It is worth remarking that the reference CO₂ capture schemes considered in this analysis are based on well established technologies, extensively documented in the literature for their application to hard-to-abate industrial sectors [49,93,94]. The optimization of these process schemes and the investigation of advanced

or hybrid carbon capture solutions [95] are beyond the scope of this study, which focuses on providing a holistic early-stage sustainability analysis of carbon capture technologies across diverse industrial emission sources.

4. Results

4.1. CO₂ captured and avoided

The net reduction of CO₂ emissions resulting from the implementation of carbon capture was quantified for the three alternative CO₂ capture schemes defined in the study (see Section 3.2) applied to the two reference HTA facilities, as illustrated in Fig. 3. The figure clarifies the distinction between the CO₂ captured, which is assumed to be, for all the alternatives, 90 % of the original CO₂ emissions of the facility without carbon capture, and the CO₂ avoided, which is defined as the CO₂ captured diminished by direct and indirect equivalent CO₂ emitted due to the operation of the carbon capture process.

While all the reference carbon capture schemes achieve the same percentage of CO₂ captured, reducing residual direct CO₂ emissions from the exhaust flue gas to 10 % of the original emissions of the facility without CCS, significant differences emerge in terms of CO₂ avoided. The CO₂ avoidance performance of AS is notably affected by the direct emissions from on-site steam generation, which is required to meet a heat demand of 2.57 MW for ceramic manufacturing and nearly 40 times higher for cement manufacturing (process data are reported in Section 1 of the Supplementary Material). The heat requirement for steam production, which relies on natural gas as its energy source, results in the AS capture process as that having the highest equivalent CO₂ emissions across both case studies.

Conversely, CaL appears to greatly benefit from the indirect CO₂ emissions reduction associated with electric power generation (–17 % and –24 % for respectively ceramic and cement manufacturing), which more than offsets direct emissions. Values of avoided emissions higher than the capture efficiency are a characteristic of the CaL carbon capture systems [96], as a significant amount of waste heat is available from the process. If such waste heat is recovered to feed a steam cycle and employed for on-site electricity production, as assumed in the present study (see Section 1 of the Supplementary Material), the electricity surplus can be exported to the grid, resulting in negative net emissions [97].

In the case of PSA, the electricity demand needed for compression significantly influences CO₂ avoidance. In ceramic manufacturing, this demand exceeds that of the other carbon capture alternatives by at least 8 times, while in cement manufacturing it is at least 6 times greater (see Section 1 of the Supplementary Material for process data). These elevated compression power requirements result in indirect CO₂ emissions that account for up to 65 % of the total equivalent CO₂ emissions in the case of cement manufacturing. Notably, PSA applied to ceramic manufacturing generates indirect CO₂ emissions nearly 3 times higher than those in cement manufacturing. This discrepancy is primarily due to the higher electricity consumption per unit of CO₂ avoided, required to compress the larger volume of impurities, such as O₂ and N₂, present in the flue gas from the reference ceramic plant.

The quantification of the avoided CO₂ emissions by each carbon capture scheme applied to each HTA facility forms the basis for the calculation of the sustainability indicators in the following, which are all normalized by CO₂ avoided, as introduced in Section 2.

4.2. Sustainability indicators

Fig. 4 shows the results obtained from the sustainability indicators quantification for the two case studies analyzed. Each indicator is discussed in the following, focusing on the effects of the emission scale.

The ranking of the CO₂ capture schemes based on the selected technological performance metric remains unchanged when

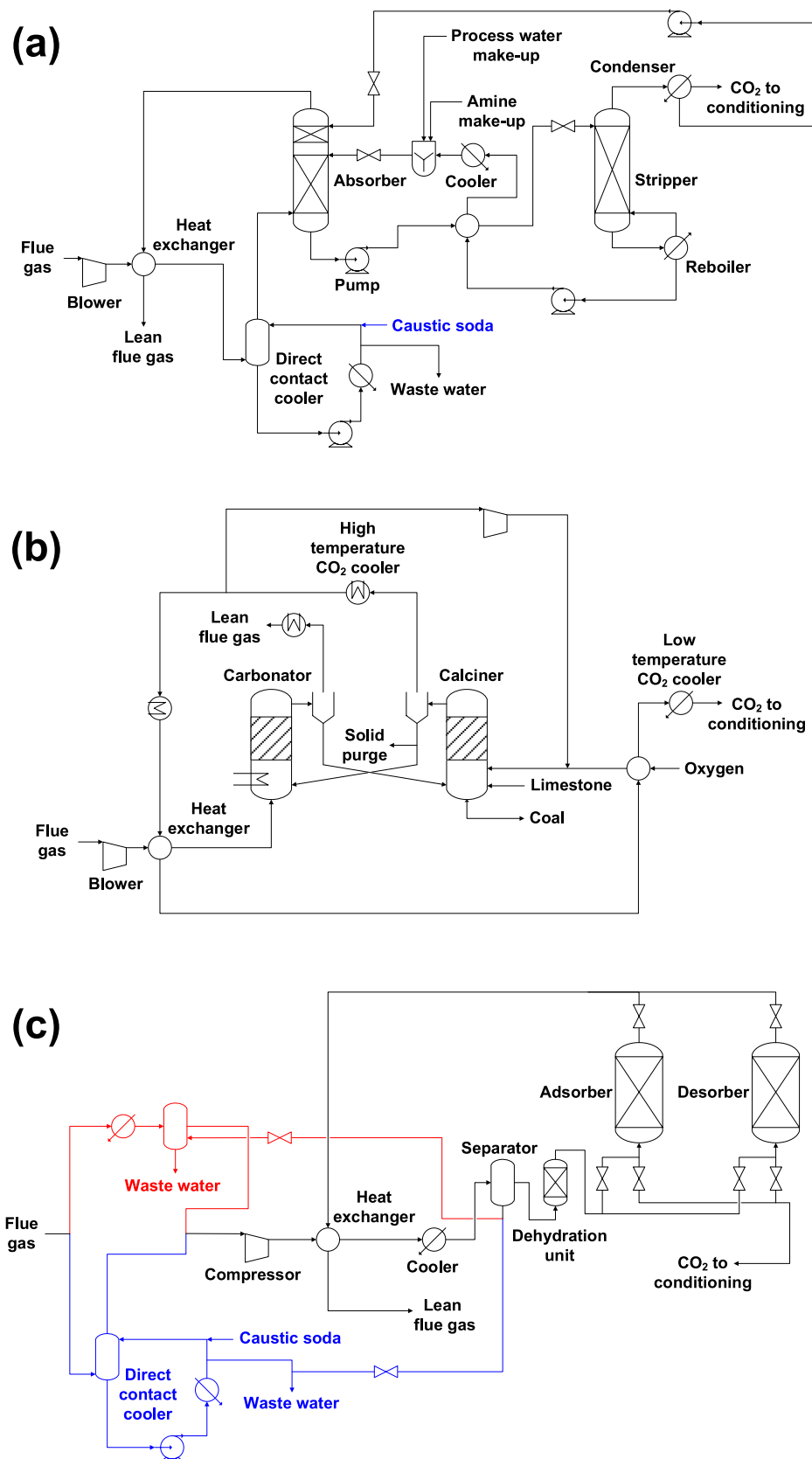


Fig. 2. Reference CO₂ capture schemes considered in the study: (a) AS – Amine scrubbing; (b) CaL – Calcium looping; (c) PSA – Pressure swing adsorption. Red and blue lines represent case-specific process variations to retrofit respectively ceramic and cement manufacturing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

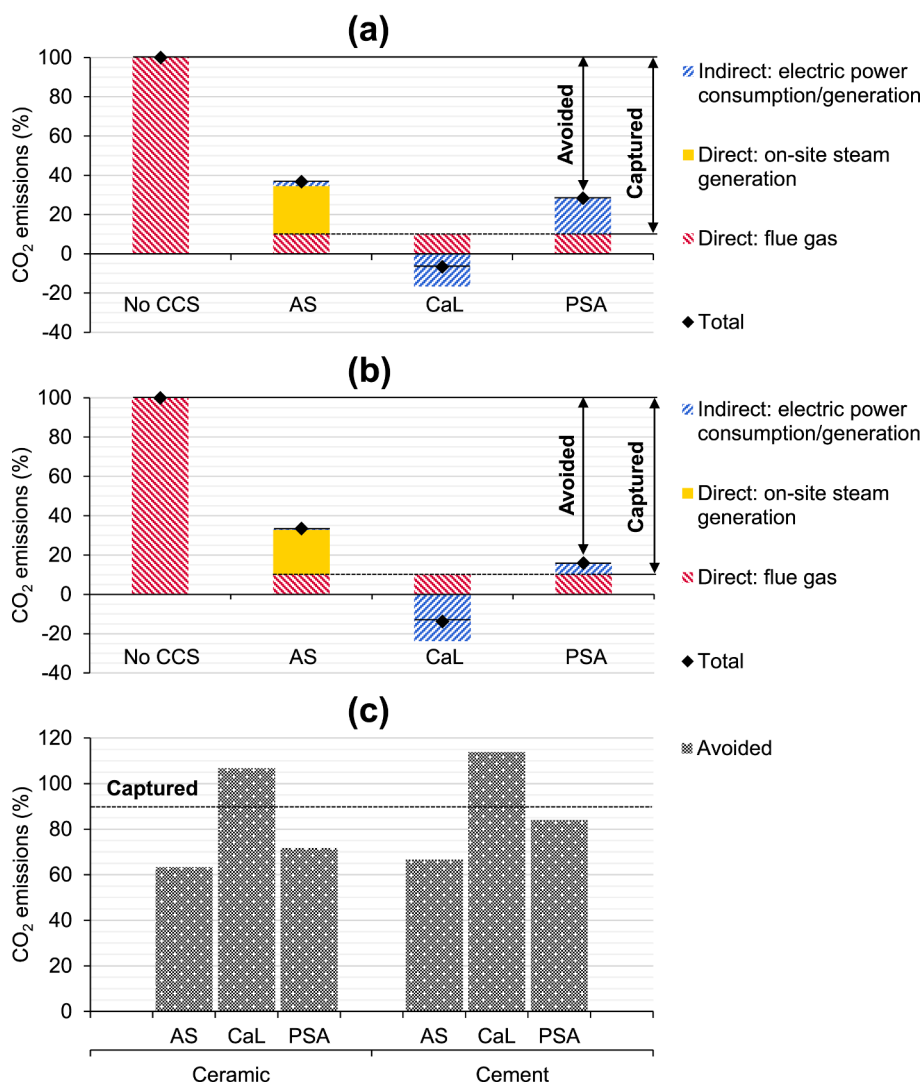


Fig. 3. CO₂ emissions calculated for the two case studies with and without carbon capture technologies (AS: Amine scrubbing, CaL: Calcium looping, PSA: Pressure swing adsorption): (a) Ceramic manufacturing; (b) Cement manufacturing; (c) Emissions captured and avoided for ceramic and cement facilities retrofitted with carbon capture technologies.

transitioning from the large-scale cement plant to the smaller ceramic manufacturing facility (see Fig. 4a). Specifically, the purity of the captured CO₂ stream from both AS e CaL proved not to be affected by the retrofitted emission point source, indicating that no significant impact derives from variations in the emission scale and in the CO₂ concentration in the inlet flue gas. In contrast, the technological performance of PSA appeared to be significantly influenced by the emission source, with the CO₂ purity index for PSA applied to the ceramic plant being approximately twice as high as that for cement manufacturing. This is due to the higher fraction of impurities in the flue gas from the ceramic plant, which significantly reduces the driving force for CO₂ adsorption/desorption, a key factor for effective CO₂ capture in pressure swing adsorption processes.

Concerning the environmental dimension (see Fig. 4c), CaL emerged as the least effective alternative for both industrial emission sources. This can be attributed to the significant share of cumulative energy consumption associated with the supply of raw materials (e.g., oxygen, coal), as high as 80 % of the total CSPECCA index value. Moreover, it can be noted that, for both the emission sources, the fraction of CSPECCA associated with the sole fuel consumption offsets alone the total CSPECCA related to PSA and AS. In particular, the latter exhibited an almost constant CSPECCA regardless of the application, whereas PSA

demonstrated the lowest environmental index value when applied to the large-scale emission source. For both ceramic and cement plants, the CSPECCA of AS is primarily influenced by fuel supply, whereas electricity consumption is the most significant factor impacting the PSA process.

Similar to the previously discussed indicator, the CO₂ avoided inherent hazard index, introduced to assess the social sustainability of CO₂ capture, yields significantly higher values when the reference technologies are scaled down to retrofit the ceramic manufacturing facility (see Fig. 4d). For each CO₂ capture scheme, the safety performance appears to be largely influenced by heat exchangers, due to their high susceptibility to loss of containment. While the safety performance of CaL and PSA is nearly identical, AS exhibits a significantly higher CAHI value, approximately 25 times greater than that of the alternative technologies. This substantial difference is primarily due to the additional hazard contribution associated with credible releases of the flammable and toxic amine solvents.

From an economic perspective, Fig. 4b shows that the CAC of carbon capture technologies increases when transitioning from the cement plant to the ceramic plant. This increase is primarily driven by the significantly smaller emission scale of the ceramic plant, which greatly limits economies of scale. Although the lower CO₂ concentration in the

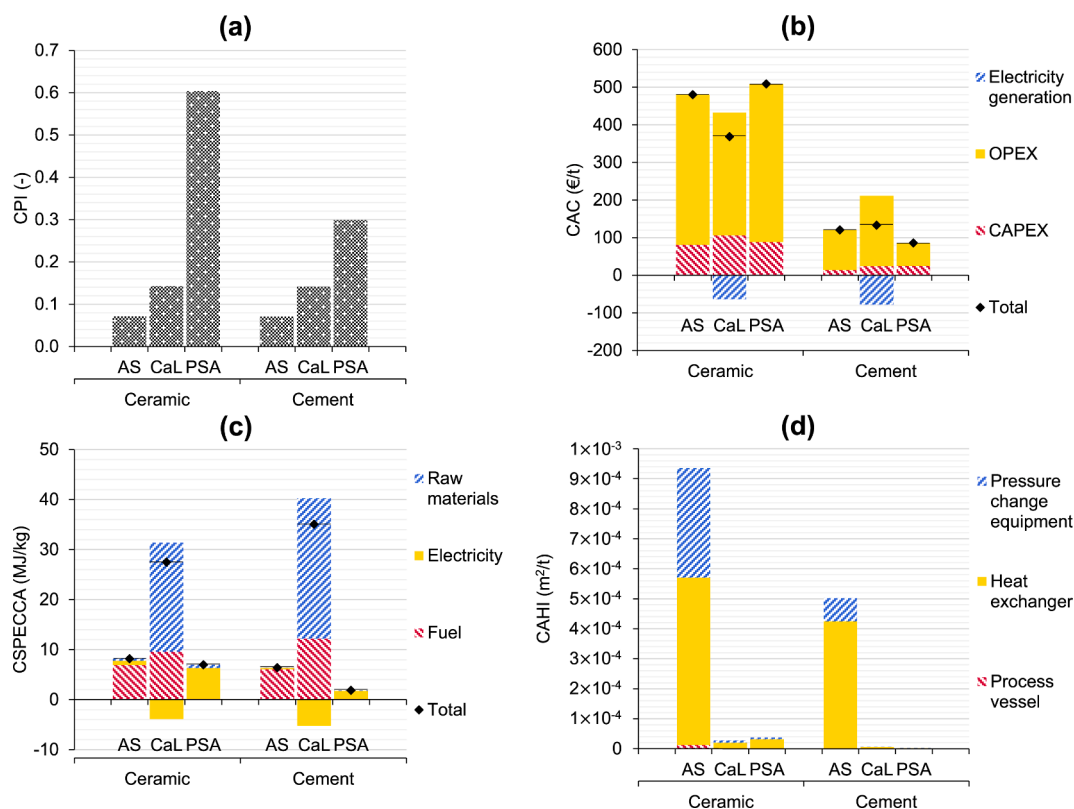


Fig. 4. Sustainability indicators calculated for the reference CO₂ capture schemes applied to the two hard-to-abate facilities considered in the study: (a) Technological, CPI; (b) Economic, CAC; (c) Environmental, CSPECCA; (d) Societal, CAHI.

ceramic plant flue gas may contribute to higher operating costs and, to a lesser extent, may cause higher capital costs, its impact on CAC is expected to be lower than the effect of the reduction in the emission scale.

For cement manufacturing, PSA emerged as the most economically viable option, followed by AS and CaL, which have nearly equal CAC values. It is worth noting that a “pure” retrofitting is considered for the implementation of post-combustion CO₂ capture schemes, with no modification of the process with respect to the case where carbon capture is absent. In this regard, the CAC of carbon capture technologies may be lowered if proper process optimization and integration with the cement manufacturing process (e.g., reusing the CaL purge for clinker production) are conducted. The pattern of economic indicator values outlines a clear ranking among the alternative CO₂ capture schemes, as the retrofitted industrial facility is scaled down to ceramic manufacturing. Specifically, high operating costs significantly limit the economic viability of PSA and AS, which have CAC index values *ca* 1.4 and 1.3 higher than that of CaL, respectively. The latter also favors of the significant volumes of CO₂ emissions that are avoided through the integration of a steam cycle-based heat recovery for electricity production, which further contributes to lowering its CAC value. In contrast, the reduced economic performance of PSA can be attributed to the substantial cost impact of the large quantities of adsorbent required for CO₂ capture.

4.3. Impact of emission scale on the sustainability dimensions

The sustainability indicators calculated in Section 4.2 revealed a strong sensitivity of the CO₂ avoided cost (CAC) to variations in the emission scale. Fig. 5 compares the CAC values obtained in this study with data reported in technical literature. While no literature data are available for CO₂ capture from ceramic manufacturing facilities, the CO₂ capture cost range provided by IEA [98] for the cement sector was used as a reference and is represented as an error bar on the chart. Notably, all

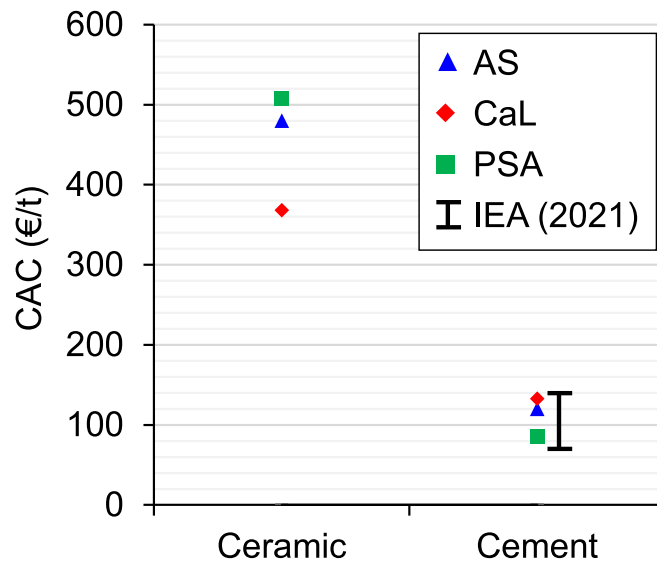


Fig. 5. CO₂ avoided costs of the carbon capture schemes assessed in the study. The error bar represents the cost range for cement manufacturing derived from IEA [98] and selected as a reference to validate the economic performance assessment model.

the CAC values calculated for cement manufacturing in this study fall within the reference cost range of 70 – 140 €₂₀₂₁/t. This outcome validates the CAC assessment procedure proposed in the present study, particularly for predicting CO₂ abatement costs at lower emission scale where specific literature-based data are typically unavailable. Furthermore, the results in Fig. 5 highlight the significant impact of economies of scale in industrial carbon capture, with CO₂ capture technologies

designed for the 14-fold higher emissions of cement manufacturing achieving a CAC up to seven times lower than in ceramic manufacturing.

Sustainability-related impacts produced by carbon capture were analyzed also in absolute terms, considering an equal amount of avoided CO₂ emissions in the two case studies of the cement and ceramic tile industries. The value of the CO₂ emissions avoided when considering the application of amine scrubbing, the most commercially developed technology [20], to the cement manufacturing plant defined in Table 4 (590,000 t/y) was considered as a reference. The absolute impacts on economic, environmental and societal sustainability pillars, i.e., those affected by emission scale variations (see Fig. 4), were computed by multiplying the corresponding performance indicators by the value of avoided CO₂ emissions. Table 5 summarizes the key findings obtained from this procedure. In the case of ceramic manufacturing, the reference CO₂ avoidance can be obtained by retrofitting *ca* 45 plants, with a total annual cost about 4 times higher than that for a single cement plant with the characteristics defined in the study, and an environmental impact 28 % higher. The results in Table 5 confirm the pronounced scale effect on the economic dimension, with impacts escalating significantly as the emission scale decreases, primarily due to soaring capital expenditures. Conversely, environmental impacts are less affected by scale reductions, as they are predominantly driven by material and energy flows, which exhibit a more limited sensitivity to changes in scale. Notably, impacts on the safety domain show an increase as high as 87 % for the ceramic case (see Table 5). Considering that the inherent hazard indicator is computed as a product of the likelihood and magnitude of credible accident scenarios, it emerges that the application of carbon capture in a high number of small-scale emission sources compared to a single larger facility produces an increase in the likelihood of potential accidents that is higher than the decrease in the magnitude of such accidents. Overall, these findings underscore that, with the currently available carbon capture technologies, retrofitting a single large-scale hard-to-abate emission source is significantly more effective from a sustainability perspective than retrofitting multiple smaller emission sources.

4.4. Comparison of sustainability footprint

Fig. 6 presents the normalized sustainability indicators of the reference CO₂ capture schemes applied to the two case studies considered.

Focusing on technological sustainability, AS emerged as the most effective solution, with the CPI index resulting up to 88 % lower than PSA in the case of ceramic manufacturing. This is counterbalanced by a significant reduction in the safety performance, with the CAHI for the two alternative technologies applied to ceramic and cement plants dropping to values as low as *ca* 0.5 % of those achieved with AS. In the environmental domain, CaL demonstrates a markedly higher CSPECCA value, at least +236 % compared to the other technologies, primarily due to its substantial raw material and fuel consumption. More broadly, Fig. 6 illustrates a clear burden shift across sustainability domains when transitioning between the three carbon capture schemes, regardless of emission scale. Each technology exhibits a distinct area of concern: CAHI for AS, CSPECCA for CaL, and CPI for PSA. In this context, incorporating the CAHI indicator into the proposed sustainability assessment framework proves essential to avoid overlooking safety-related impacts,

Table 5

Variation of economic, environmental and societal impacts of CO₂ capture with the emission scale, considering a fixed CO₂ avoidance. Amine scrubbing is considered as the reference technology.

	Cement	Ceramic
Reference CO ₂ avoided (t/yr)	5.90×10^5	5.90×10^5
Number of retrofitted plants	1	45
Economic impact (M€/yr)	70.91	283.26
Environmental impact (MW)	119.69	152.95
Societal impact (m ² /yr)	295.94	552.22

which may not correlate with other sustainability indicators. Ultimately, normalized results evidence the significant influence of the emission scale on the economic comparison of CO₂ capture alternatives.

4.5. Aggregated sustainability indices

The multi-criteria aggregation procedure outlined in Section 2.4 allowed the investigation of the overall sustainability profile of carbon capture schemes with respect to different decision-making perspectives. Fig. 7 presents the OSI_n values calculated for the two baseline emission sources retrofitted with carbon capture schemes.

When considering the OSI_n calculated under an equal weighting perspective, the sustainability-based ranking of alternative CO₂ capture technologies appears to be strongly influenced by the type of targeted industrial emission source. Conversely, adopting an environment-oriented egalitarian or hierarchist perspective results in a more robust comparative assessment of CO₂ capture technologies across the two industrial case studies, consistently identifying AS as the best-performing alternative. This is primarily due to the significant environmental impact caused by raw material consumption in CaL and PSA processes. An individualist archetype prioritizing short-term safety-related impacts produces a markedly different outcome, with AS ranking lowest among the alternatives. This result can be attributed to the significant inherent hazard associated with the use of chemical solvents for CO₂ absorption. Moreover, the individualist-based sustainability assessment of technologies appears to be more sensitive to variations in the scale of emissions, as evidenced by CaL and PSA ranking differently between ceramic and cement manufacturing.

4.6. Sensitivity analysis

The robustness of the results obtained in the analysis was verified with respect to variations in the electricity generation CO₂ emission factor, EF_{el}. Indeed, this input parameter can vary widely, ranging from a theoretical value of 0 (representing a fully decarbonized electricity generation system) to several hundred grams of CO₂ equivalents emitted per kWh of electricity produced [57]. Consequently, the EF_{el} assumed in the analysis is expected to significantly influence the CO₂ avoidance performance of the carbon capture schemes considered. A sensitivity analysis of the economic, environmental and safety indicators considering variations of the electricity generation CO₂ emission factor was therefore conducted, being the formulation of these metrics intrinsically dependent on EF_{el} through the amount of CO₂ emissions avoided. Specifically, the uncertainty range identified for EF_{el} spans from 0 to 721 g/kWh, with the latter representing the highest value recorded among EU countries during the reference year of the analysis [57]. Fig. 8 presents the results of the sensitivity analysis.

For the economic pillar, PSA applied to ceramic manufacturing emerged as the carbon capture scheme most affected by variations in EF_{el}, with the CAC index potentially ranging from 646 to 1679 €/t. This is because EF_{el} directly influences the economic index by altering the indirect emissions associated with the significant electricity consumption of the PSA upstream compressor per CO₂ avoided. Nevertheless, the ranking of CO₂ capture schemes remains unvaried for the ceramic plant. In contrast, variations in EF_{el} are critical for the comparative economic assessment of CO₂ capture solutions for the cement plant, given the similar economic index values shared by the reference technologies in the analysis. Specifically, CaL emerges as the most cost-effective alternative as EF_{el} increases, primarily due to the critical role of the integrated heat recovery steam cycle in avoiding indirect CO₂ emissions associated with a carbon-intensive electricity supply. In the case of a completely decarbonized electric power distribution system (i.e., EF_{el} equal to 0), AS and PSA outperform CaL, being the higher annual cost of the latter not counterbalanced by the electricity-related CO₂ avoidance contribution provided by the heat recovery steam cycle. The sensitivity analysis of the environmental indicator revealed that CaL consistently

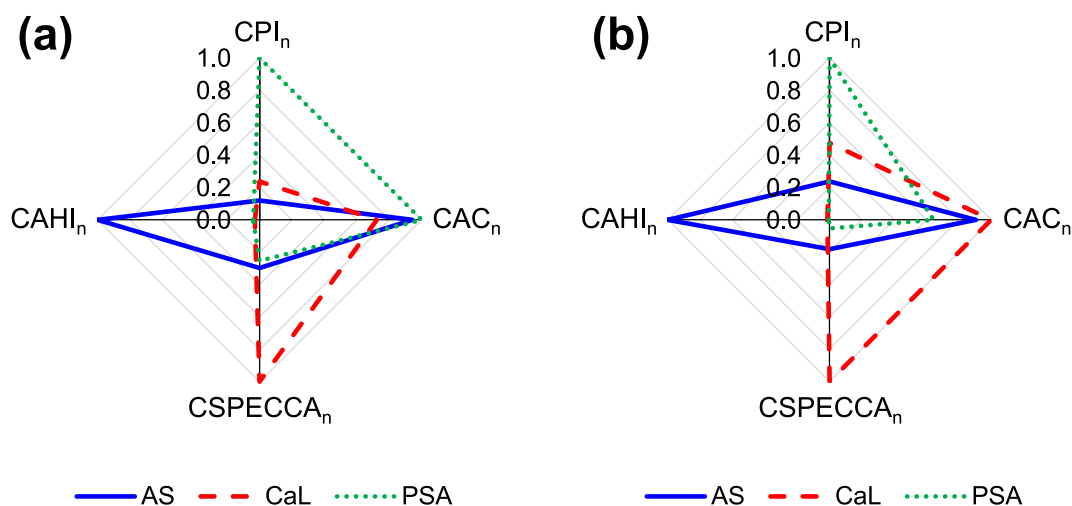


Fig. 6. Normalized sustainability indicators computed for the alternative reference CO₂ capture schemes considered for: (a) Ceramic manufacturing; (b) Cement manufacturing.

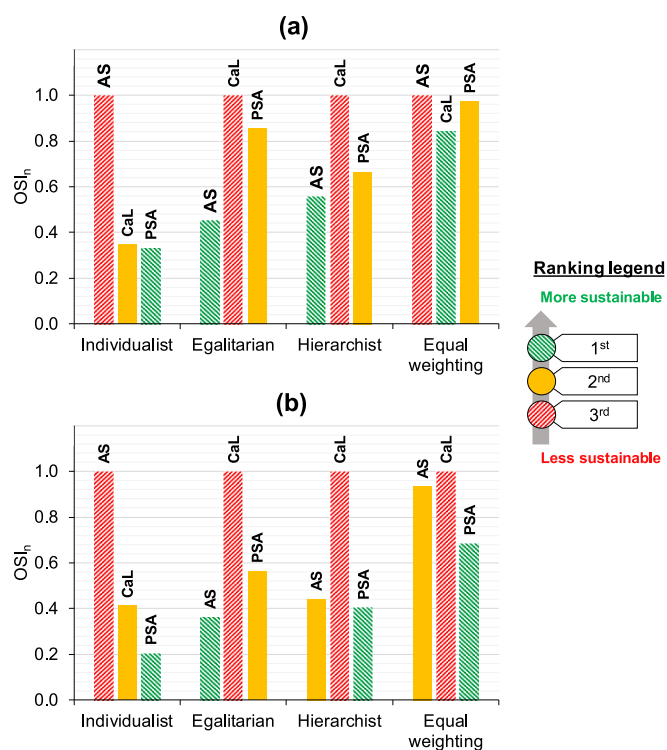


Fig. 7. Ranking of CO₂ capture technologies based on the normalized overall sustainability index (OSI_n) and considering the different decision-making perspectives: (a) Ceramic; (b) Cement.

emerged as the least environmentally sustainable CO₂ capture solution, regardless of EF_{el}, with CSPECCA index values reaching as high as 33 MJ/kg and 44 MJ/kg for ceramic and cement manufacturing, respectively. This finding underscores the significant environmental impact associated with the high resource consumption of the technology, which outweighs any potential benefits from its CO₂ avoidance capabilities provided by the heat recovery steam cycle. For AS and PSA, the comparison of their environmental performance remains robust in the case of cement manufacturing. However, for the ceramic facility, a ranking inversion is likely due to the high degree of uncertainty in the CSPECCA of PSA, driven by the substantial electric power requirements for compression per tonne of CO₂ avoided. Ultimately, the safety-based

comparison of CO₂ capture schemes shows minimal sensitivity to variations in EF_{el}, demonstrating the robustness of the inherent safety assessment method developed in this study against changes in input parameters.

5. Discussion

The results demonstrated the applicability of the methodology through two significant case studies focused on the comparative assessment of alternative post-combustion CO₂ capture technologies in hard-to-abate industries. This study introduced several elements of novelty, both in terms of the innovative methodological framework and the insights derived from the case studies. The methodology enables a comprehensive sustainability assessment of industrial carbon capture technologies, integrating inherent safety quantification used as a proxy for social sustainability alongside technological, economic, and environmental metrics. Additionally, the developed method requires limited technical input data, making it particularly well-suited for early-stage design and screening of CO₂ capture processes. The case studies identified critical aspects for implementing CO₂ capture at smaller industrial emission scales. While CO₂ avoidance costs proved to be highly sensitive to the emission scale, safety also emerged as a concern, with the retrofitting of multiple small emitters with CO₂ capture systems posing an increased risk of major accidents. The integration of inherent safety into a multi-criteria sustainability assessment yielded consistent findings across the two case studies. Notably, conventional amine scrubbing (AS) technology was identified as the least favorable option under an individualist archetype, emphasizing the critical importance of addressing safety aspects to ensure sustainable CO₂ capture applications.

Two main limitations of the present analysis should be highlighted. First, the scope of this study is limited to the CO₂ capture stage within the CCS value chain, excluding downstream processes such as conditioning, transport, and injection. While the assessment framework considers CO₂ purity as a key element of the technological pillar (as detailed in Section 4.2), it does not address the specific requirements imposed by downstream processes. For instance, pipeline transport typically necessitates high CO₂ purity levels [99], leaving no room for trade-offs with other indicators. Conversely, alternative applications such as carbon capture and utilization (CCU) or CO₂ mineralization may allow different CO₂ purities, depending on the intended end use. Decision-makers can adapt the assessment by adjusting the weighting of sustainability criteria to align with the specific context of CO₂ capture application. In addition, it is worth considering that the methodology and the indicators introduced in this study can in principle be applied

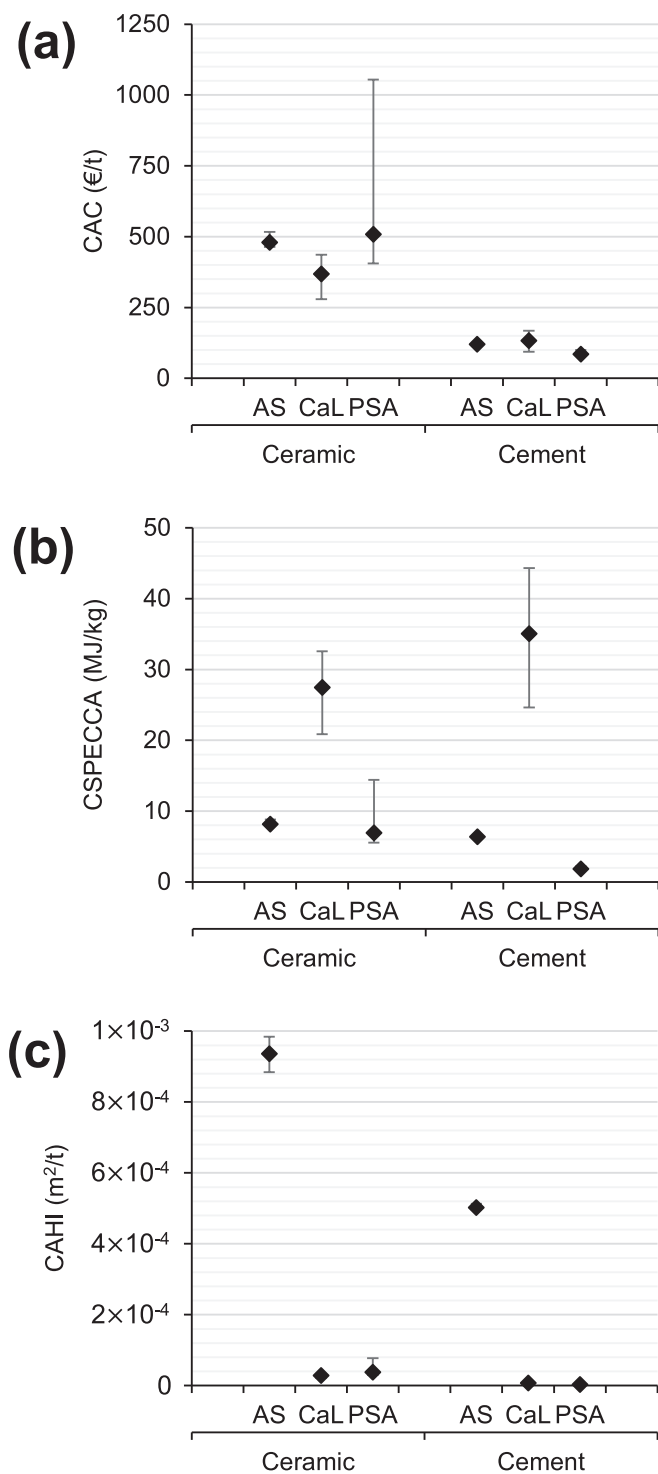


Fig. 8. Results of the sensitivity analysis of the sustainability indicators with respect to the electricity generation CO₂ emission factor: (a) Economic; (b) Environmental; (c) Societal.

also to include downstream stages such as conditioning, transport and injection of CO₂, thus allowing a comparative assessment of the implications of technological alternatives over the entire CCS value chain.

Second, the comparative assessments in Section 4 were carried out under the assumption that CO₂ capture technologies would be retrofitted as standalone post-combustion systems, without heat or energy integration with other on-site processes. However, such integration could substantially reduce the energy penalty associated with CO₂

capture retrofits in specific cases [100]. Consequently, the proposed sustainability assessment approach is well-suited for incorporation into early design stages but may overlook potential optimization opportunities specific to individual industrial plants. However, it is worth noting that many hard-to-abate (HTA) industrial facilities, especially in manufacturing sectors, often lack readily available high-quality excess heat, and ongoing energy efficiency improvements are expected to further reduce its availability [53]. Therefore, the exclusion of energy integration considerations for an early screening of CO₂ capture options is a conservative assumption that can be justified in the perspective of the improvement of energy efficiency measures.

Finally, it should be remarked that defining a set of KPIs suitable for the application of the proposed approach is a critical task, particularly in the case of emerging technologies where technical data may be limited. The selected metrics should capture significant performance variations within each sustainability domain driven by design or technology choices and should be quantifiable based on the data available at the corresponding design stage. For early technology development and design stages, the emphasis should be on metrics derived from readily available preliminary technical information, such as thermodynamic limits, material and energy flow estimates, reaction stoichiometry for reactive CO₂ capture systems, and expected operating conditions (e.g., pressure and temperature ranges). In this study, a single representative metric per each sustainability domain was selected to provide a practical yet comprehensive sustainability analysis. However, the methodology is designed to remain flexible, allowing for the incorporation of additional sustainability metrics as the technology advances through its design stages and more detailed technical data are obtained.

6. Conclusions

In the present study, a quantitative method for the comparative assessment of the sustainability of CO₂ capture technologies was developed and demonstrated with reference to post-combustion capture processes designed for different industrial emission sources. Alternative CO₂ capture schemes were defined for retrofitting a ceramic plant and a cement plant, representing medium and large “hard-to-abate” CO₂ emission sources, respectively. Specific KPIs were proposed to quantify sustainability impacts of CO₂ capture with reference to each pillar considered, as well as from a global viewpoint.

Except for technological performance, all sustainability-related impacts of the assessed carbon capture technologies were found to increase as the targeted emission scale decreased. Among these, the economic pillar proved to be the most sensitive, with CO₂ avoidance costs increasing from 70 to 140 €/tCO₂ in the case of cement manufacturing up to 369–509 €/tCO₂ in the case of ceramic manufacturing. Notably, the findings reveal that achieving the same target of avoided CO₂ emissions can result in substantially different costs and safety-related impacts depending on whether the retrofitting is applied to a single large emission point source, such as a cement manufacturing plant, or multiple smaller industrial emitters, such as ceramic tile manufacturing plants. When CO₂ capture technologies are retrofitted to the ceramic plant considered in this study, which has an emission scale approximately 14 times lower than that of the reference cement plant, costs per unit of avoided CO₂ increase by as much as 300 %. Safety-related impacts, measured as the risk of major accidents, rise by up to 87 %, driven by the higher number of installations and/or components required for retrofitting multiple smaller emission point sources.

Different aggregation approaches were evaluated to combine the defined sustainability KPIs into a single index. The analysis revealed that adopting a neutral equal-weighting perspective, which does not account for case-specific sustainability policies or prioritization of sustainability aspects, may lead to a weaker comparative sustainability assessment of CO₂ capture solutions across different hard-to-abate industrial sectors. Conversely, the inclusion of stakeholders’ preferences through reference decision-making archetypes provided a more distinct ranking of CO₂

capture solutions. Specifically, carbon capture by amine scrubbing was identified as the least effective option when prioritizing short-term societal aspects based on an individualist archetype, in contrast to sustainability assessment perspectives aimed at medium-to-long-term environmental preservation, such as the egalitarian and hierarchist archetypes. The sensitivity analysis confirmed the critical role of location-specific carbon intensity of electricity generation in influencing the results of the comparative analysis, particularly concerning economic and environmental aspects.

Overall, the present study highlighted the potential limitations of existing industrial carbon capture solutions when applied to small- and medium-sized industrial emitters. Innovative solutions centered on process intensification, the adoption of less hazardous materials, and the efficient use of resources will be pivotal for advancing sustainable CO₂ capture applications at smaller emission scales.

CRedit authorship contribution statement

Francesco Zanobetti: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Alessandro Dal Pozzo:** Writing – review & editing, Methodology, Investigation, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cej.2025.159466>.

Data availability

Data will be made available on request.

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