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Weighing risks against GHG reduction benefits in emerging green technologies

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Abstract

Green technologies represent promising strategies for mitigating carbon emissions and combating global warming. However, their implementation in civil and industrial applications is not without risks, as intrinsic uncertainties and latent safety concerns can threaten their effective deployment. To quantitatively evaluate the trade-off between environmental benefits and safety issues, this work develops an innovative methodological approach. This approach aims to determine the risk–benefit profile of emerging green solutions through the definition and calculation of a new key performance indicator, the risk of CO_2 avoided index (RCAI). By doing so, it provides a comprehensive understanding of the effectiveness of the green technology implementation and serves as a powerful tool for supporting stakeholder decision-making. In order to demonstrate the systematic nature and versatility of the methodological approach, it has been applied to a case study involving a carbon capture and storage (CCS) system retrofitted onto a power plant. The results underscore its flexibility and effectiveness, highlighting the importance of sustainable and safe technological advancements in the fight against global warming.

KEYWORDS

carbon capture and storage, CO_2 avoided, green technologies, key performance indicator, risk assessment

Acronyms: AC, alternating current; C, column; CCS, carbon capture and storage; CE, critical event; CO_2, carbon dioxide; D, direct contact cooler; E, heat exchanger; EC, equipment item classes; EI, equipment item; FB, fireball; FF, flash fire; FMEA, failure mode and effects analysis; GHG, greenhouse gas; H_2O, water; IRPA, individual risk per annum; JF, jet fire; K, compressor; LC, lethal concentration; LCA, life cycle assessment; LFL, lower flammability limit; LP, low-pressure; MEA, monoethanolamine; MIMAH, methodology for the identification of major accident hazards; MIRAS, methodology for the identification of reference accident scenarios; N_2, nitrogen; NG, natural gas; O_2, oxygen; P, pump; PCC, post-combustion capture; PE, physical explosion; PF, pool fire; PFD, process flow diagram; PLL, potential loss of life; QRA, quantitative risk assessment; RCAI, risk of CO_2 avoided index; RM, release mode; S, separator; T, pipeline; TC, toxic cloud; VCE, vapour cloud explosion; VCS, value chain stage; λ, credit factor.

1 | INTRODUCTION

Green technologies, encompassing a diverse spectrum of environmentally friendly innovations based on their production processes or supply chains,[1] have emerged as pivotal in the global attempt to attenuate the impacts of global warming.[2–4] These technologies span various sectors, from renewable energy generation and energy-efficient systems to sustainable transportation and circular economy practices,[5,6] offering opportunities for significant carbon emissions reductions.[7] By facilitating the transition from fossil fuels, they address climate change directly while improving energy efficiency, reducing waste, and promoting sustainable consumption patterns, ultimately driving a shift toward a low-carbon economy.[8,9]

However, the widespread implementation of green technologies is not without challenges.[10] While these solutions promise substantial environmental benefits, they also introduce new potential risks. Intrinsic uncertainties associated with emerging technologies,[11] coupled with the scale and complexity of their responsible deployment in civil and industrial applications, can generate multiple safety concerns.

Carbon capture and storage (CCS) exemplifies the complexities inherent in green technologies.[12–14] CCS involves the direct capture of carbon dioxide (CO_2) from large emitters, such as power plants[15] and industrial facilities (e.g., hydrogen production plants, glass industries, etc.), their compression, and finally transportation, typically via pipelines,[16] toward permanent storage sites like saline aquifers or depleted oil and gas reservoirs.[17,18] While its potential to mitigate climate change during the prolonged period of the energy transition is evident,[19–21] concerns regarding the potential CO_2 leakages throughout all stages of the CCS chain, from capture to transportation and storage, have raised questions about its safety.[22] During the capture phase, equipment failure, inadequate maintenance protocols, or human action can lead to leaks at the facility itself. Transportation, whether by pipelines or other means, introduces additional opportunities for leaks or accidents along the route. Pipeline or tank ruptures, corrosion, or accidental releases can lead to fugitive CO_2 emissions or soil contamination.[23–25] Lastly, the possibility of leakage remains a major concern during the storage phase, when CO_2 is injected into deep geological formations for long-term storage.[26,27] Although exhausted reservoirs and saline aquifers appear to be suitable geological formations,[28] there is still concern about the possibility of CO_2 movement through faults or fractures in the rock formation. According to Rizzo et al.,[29] this movement may undermine the integrity of the storage site and cause CO_2 to leak into the groundwater or atmosphere.

Given these challenges, a comprehensive understanding of the trade-off between the environmental advantages and potential risks of green technologies is essential. This knowledge is crucial for informed decision-making by policymakers and industry stakeholders.

To assess the environmental performance of green technologies comprehensively, life cycle assessment (LCA) has been widely recognized as a systematic framework. Defined by ISO 14040,[30] LCA provides a structured approach to evaluating environmental impacts across all life cycle stages of a product or technology, from raw material extraction to disposal. LCA facilitates informed decision-making by identifying environmental trade-offs and optimizing sustainability performance.[31] However, conventional LCA primarily focuses on environmental burdens such as carbon footprints[32] and resource consumption,[33] often overlooking safety risks and technological uncertainties.[34]

The same conclusion can be drawn for risk assessment approaches, which primarily emphasize hazard identification, exposure assessment, and consequence analysis while often neglecting broader environmental trade-offs and life cycle considerations.[35] Traditional risk assessment frameworks, such as quantitative risk assessment (QRA), focus on estimating potential failures, human health impacts, and safety hazards associated with a given technology or process.[36] However, these methods rarely integrate environmental sustainability metrics, leading to fragmented assessments that fail to capture the full spectrum of ecological and human health implications.[37]

Given the potential hazards associated with green technologies, a growing body of literature has explored integrating LCA with risk assessment methodologies to provide a holistic evaluation of both environmental and safety considerations.[34,38,39] Historically, the link between LCA and risk assessment has been explored through various methodological approaches. Some studies advocate for incorporating probabilistic risk assessment within the LCA framework to quantify uncertainties and potential hazards.[40] Others propose hybrid models that integrate LCA with failure mode and effects analysis (FMEA) or hazard analysis techniques to assess systemic vulnerabilities.[41] These interdisciplinary efforts highlight the need for an expanded LCA framework that explicitly incorporates risk quantification, particularly for emerging green technologies.

To date, to the best of the authors' knowledge, no available metrics systematically quantify and compare the dual impact of green technologies—both in terms of

their environmental benefits (i.e., greenhouse gas (GHG) emission reductions) and inherent risks (i.e., safety concerns related to technology deployment)—to support their sustainable and safe implementation. Therefore, this study addresses this critical gap by proposing the 'Risk of CO_2 Avoided Index' (RCAI), a novel key performance indicator that integrates an assessment of the potential safety impacts on surrounding communities using established risk-quantification methods together with established GHG emission calculations. By offering a comprehensive risk–benefit evaluation of green technologies, the RCAI answers the following research question: '*How can the trade-off between the environmental benefits and potential risks of green technologies be systematically quantified to support informed decision-making?*'. Indeed, this unified metric enables direct comparisons between different green technologies, facilitating knowledge-based decision-making and prioritizing solutions that strike the optimal balance between benefits and risks.

By applying this methodology to an original case study involving a CCS system retrofitted onto a power generation plant, this work demonstrates its versatility and applicability in real-world scenarios. The findings will contribute to the responsible and effective deployment of green technologies, ultimately supporting the transition to a sustainable and resilient future.

2 | METHODOLOGY

The methodology developed in the current study is organized into 15 distinct steps grouped into five main phases (i.e., preliminary phase, critical event assessment, consequence assessment, risk assessment, and risk indexes calculation). Figure 1 illustrates the flowchart of the methodology. Its systematic approach enhances rigour, transparency, and replicability in the assessment process, allowing for a nuanced understanding of risks and facilitating more informed decision-making. Furthermore, its cyclical approach emphasizes continuous refinement and adaptation throughout the process. This iterative nature is reflected in the feedback loops that connect various steps, ensuring that new insights and potential modifications are incorporated as the analysis progresses.

At the basis of this methodology there is the concept of green technology value chain.[5] Each green technology can be structured into a sequence of process operations, each characterized by different components with various functional activities, constituting the technology life cycle.[42] Examples can be the CCS value chain[17] or the ones associated with renewable energy sources, such as wind[9] or solar power.[8] The first one consists of four successive stages: capture, conditioning (compression), transport, and storage, while the renewable value chains can be broken down into three main stages that are upstream, midstream, and downstream. The upstream stage encompasses activities related to the development, production, and transportation of renewable energy technologies, such as mining raw materials for solar panels or manufacturing wind turbine blades. The midstream stage involves the transmission and distribution of renewable energy to consumers. Finally, the downstream stage is the delivery of renewable energy to the end user.

As a result, this new methodology allows for the rating of the criticality of the various green technology value chain stages, indicating the most vulnerable equipment items that require additional examination within the context of risk assessment and management. Furthermore, the findings educate industry stakeholders about their sustainability impact.

Before delving into each individual stage, it is important to note that, due to the systematic nature of the methodology, it may be applied to any green technology with appropriate changes.

2.1 | Preliminary phase (Steps 1–3)

This preliminary phase encompasses the initial steps of the methodology and is fundamental in laying the foundation for the subsequent estimation of the final RCAI.

Step 1 involves the initial task of defining the boundaries of the system under evaluation. Since the methodology aims to assess how risk varies when green solutions are taken into consideration, two different systems (i.e., value chains) must be defined. The first, referred to as the *base case* (status quo), represents the system with no carbon reduction solutions implemented, while the second one, named the *green case*, represents the low-carbon system under evaluation. Then, comprehensive data pertaining to the systems must be gathered. This includes acquiring detailed information regarding the layouts and components, their functional activities, operational characteristics (e.g., pressure and temperature), substances involved (in terms of thermodynamic and hazardous properties), and any relevant historical data (if available).

Step 2 concerns the systematic decomposition of the value chains of the base and green cases into individual value chain stages (VCSs), each representing a distinct functional activity within the overall process. An example is the CCS value chain (described above) that is composed of four subsequent VCSs (capture, conditioning, transport, and storage). This breakdown facilitates a granular analysis of potential risks associated with specific operations.

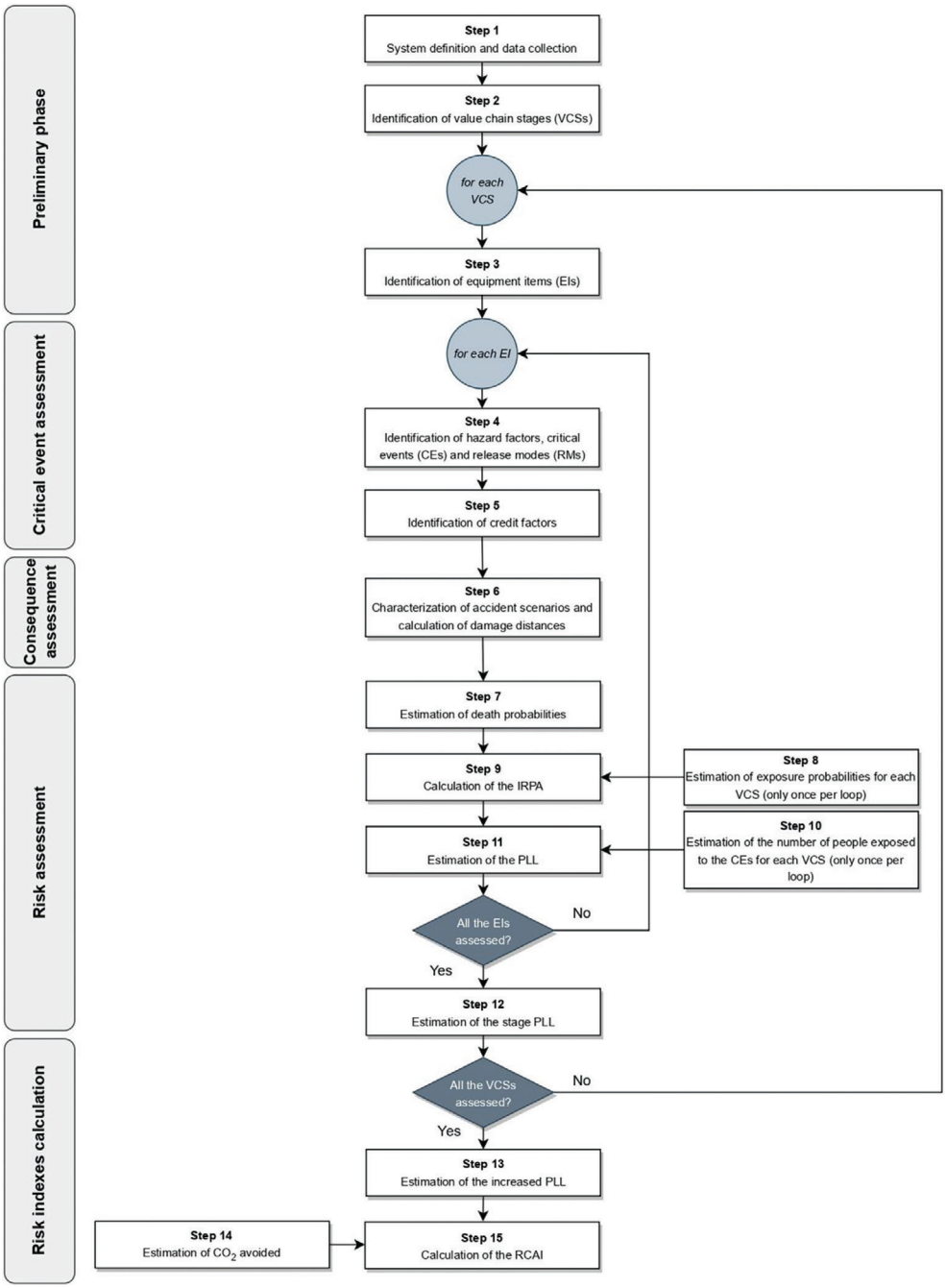

FIGURE 1 Flow chart of the methodology presented in the current study.

For each identified VCS (*s*), the relevant hazardous equipment items (EIs) must be meticulously recognized and listed (***Step 3***). To accomplish this, the Methodology for the Identification of Major Accident Hazards (MIMAH) procedure[43] shall be employed. It begins by identifying potentially hazardous EIs based on the type of hazardous substance they store. The classification of these hazardous substances follows the guidelines outlined in the Seveso II Directive[44] and the risk sentences specified in the 1272/2008/EC Regulation.[45] Once identified, the potentially hazardous EIs are categorized into 16 different classes, as shown in Table 1.

Then, the MIMAH procedure involves the selection of the EIs that contribute significantly to the risk posed by the value chain. The identification of these relevant hazardous EIs is based on an indexing approach, where the mass of the hazardous material is compared to a threshold quantity. The threshold is determined by the hazardous properties of the substance, its physical state, tendency to vaporize, and proximity to other hazardous EIs. Overall, the data required to apply this criterion includes the following[46]:

- EI code;
- EI class (refer to Table 1);

- Substance handled;
- Physical state;
- Boiling temperature;
- Service temperature;
- Risk sentence;
- Hazardous classification;
- Volume;
- Mass contained in the equipment or mass released in 10 min (for flow through equipment).

2.2 | Critical event assessment (Steps 4 and 5)

This second phase involves the assessment of the critical events impacting the facilities of the systems under investigation.

Step 4 encompasses a thorough examination of each hazardous EI (e) identified in the preliminary phase (see Section 2.1) in order to first detect the hazard factors and then determine the critical events (CEs) potentially affecting each EI. The term 'hazard factor' is introduced to indicate the source of the hazard, that is, which element between the equipment inventory and the inlet streams dominate the release severity.[47]

TABLE 1 List of equipment item classes (EC) considered in the methodology for the identification of major accident hazards (MIMAH) procedure (adapted from Delvosalle et al.[43]).

EI class	Description
EC1	Mass solid storage
EC2	Storage of solid in small packages
EC3	Storage of fluid in small packages
EC4	Pressure storage
EC5	Padded storage
EC6	Atmospheric storage
EC7	Cryogenic storage
EC8	Pressure transport equipment
EC9	Atmospheric transport equipment
EC10	Pipes networks
EC11	Intermediate storage equipment integrated into the process
EC12	Equipment devoted to the physical or chemical separation of substances
EC13	Equipment involving chemical reactions
EC14	Equipment designed for energy production and supply
EC15	Packaging equipment
EC16	Other facilities

The following formula illustrates the condition where the equipment inventory determines the release severity:

$$I > \max_k \left(\dot{V}_k\right) \cdot t \tag{1}$$

where I is the equipment item inventory (m^3), $\dot{V}_k$ is the flow rate of the k-th stream entering or leaving the equipment item (m^3/s), and t is a constant equal to 180 s. It is worth noting that the term 'inventory' generally refers to the total mass of fluids contained within the equipment under operating conditions. However, if the inventory fluctuates during normal operations (e.g., in storage tanks), the highest recorded value for each fluid phase is considered. Additionally, this criterion applies solely to connecting pipes within the plant, not to external pipelines.

Subsequently, it is necessary to identify the critical events impacting the EIs, intended as losses of containment of materials and/or energy from process equipment and pipework. The MIMAH procedure,[43] outlining 12 possible critical events (CEs), as reported in Table 2, can also be used for this purpose. Two matrices are employed to determine which CEs should be associated with a given EI containing a specific substance. The first matrix crosses the EI classes (refer to Table 1) and the 12 potential critical events (refer to Table 2), while the second matrix crosses the physical state of the substance (refer to Step 3) and the 12 potential critical events (refer to Table 2).

TABLE 2 List of critical events (CEs) considered in the methodology for the identification of major accident hazards (MIMAH) procedure (adapted from Delvosalle et al.[43]).

Critical event	Description
CE1	Decomposition
CE2	Explosion
CE3	Materials set in motion (entrainment by air)
CE4	Materials set in motion (entrainment by a liquid)
CE5	Start of fire (loss of physical integrity)
CE6	Breach on the shell in vapour phase
CE7	Breach in the shell in liquid phase
CE8	Leak from liquid pipe
CE9	Leak from gas pipe
CE10	Catastrophic rupture
CE11	Vessel collapse
CE12	Collapse of the roof

Once both the hazard factors and critical events are determined, reference release modes (RMs) for each potential CE have to be associated to the EIs, based on the identified hazard factor. The definition of these reference RMs helps to characterize the CEs, accounting for factors such as release geometry, duration, entity, or conditions.[48,49] Baseline reference data can be sourced from non-specific documents, like the MIMAH procedure[43] or the TNO Purple Book,[50] along with other approaches such as the those reported in the literature.[48,51] Table 3 provides an example of standard sets of reference RMs proposed for process and transport EIs.[49,51]

For each identified reference RM (i), relevant credit factors (λ_i) must be precisely assessed in ***Step 5***. Credit factors are used in this methodology to account for the varying degrees of credibility of potential loss of containment occurrences linked to each EI. Indeed, a given CE has a different likelihood to occur in different EIs, because of the fundamental characteristics of their design and operation mode (moving sections, multiple connections, etc.). Credit factors correspond to the reference frequencies of the RMs defined in Step 4 (and reported in Table 3 for exemplificative purposes) on the basis of expected release and failure frequency data reported for standard technologies in several literature publications.[50–56] In the current evaluation, the impact of active and procedural barriers on frequency reduction is ignored. Further details about credit factors can be found in previous studies.[57,58]

2.3 | Consequence assessment (Step 6)

This phase, consisting solely of ***Step 6***, involves the analysis of the consequences of the release events. Specifically, it entails characterizing the accident scenarios linked to each reference RM associated to each EI in each VCS. In the current analysis, the term 'accident scenario' refers to the end-point event that may be the source of a potential accident risk.[49] Case-specific or reference post-release event trees are typically used to characterize the accident scenarios. In general, the construction of the event trees relies on two elements: the type of equipment item and the physical state of the substance after the release (liquid phase, gas phase, gas–liquid mixture). An exhaustive collection of event trees can be derived from the MIMAH procedure[43] and the TNO Purple Book.[50] However, for specialized event trees, techniques available in the literature[48–50] can be employed. Then, for each identified accident scenario (j), it is essential to estimate the damage distances considering threshold values of physical effects defined for human target (refer to Table 4[59]). In the current analysis, the damage distance is defined as the maximum distance from the release location at which the damage thresholds of Table 4 are achieved from consequence simulations of the reference scenarios. Based on this, the worst-case damage distances among the possible accident scenarios can be assessed. In this analysis, the domino effect[60] is omitted.

TABLE 3 Reference release modes (RMs) of interest in the case study for equipment items (process units and pipelines) (n.a., not applicable).[49,51]

		Reference release mode	
Hazard factor	**Critical event**	**Code**	**Description**
Process units			
In/out streams	CE8/CE9	RM1	Small pipe leak, continuous release from a hose having 10% of pipe diameter
		RM2	Medium pipe leak, continuous release from a hose having 22% of pipe diameter
		RM3	Pipe rupture, continuous release from the full-bore pipe
Inventory	CE7/CE10	RM4	Small leak, continuous release from a 10 mm equivalent diameter hole
		RM5	Medium leak, continuous release from a 35 mm equivalent diameter hole
		RM6	Large leak, continuous release from a 100 mm equivalent diameter hole
		RM7	Catastrophic rupture, release of the entire inventory in 600 s at constant rate
		RM8	Catastrophic rupture, instantaneous release of the entire inventory
Pipelines			
n.a.	CE8	RM9	Small pipeline leak, continuous release from a 10 mm diameter hole
		RM10	Medium pipeline leak, continuous release from a 50 mm diameter hole
		RM11	Large pipeline leak, continuous release from a 100 mm diameter hole
		RM12	Pipeline rupture, continuous release from both sides of the full-bore conduit

TABLE 4 Human threshold values assumed for the estimation of the expected damage distances.[59]

Accident scenario	Physical effect	Human threshold value
Flash fire (FF)	Transient radiation	LFL[a]
Fireball (FB)	Transient radiation	12.5 kW/m^2
Jet fire (JF)	Stationary radiation	12.5 kW/m^2
Pool fire (PF)	Stationary radiation	12.5 kW/m^2
Vapour cloud explosion (VCE)	Overpressure	0.3 bar
Physical explosion (PE)	Overpressure	0.3 bar
Toxic cloud (TC)	Toxic concentration	LC_{50}[b]

[a]LFL, lower flammability limit (ppm).
[b]LC_{50}, lethal concentration able to lead to the death of 50% of the population after 30 min of exposure to the hazard (ppm).

For calculating the damage distances, models for consequence analysis can be employed,[48,61] alongside software tools such as PHAST,[62] EFFECTS,[63] SHELL FRED,[64] or ALOHA.[65] It is worth noting that traditional models often struggle to accurately describe consequences within 5 m of the accident site, known as the 'near field' zone. To address this, any predicted damage distance within 5 m is assumed to be exactly 5 m, thereby improving the reliability of 'near field' results. This assumption allows to determine the worst-case damage distance, $D_{i,e,s}$ (m), of the i-th reference RM of the e-th EI in the s-th VCS, as follows:

$$D_{i,e,s} = \max_{j}\left(\max\left(d_{i,j,e,s}, 5\,m\right)\right) \tag{2}$$

where $d_{i,j,e,s}$ (m) represents the damage distance calculated for the j-th accident scenario following the i-th reference RM affecting the e-th EI in the s-th VCS with reference to human target.

2.4 | Risk assessment (Steps 7–12)

Once consequences are assessed, risk can be determined in the fourth phase of the methodology.

Step 7 concerns the assessment of the probability of death, $Pr(D_{i,e,s}|E_{i,e,s})$, resulting from the exposure of individuals to a specific reference RM ($E_{i,e,s}$), as follows:

$$Pr(D_{i,e,s}|E_{i,e,s}) = \frac{N_e \cdot A_{\text{impacted,i,e,s}}}{A_{\text{system}}} \tag{3}$$

where N_e indicates the number of individual EIs contributing to the impacted area, and $A_{\text{impacted,i,e,s}}$ (m^2) represents the worst-case damage area following the i-th reference RM of the e-th EI in the s-th VCS, as follows:

$$A_{\text{impacted,i,e,s}} = \pi \cdot D_{\text{i,e,s}}{}^2 \tag{4}$$

and A_{system} (m^2) represents the extent of the system under investigation in terms of occupied surface. This data can be retrieved from company technical reports or documents, government databases,[66] or satellite imagery[67] and geographic information system (GIS) tools.[68]

The estimation of the probability of death considers the nature of the hazard, but not the potential exposure of individuals to specific release events, $Pr(E_{i,e,s})$, that is assessed in ***Step 8*** accounting for factors such as the frequency of human presence in the vicinity and the operational conditions of the plant in question. Such information can be retrieved from specific industry reports or company databases.

Once Steps 7 and 8 are performed, the individual risk per annum (IRPA)[36] can be calculated (***Step 9***) for each reference RM of each EI in each VCS, as follows:

$$\text{IRPA}_{\text{i,e,s}} = \lambda_{i,e} \cdot Pr(E_{i,e,s}) \cdot Pr(D_{i,e,s}|E_{i,e,s}) \tag{5}$$

where $\lambda_{i,e}$ is the failure frequency associated with the i-th reference RM of the e-th EI, $Pr(E_{i,e,s})$ is the probability of exposure of individuals to the i-th reference RM of the e-th EI in the s-th VCS, and $Pr(D_{i,e,s}|E_{i,e,s})$ is the probability of death resulting from the exposure of individuals to the i-th reference RM of the e-th EI in the s-th VCS.

Then, ***Step 10*** requires the estimation of the total number of individuals potentially exposed to the release events affecting the industrial equipment items for each VCS (n_{p_s}). This estimation considers factors such as population density, occupancy patterns, and system throughput. Therefore, choropleth maps, highlighting different levels of population density across geographic areas using varying shades of colour, or human resources management plans, providing information regarding the number of personnel per shift, their qualifications, and specific responsibilities, can be taken into account.

The inputs to estimate the potential loss of life (PLL)[36] for each EI of each VCS ($\text{PLL}_{e,s}$) are now available (***Step 11***). This parameter represents the expected number of deaths (fatalities) within a definite group of individuals exposed to the reference RMs affecting a specific EI during a specified period of time (usually a year). It can be derived as follows:

$$\text{PLL}_{e,s} = \sum_{i=1}^{R_e} \text{IRPA}_{i,e,s} \cdot n_{p_s} \tag{6}$$

with R_e representing the total number of reference RMs potentially affecting the e-th EI in the s-th VCS.

At this point, an iterative approach must be adopted to ensure that all the EIs constituting a specific VCS are assessed following the procedure from Steps 3 to 11.

Afterward, ***Step 12*** can be performed and the PLL can be aggregated across all EIs within each VCS, as follows:

$$\mathrm{PLL}_s = \sum_{e=1}^{M_s} \mathrm{PLL}_{e,s} \tag{7}$$

with M_s indicating the total number of EIs included in a specific VCS.

This provides an overall risk assessment for each VCS of both the systems' operations. Before proceeding with the last phase of the methodology, it is necessary to check whether all the VCSs constituting the value chains are assessed or not. If yes, the following phase can be completed, otherwise Steps 3–12 must be performed again.

2.5 | Risk indexes calculation (Steps 13–15)

This last phase involves the calculation of the risk index (RCAI), which is the focus of the current work. It is estimated as the ratio between the increased risk from adopting the green technology and the CO_2 avoided by adopting that specific green technology, as follows:

$$\mathrm{RCAI} = \frac{\text{Increased Risk from Adopting the Green Technology}}{\text{CO}_2\text{ Avoided by Adopting the Green Technology}} \tag{8}$$

To elaborate, the numerator of the RCAI (see Equation (8)) is calculated in ***Step 13*** by determining the increased number of deaths resulting from the implementation of the green technology:

$$\text{Increased Risk from Adopting the Green Technology} = \mathrm{PLL}_{\text{green case}} - \mathrm{PLL}_{\text{base case}} \tag{9}$$

where $\mathrm{PLL}_{\text{base case}}$ (fatalities/y) represents the annual number of deaths in the system where no carbon reduction solutions are implemented, while $\mathrm{PLL}_{\text{green case}}$ (fatalities/y) represents the annual number of deaths from the low-carbon system being evaluated.

More in detail, $\mathrm{PLL}_{\text{base case}}$ and $\mathrm{PLL}_{\text{green case}}$ can be assessed as follows:

$$\mathrm{PLL}_{\text{base case}} = \sum_{s=1}^{X} \mathrm{PLL}_s \tag{10}$$

$$\mathrm{PLL}_{\text{green case}} = \sum_{s=1}^{Y} \mathrm{PLL}_s \tag{11}$$

with X and Y representing the number of VCSs constituting the value chain of the base and green cases, respectively.

In ***Step 14***, the denominator of the RCAI is computed by determining the amount of CO_2 emissions avoided through the use of the green technology:

$$\text{CO}_2\text{ Avoided by Adopting the Green Technology} = \mathrm{CO_{2\,base\ case}} - \mathrm{CO_{2\,green\ case}} \tag{12}$$

where $\mathrm{CO_{2\,base\ case}}$ ($\mathrm{MtCO_2e/y}$) refers to the equivalent emissions from the system without carbon reduction measures, while $\mathrm{CO_{2\,green\ case}}$ ($\mathrm{MtCO_2e/y}$) represents the equivalent emissions from the low-carbon system being evaluated.

Finally, in ***Step 15***, the RCAI is calculated based on Equation (8), delineating a clear risk–benefit profile of the green technology under consideration. It should be noted that the metric is only meaningful for analysis when the denominator is positive—indicating that the green technology indeed produces lower greenhouse gas emissions than the base case. A negative numerator, however, is acceptable, meaning that the green technology may also have a lower associated risk than the base case technology.

2.6 | Case study

To demonstrate the applicability of the methodology described in Section 2, a notional case study is considered. It entails a CCS system that involves the capture of CO_2 emissions from the stacks of a thermoelectric plant, their compression and, finally, transportation, via pipeline, to a depleted natural gas (NG) field where they will be injected and permanently stored. This chosen case study was inspired by various planned and ongoing European CCS projects[69]; however, it does not represent a specific real-life case.

Figure 2 displays the complete process flow diagram (PFD) of the CCS facility considered, highlighting the different stages: capture, conditioning (compression), and transport. The study focuses on the human impacts of the CCS process; therefore, the investigation of the storage site is excluded, as its potential to harm humans in the event of leakage is unproven.[17] Consequently, no details about the final storage stage of the CCS value chain are provided in this analysis. However, it is important to note that if environmental risk assessments are required, the storage site must be included in the analysis.

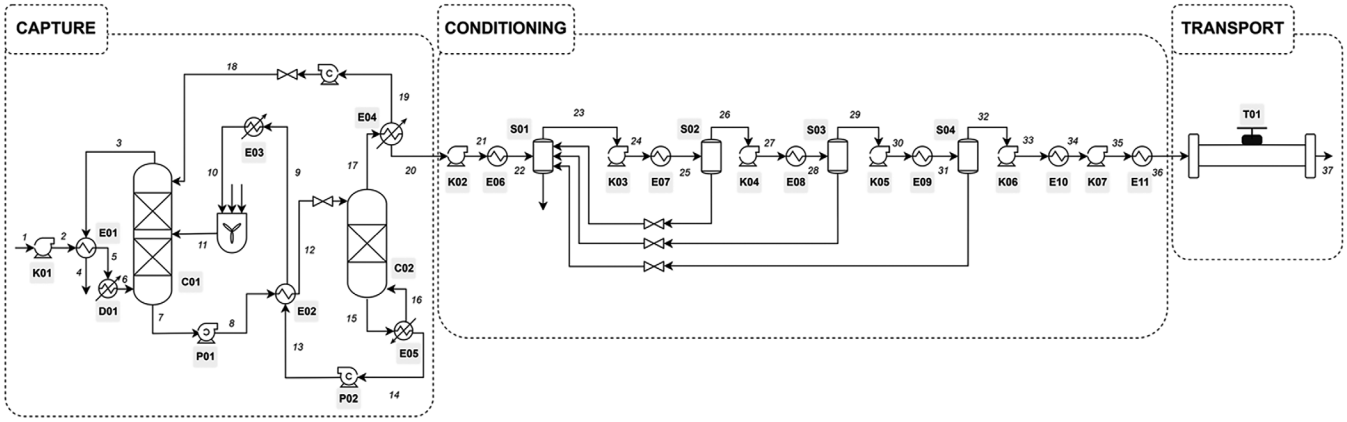

FIGURE 2 Reference process flow diagram of the carbon capture and storage (CCS) facility considered in the case study (not to scale) (K, compressor; D, direct contact cooler; C, column; P, pump; S, separator; E, heat exchanger; T, pipeline).

Power plants are among the primary sources of CO_2 emissions,[2] making it imperative to implement rigorous interventions to address the challenges of global warming. Thus, the emitting source considered in this case study is a thermoelectric plant with a nameplate capacity of 972 MW and a flue gas stream rate of 2820 t/h composed of 5 mol.% of CO_2, 75 mol.% of nitrogen (N_2), 10 mol.% of oxygen (O_2), and 10 mol.% of water (H_2O). An amine scrubbing-based post-combustion CO_2 capture (PCC) process is taken into consideration for separating the CO_2 from the exhaust gases after fuel combustion. To design the process, guidelines in the work of Madeddu et al.[70] are accessed, with monoethanolamine (MEA) chosen as the solvent. Typically, MEA technologies achieve a carbon capture rate of around 85%–90%.[71,72] In the current study, 89.8% of CO_2 is captured from the flue gas. The absorber and stripper are subjected to rigorous calculations for material and energy balances, mass transfer coefficients, and interfacial equilibrium with Aspen Plus software[73] following the procedure of Adams[74] and using the ENRTL-RK as physical property package. Overall, the capture plant (refer to 'capture' in Figure 2) comprises absorption and stripping columns, pumps, heat exchangers, thermal recovery units, and a kettle reboiler.

In the PCC system, a portion of the low-pressure (LP) steam fed to the low-pressure steam turbine of the combined cycle of the power plant is diverted to supply the reboiler (unit E05 in Figure 2) of the stripper (unit C02 in Figure 2) with the required heat. This method aligns with common PCC integration practices[75] and is more efficient than directly combusting natural gas to provide reboiler heat. In fact, direct combustion of NG for reboiler heat yields larger net GHG emissions than the LP steam diversion approach. The steam flow rate at the reboiler inlet is determined to ensure that the required amount of heat duty is transferred via steam condensation, while keeping the steam at a minimum temperature difference of 9°C higher than the liquid being heated. It is assumed that the LP steam available for diversion from the power plant is at 305°C and 5.1 bar, with the LP turbine having a 0.069 bar pressure output, based on the work of Schmitt et al.[76] Using this information in Aspen Plus software,[73] it was computed that 52% of the LP steam from the LP turbine should be diverted to the reboiler. This diversion provides 231 MW of heat but reduces the LP steam turbine's power production by 50 MW. As will be noted later, this power loss is compensated by an equivalent increase in electricity drawn from the Italian electric grid.

Following the capture process, the outlet stream, composed of 0.97 mol.% of CO_2 and 0.03 mol.% of H_2O, is directed to the conditioning unit, consisting of six compression stages with centrifugal compressors and intercooling at 40°C (refer to 'conditioning' in Figure 2). During conditioning operations, the stream undergoes purification through knock-out drums to meet the impurity acceptance criteria specified in ISO 27913:2016[77] for dense phase CO_2 pipeline transportation. Also for conditioning, Aspen Plus software[73] is used for heat and mass balance calculations. The physical property package adopted is the GERG2008, previously validated against experimental data available in the work of Adams and Barton.[78] The combined capture and conditioning units have a total footprint of approximately 2500 m^2. This value is obtained by using the sizing information provided by Aspen Plus software and creating a base layout accounting for space requirements and safety-distance constraints.

Based on the composition of the outlet stream from the conditioning unit (>95 vol.% of CO_2 and 200 ppm of

H_2O), it is possible to assume pure CO_2 for the inlet stream to the transport unit. Therefore, the transportation involves 198 t/h of pure dense CO_2 through a 15 km-long horizontal pipeline with a nominal diameter of 8 inches (refer to 'transport' in Figure 2). The entire transport process is considered adiabatic. OLGA software,[79] a multiphase dynamic flow simulator, is employed to investigate the transient CO_2 flow along the pipeline. As for the pipeline route, it extends from the thermoelectric plant, previously identified as the emitting source, to the selected storage site that involves a 13 m-deep depleted natural gas field. Consequently, the pipeline is comprised of two sections: an 8 km-long buried onshore section and a 7 km-long offshore section. Reusing exhausted natural gas reservoirs allows for keeping costs highly competitive and relying on well-known site features.[18]

More detailed information regarding the equipment items of the three CCS value chain stages is provided in Table 5.

TABLE 5 Details of the equipment items constituting the CCS system (refer to Figure 2) that are of interest for the application of the methodology illustrated in Section 2.

Code	Number of EIs	Description	Pressure (bar)	Temperature (°C)	Main substance	Energy consumption (kW)
Capture						
K01	1	Blower	1.0–1.2	100–123	CO_2	19933
E01	10	Heat exchanger	1.2	56–123	CO_2	–
D01	2	Direct contact cooler	1.2	40–96	CO_2	–
C01	2	Absorption column	1.2	40–56	CO_2/MEA	–
P01	1	Pump	1.2–7.0	43	MEA	765
E02	35	Heat exchanger	6.0–7.0	43–121	MEA	–
E03	3	Cooler	6.0	40–53	MEA	44119
C02	1	Regeneration column	1.8	104–120	CO_2/MEA	–
E04	4	Condenser	1.8	50–105	CO_2	82271
E05	4	Reboiler	1.8	120–121	MEA	231355
P02	1	Pump	1.8–6.0	121	MEA	563
Conditioning						
K02	1	Compressor	1.8–3.6	50–112	CO_2	2591
E06	1	Cooler	3.6	40–112	CO_2	4636
S01	1	Separator	3.6	40	CO_2	–
K03	1	Compressor	3.6–7.4	40–100	CO_2	2077
E07	1	Cooler	7.4	40–100	CO_2	10491
S02	1	Separator	7.4	40	CO_2	–
K04	1	Compressor	7.4–14.9	40–101	CO_2	3364
E08	1	Cooler	15	40–101	CO_2	6658
S03	1	Separator	15	40	CO_2	–
K05	1	Compressor	15–30	40–101	CO_2	3073
E09	1	Cooler	30	40–101	CO_2	3668
S04	1	Separator	30	40	CO_2	–
K06	1	Compressor	30–60	40–101	CO_2	2990
E10	1	Cooler	60	40–101	CO_2	3489
K07	1	Compressor	60–120	40–100	CO_2	2869
E11	1	Cooler	120	40–100	CO_2	3686
Transport						
T01	1	Pipeline	120	40	CO_2	–

Abbreviations: CCS, carbon capture and storage; EI, equipment item.

Further information about process streams (numbered in Figure 2) is provided in the Appendix in Table A1.

3 | RESULTS AND DISCUSSION

In the present Section, the results obtained by the application of the methodology illustrated in Section 2 to the case study described in Section 3 are presented and discussed.

The *base case* of the analysis is represented by the value chain of an existing (theoretical) power generation plant located in Italy, while the *green case* is represented by the value chain associated with the CCS facility retrofitted onto the existing power generation plant for the purpose of carbon emission reduction with increased power production from the Italian electric grid to make up CCS electricity consumption. These two cases are briefly schematized in Figure 3.

As illustrated in the diagram, parts of the value chains are identical, and both deliver the same end product to the consumer in the same quantity. Therefore, the developed methodology, which aims to analyze how the introduction of new green technologies increases risk and reduces CO_2 emissions, can focus solely on the differing sections of the two chains. In this case, the risk analysis is centred on the CCS value chain.

Once the boundaries of the system are defined, comprehensive input data necessary to apply the developed methodology must be gathered. Most of this data has already been provided in Section 3, including information regarding system layout and components, space requirements, substances involved, and operating conditions. The only missing information concerns the dangerous characteristics of the main hazardous substances, MEA and CO_2. MEA represents both a flammable and toxic substance, while CO_2 is solely a mildly toxicant.[18] As indicated in Table 4 for the toxic cloud (TC) scenario, the LC_{50}, referring to a death probability of 50% of the exposed population after an inhalation exposure of 30 min, is equal to 291 ppm for MEA[80] and 92,000 ppm for CO_2.[81] Regarding flammability threshold values, the LFL of MEA is 55,000 ppm.[82] Based on this information, Step 1 of the methodology (see Figure 1) is considered complete.

Similarly, the results of Steps 2 and 3 (see Figure 1), which involve the identification of the value chain stages of the system under assessment and the relevant hazardous equipment items constituting each VCS, respectively, have already been provided in Section 3. Specifically, the value chain stages of the CCS facility considered are three, that is, capture, conditioning (compression), and transport (with storage stage omitted as it is out of scope), and all the relevant hazardous equipment items of interest for each VCS are collected and extensively detailed in Table 5.

Considering the hazardous EIs of the capture and conditioning stages, following the guidelines provided by the TNO Purple Book,[50] they have been grouped into four main categories: compressors (including blowers), pumps, heat exchangers (comprising coolers, condensers, direct contact coolers, and reboilers), and process pressure vessels (columns and separators).

Based on these results and the ones of Step 4 (see Figure 1) reported in Table 3, Step 5 (see Figure 1), which

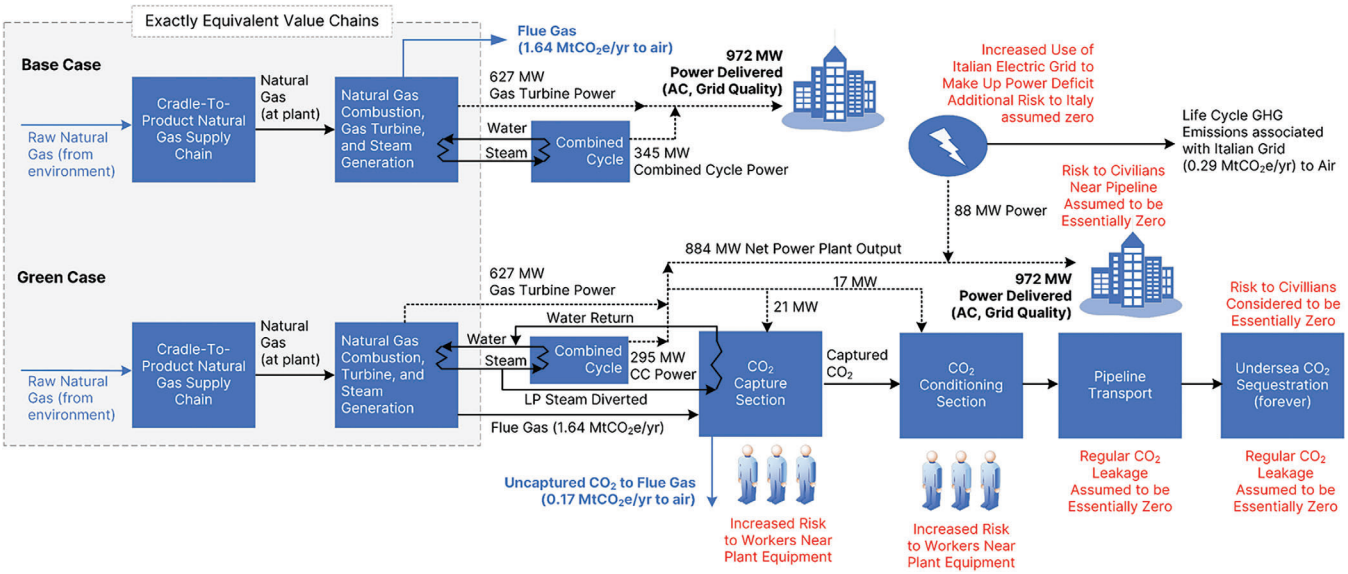

FIGURE 3 Schematization of the base case and the green case considered in the case study.

involves identifying credit factors for each reference RM affecting the different EIs, has been performed. Retrieved values for each EI are collected in Table 6.

For process EIs of the CO_2 capture and conditioning stages, no literature source reports specific critical scenarios and/or failure frequency data. Thus, baseline failure frequency datasets have been obtained from the TNO Purple Book[50] and the ARAMIS project,[54] and/or other literature sources.[51–53] On the contrary, historical data are available for on-land CO_2 pipelines.[23] For CO_2 subsea pipelines (i.e., CO_2 sealines), there is a lack of failure data in the open literature; however, several studies[51,83] suggest that CO_2 sealines can be considered analogous to NG sealines for the purpose of identifying critical scenarios and estimating leakage frequency, due to the similarity of their features in terms of the operating pressure and the design characteristics. Therefore, specific information is available in the context of CO_2 on-land pipelines, while recommendations (somewhat not so generic) can be used for CO_2 sealines.

Then, Step 6, and thus Step 7 of the methodology (see Figure 1), require estimating the worst-case damage distance associated with the worst accident scenario for each reference RMs, considering threshold values related to humans (refer to Table 4). In this regard, standard event trees have been used to identify the accident scenarios, while consequence modelling tools have been employed to assess the impacts of such scenarios, hence their physical effects.

Since the selected targets for the analysis are humans, reference guidelines provided in the technical literature (i.e., Methodology for the Identification of Reference Accident Scenarios (MIRAS) procedure[49] and TNO Purple Book[50]) suggest, for the capture stage, blasts (i.e., vapour cloud explosions (VCEs) and physical explosions (PEs)), fires (i.e., flash fires (FFs) and pool fires (PFs)), and toxic clouds (TCs) as potential accident scenarios, as both MEA and CO_2 are involved in the process operations. Fire ceases to be a potential accident scenario when considering the conditioning and transport stages where CO_2 is the only hazardous substance involved. In these latter cases, the toxic cloud (in air)/plume (subsea) becomes the major accident scenario.

Different tools have been employed for simulating the impacts of the accident scenarios depending on the location of the release event, whether it occurs in the air or subsea. The PHAST software by DNV[62] has been adopted to simulate atmospheric releases, while OLGA software by Schlumberger[79] and TAMOC software by the Texas A&M University[84] have been employed for modelling the dispersion of hazardous substances in the water column. Specifically, PHAST is a consequence analysis software commonly adopted in the context of major accident scenarios affecting industrial plants. Its capability to model both the source term and the physical effects of the accident scenarios following atmospheric hazardous releases makes it suitable for simulating the consequences of the reference RMs affecting the equipment items of the capture, conditioning, and on-land transport stages of the CCS value chain.[85] Actually, PHAST software has also been employed in accident

TABLE 6 Credit factors related to the reference release modes (RMs) of interest in the case study for process equipment items (y^{-1}) and pipelines ($km^{-1}y^{-1}$).

RM	Equipment item					
	Process equipment items				Pipelines	
	Compressor	Pump	Heat exchanger	Process pressure vessel	On-land pipeline	Sealine
RM1	1.0×10^{-3}	5.0×10^{-4}	1.8×10^{-6}	1.8×10^{-6}	n.a.	n.a.
RM2	8.8×10^{-4}	4.5×10^{-4}	6.5×10^{-7}	6.5×10^{-7}	n.a.	n.a.
RM3	1.0×10^{-4}	1.0×10^{-4}	1.2×10^{-7}	1.2×10^{-7}	n.a.	n.a.
RM4	n.c.	n.a.	n.c.	5.0×10^{-4}	n.a.	n.a.
RM5	n.c.	n.a.	n.c.	5.0×10^{-5}	n.a.	n.a.
RM6	n.c.	n.a.	n.c.	5.0×10^{-6}	n.a.	n.a.
RM7	n.c.	n.a.	n.c.	5.0×10^{-6}	n.a.	n.a.
RM8	5.0×10^{-6}	n.c.	5.0×10^{-6}	5.0×10^{-6}	n.a.	n.a.
RM9	n.a.	n.a.	n.a.	n.a.	2.8×10^{-4}	7.2×10^{-3}
RM10	n.a.	n.a.	n.a.	n.a.	4.0×10^{-5}	8.5×10^{-4}
RM11	n.a.	n.a.	n.a.	n.a.	1.4×10^{-5}	1.7×10^{-4}
RM12	n.a.	n.a.	n.a.	n.a.	2.6×10^{-5}	2.6×10^{-4}

Abbreviations: n.a., not applicable; n.c., not considered; RM, release mode.

scenarios involving CO_2 sealines, but primarily when the released plume reaches the sea surface (e.g., shallow releases) and, thus, atmospheric dispersion is involved.[18] For subsea plume modelling, OLGA, a dynamic multiphase flow simulator, and TAMOC, a modelling suite developed for the reproduction of wide ranges of subsea single- and multi-phase spills, assuming steady-state conditions,[84] have been used. These tools enable the simulation of the source term and seawater dispersion, respectively.

Simulations highlighted that blasts represent the majority of the worst-case accident scenarios for the capture stage, followed by toxic clouds and flash fires. Toxic clouds remain the worst-case accident scenarios also for the conditioning and transport stages, with the conditioning stage also including physical explosions. Figure 4 reports the percentages of the worst-case accident scenarios resulting from critical events affecting the equipment items of the three stages of the CCS value chain.

During the capture stage, blasts are the accident scenarios that lead to the greatest damage distances. Physical explosions, resulting from catastrophic ruptures leading to the instantaneous release of the inventory (RM8), generate damage distances up to 59 m, while vapour cloud explosions, resulting from leaks of various geometries (RM1, RM2, and RM3) affecting equipment items handling MEA, generate damage distances up to 65 m, thus slightly higher than those obtained from PEs. Flash fires are deemed the worst-case accident scenarios only when critical events impact C01, E02, and C02, resulting in damage distances around 10 m. Similar distances are observed in toxic cloud scenarios originating from release modes RM1, RM2, and RM3 affecting equipment items handling CO_2 (i.e., C01, C02, E04).

Shifting the focus on the conditioning stage, CO_2 toxic clouds lead to the highest damage distances, reaching up to 60 m. In these cases, the reference release modes associated with 'in/out streams' as hazard factor (refer to Table 3) are the only ones of concern. Catastrophic ruptures resulting in the instantaneous release of the inventory (RM8) are identified as the critical events leading to physical explosions, with detected damage distances around 35 m.

Clearly, the operating conditions of the equipment item under assessment significantly influence the nature and extent of the consequences of the release event.[48,61] Equipment operating at high pressure tends to result in high-pressure jet releases, causing extensive damage due to the rapid dispersion of hazardous materials. The physical state of the released substance—gas, liquid, or solid—also plays a crucial role, with gases typically spreading more rapidly and covering greater distances than liquids or solids. Temperature is another vital factor; higher temperatures can increase the volatility of substances, leading to quicker vaporization and broader dispersion. Thus, the combined influence of these parameters determines the severity of the accident scenario effects. Although weather conditions usually impact results, in the current analysis they were held constant across simulations.

In the context of on-land pipelines, burial significantly enhances safety. In the present analysis, PHAST simulations indicate damage distances below 25 ft, aligning with safety distance values established by the cited standard.[86] Consequently, on-land transport poses minimal risk to surrounding populations therefore is not considered for the application of the methodology. For the sealine under examination, the height of the plumes escaping the water column represents the damage distance relevant to humans on topside facility decks. Similarly to the on-land pipeline, given that personnel on the lowest deck are commonly positioned at 15/20 m

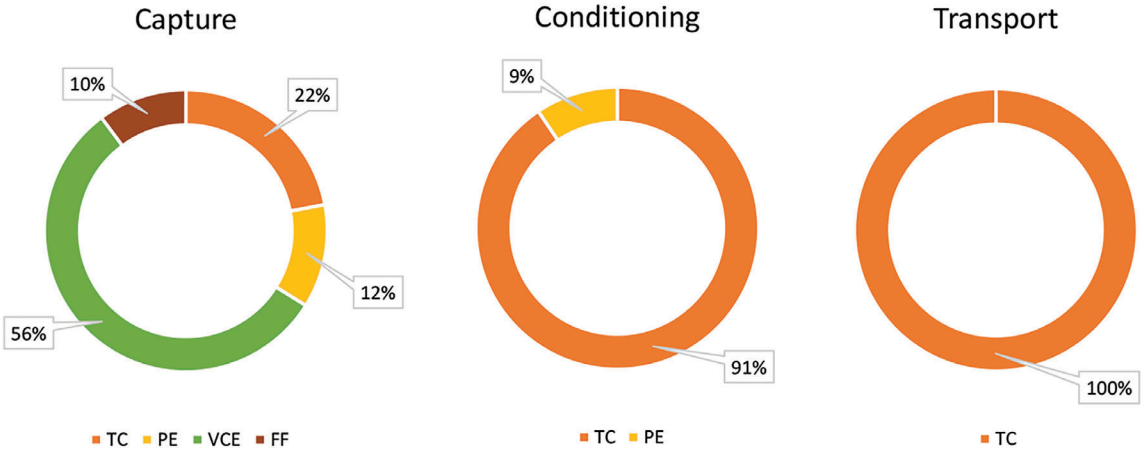

FIGURE 4 Percentages of the different typologies of the worst accident scenarios affecting the carbon capture and storage (CCS) value chain stages. FF, flash fire; PE, physical explosion; TC, toxic cloud; VCE, vapour cloud explosion.

height[18,58,87] and toxic clouds from subsea pipeline releases reach a maximum height of 9 m, no impact on human targets was observed. Based on this, we assume that the storage phase has effectively zero risk on human populations and so the successive steps of the methodology have only been applied to capture and conditioning stages.

In order to complete Step 8 of the methodology (see Figure 1) and thereby have all the necessary elements to perform Step 9 (see Figure 1), which involves estimating the individual risk per annum (IRPA) for each reference RM, the probability of exposure to critical release events for personnel in the capture and conditioning stages has been defined. Based on four 6-h daily work shifts, a probability of 25% is assumed for the personnel.

Since transport has been omitted from the current analysis, discussing the IRPA (Step 9 in Figure 1) or potential loss of life (PLL) (Step 11 in Figure 1) results makes no significant change. In fact, according to Equation (6), PLL is proportional to IRPA based on the number of personnel (maintenance operators, cleaning teams, and office members) located in the industrial area under evaluation. In this case study, both the capture and conditioning stages extend within the same plant area, meaning they share the same personnel and thus the same proportional constant. In this case study, the number of exposed personnel is assumed equal to 10. This aligns with the completion of Step 10 of the methodology (see Figure 1).

The results of Step 11 (see Figure 1) are shown in Figure 5A for the capture and in Figure 5B for the conditioning stages of the CCS value chain, respectively.

Considering the capture stage, it can be observed that the majority of equipment items, such as the blower (K01), heat exchanger (E01), direct contact cooler (D01), absorption column (C01), regeneration column (C02), cooler (E03), reboiler (E05), and condenser (E04), have relatively low PLL values, each below 0.001 fatalities per year. The pumps (P01 and P02) have higher PLL values, indicating a higher potential risk associated with these components. This increased risk is partly due to the high failure frequencies associated with the reference release modes (RM1, RM2, and RM3) affecting the rotating devices. The heat exchanger (E02) shows the greater PLL value, around 0.008 fatalities per year, because of the elevated number of equipment items necessary in the capture process.

Generally, the conditioning stage's equipment items show lower PLL values. From Figure 5B, it can be observed that most components, such as coolers (E06–E11) and separators (S01–S04), have very low PLL values, each below 0.0002 fatalities per year. Compressors (K02–K07) show increasingly higher PLL values, nearing 0.0015 fatalities per year. This trend is due to the progressively increasing pressures in the conditioning stage, spanning from compressor K01 to compressor K06, which, in turn, lead to higher toxic cloud impacts.

Once all EIs have been assessed, Step 12 of the methodology (see Figure 1), which consists of determining the aggregated PLL, is executed. The aggregated PLL indicates the combined risk from all individual equipment items within each stage and is approximately 0.016 fatalities per year for capture and 0.0042 fatalities per year for conditioning. These results emphasize the importance of addressing safety and risk mitigation strategies across all equipment to minimize the potential loss of life in the capture stage of the CCS value chain stages where both MEA and CO_2 are handled.

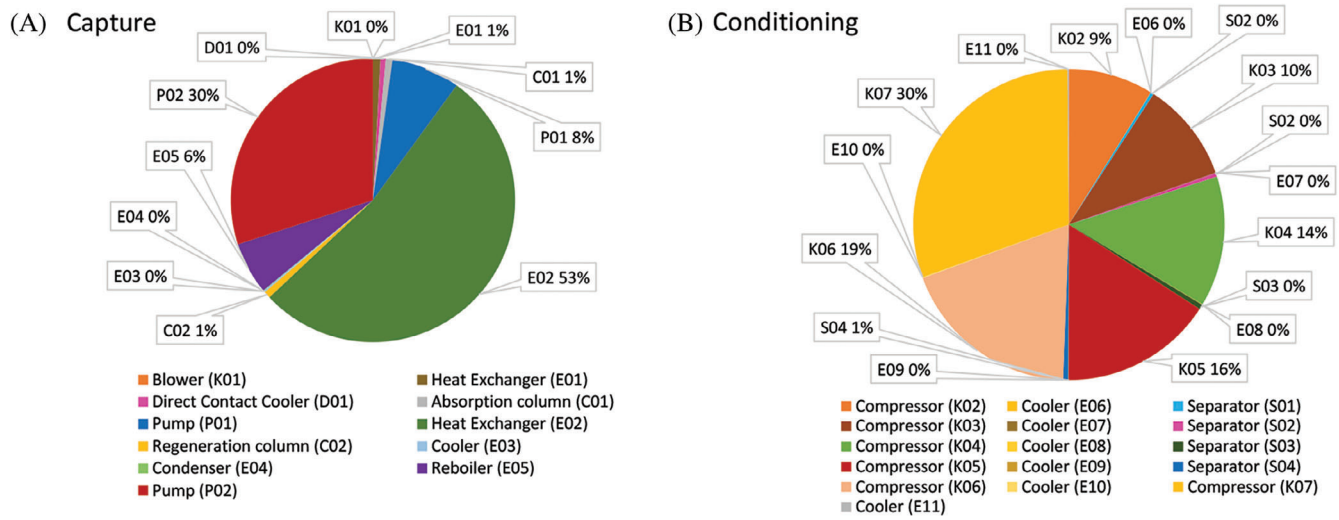

FIGURE 5 Estimated potential loss of life (PLL) for the equipment items of the (A) capture stage and (B) conditioning stage.

Finally, the RCAI (Step 15 in Figure 1) must be calculated. In this demonstrative application, the RCAI is implemented, as follows:

$$\mathrm{RCAI} = \frac{\sum_{s=1}^{Z} \mathrm{PLL}_s}{\mathrm{CO_{2avoided}}} \tag{13}$$

Based on how the two reference cases (base case and green case) have been defined in the current case study, the assessment of the increased risk (Step 13 in Figure 1) due to the adoption of the green technology is attributed solely to the risk posed by the CCS value chain. Thus, in the numerator of the formula, PLL_s represents the PLL of the s-th VCS, with $\mathrm{s} = \{\mathrm{capture}, \mathrm{conditioning}\}$ and Z is the total number of VCSs, equal to two. In the denominator, the $\mathrm{CO_{2avoided}}$ represents the net amount of emissions prevented from entering the atmosphere due to the retrofitting of CCS onto the existing power generation plant (Step 14 in Figure 1).

From the results of Step 12, the numerator of the RCAI resulted to be equal to 0.02 fatalities per year. The denominator, instead, is based on the difference between the two following contributions:

$$\mathrm{CO_{2base\ case}} = \mathrm{CO_{2power\ plant}} \tag{14}$$

and

$$\mathrm{CO_{2green\ case}} = \mathrm{CO_{2capture\ plant}} + \mathrm{CO_{2indirect}} \tag{15}$$

In more detail:

- $\mathrm{CO_{2power\ plant}}$, representing the emissions from the existing power generation plant (*base case*), has been retrieved from sustainability reports of the plant and is 1.64 $\mathrm{MtCO_2e/y}$.
- $\mathrm{CO_{2capture\ plant}}$, representing the emissions from the exhaust flue gases of the capture plant, has been assessed through the simulations performed with Aspen Plus[73] considering an 89.8% capture rate. It was computed to be 0.17 $\mathrm{MtCO_2e/y}$.
- $\mathrm{CO_{2indirect}}$, representing the emissions associated with increased grid electricity consumption, has been defined by the indirect emissions from pumps and compressors in the capture and conditioning stages, as well as the additional electricity required from the grid to compensate for the lost power production in the combined cycle due to steam diversion. Assuming the external electric grid as the source—with a global warming potential of 436 $\mathrm{gCO_2/kWh}$ for electricity generation in Italy[88]—these emissions amounted to 0.29 $\mathrm{MtCO_2e/y}$, the sum of 0.124 $\mathrm{MtCO_2e/y}$ due to pumps and compressors and 0.162 $\mathrm{MtCO_2e/y}$ due to steam diversion.

Based on these estimates, the $\mathrm{CO_{2avoided}}$ was 1.18 $\mathrm{MtCO_2e/y}$, representing a 72% reduction. It is worth noting that this assessment considers an availability factor of 0.85 to account for reduced plant operations hours per year due to periodic interruptions (maintenance or emergency interventions).[89]

The final value of the RCAI resulted to be 0.017 fatalities/$\mathrm{MtCO_2e}$. This result quantitatively represents the trade-off between the amount of $\mathrm{CO_2}$ avoided from entering the atmosphere and contributing to global warming, and the risks associated with emerging greener technologies.

For convenience, it is useful to break down the contribution of each VCS to the total risk, by reporting a stage-wise $\mathrm{RCAI_s}$, as follows:

$$\mathrm{RCAI}_s = \frac{\mathrm{PLL}_s}{\mathrm{CO_{2avoided}}} \tag{16}$$

such that

$$\mathrm{RCAI} = \sum_{s=1}^{Z} \mathrm{RCAI}_s \tag{17}$$

The risk–benefit profile is thus delineated for each stage of the CCS value chain, as reported in Figure 6.

Clearly, these results underscore the varying degrees of safety concerns associated with each stage, with the conditioning stage emerging as the safest in comparison to the capture stage. The higher risk associated with the

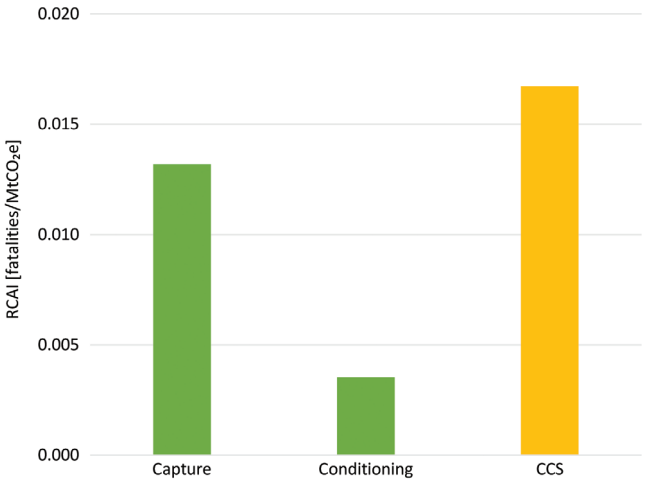

FIGURE 6 Risk of $\mathrm{CO_2}$ avoided index (RCAI) for the different stages of the carbon capture and storage (CCS) value chain and the whole CCS value chain.

capture stage suggests that additional safety measures and protocols are necessary within the context of risk management and mitigation strategies to ensure the effective implementation of the entire CCS facility. Furthermore, the data emphasizes the importance of continuous monitoring, supported by advanced technologies, stricter regulations, and enhanced safety training for personnel involved in CCS operations.

Despite potential limitations, the effective implementation of the RCAI remains highly achievable. Challenges such as limited data accessibility, confidentiality restrictions, and inconsistencies across sectors can be readily addressed through targeted solutions. Enhancing stakeholder collaboration fosters data sharing, while standardized collection methods ensure consistency and reliability. Even when direct data is unavailable, estimation models can provide viable alternatives with minimal effort. A crucial factor in this process is the role of automated systems and digital tools, which not only optimize data management—improving accuracy, efficiency, and resource allocation—but also help simplify the application of the methodology itself. While the 15-step process may appear complex and resource-intensive, many of its components are not highly demanding, making it well-suited for software-based implementation. Automation streamlines workflows and enables the integration of diverse perspectives, ultimately enhancing the reliability of risk assessments. This approach aligns with well-established safety management frameworks such as ISO 31000[35] and the ARAMIS project,[49] reinforcing the methodology's practicality and applicability across different contexts.

Across different contexts, the RCAI, being defined based on a traditional risk assessment methodology, does not fully capture the complex interactions and interdependencies within value chains; however, it still provides a solid foundation for safety analysis. This limitation, though, could result in an incomplete understanding of the risks associated with deploying green technologies. To address this, future refinements could integrate system dynamics modelling or network-based risk analysis, offering a more holistic perspective on value chain interactions. Moreover, techniques like Monte Carlo simulations or probabilistic sensitivity analysis could improve the robustness of the risk profile by better capturing and modelling uncertainties. Incorporating Bayesian networks could also provide a structured framework for systematically handling uncertainties, enhancing the overall risk assessment. Additionally, incorporating qualitative factors—such as regulatory shifts, supply chain disruptions, and societal acceptance—alongside quantitative assessments would enhance comprehensiveness. A multidisciplinary approach combining technical, economic, and social dimensions could further strengthen the methodology while maintaining its structured and comparative nature.

Following this, future research could benefit from applying the same analytical approach to other green technologies, such as wind and solar power, biofuels, electric vehicles, and hydrogen-powered cars. This is possible since the structured methodology is designed to be adaptable to various green technologies with the necessary adjustments. These adjustments would mainly involve defining system boundaries and hazard identification to account for the different risk profiles of each technology. For instance, renewable energy technologies like wind or solar would require modifications to address their unique operational processes and associated risks. Likewise, technologies such as electric vehicles or hydrogen-powered cars would need to consider factors like energy storage and infrastructure. By broadening the scope of the study, it would be possible to assess whether the risk levels identified in this research are consistent across different technologies. In particular, understanding whether the reduction in CO_2 emissions provided by these alternatives justifies any additional risks is essential. A comparative analysis could reveal whether the increased mortality risk associated with the technology examined here represents a significant trade-off, or if it is relatively minor compared to the risks posed by other green technologies. This would ultimately contribute to a more comprehensive evaluation of the risk–benefit balance of various sustainable development options.

4 | CONCLUSIONS

A novel quantitative methodological approach for assessing the trade-off between environmental benefits and safety concerns in the deployment of green technologies has been developed. This methodology introduces an innovative key performance indicator named the RCAI, which aims to estimate both the reduction in greenhouse gas emissions and the associated safety risks posed by implementing cutting-edge green solutions. By doing so, it delineates the risk–benefit profile of the technology under assessment, providing a comprehensive evaluation of its effectiveness.

This development addresses the gap in available metrics that account for both environmental benefits and safety issues in green technology value chains. By leveraging a systematic risk-based approach, it reveals significant insights into potential hazards, such as equipment failures leading to hazardous releases, that may arise during various stages of the value chains. Furthermore, it enables the ranking of the criticality of individual stages, highlighting the most vulnerable equipment

items that require further analysis within the framework of risk assessment and management. By identifying high-risk equipment, targeted safety measures can be implemented to mitigate these hazards. Consequently, the newly developed metric—the RCAI—becomes a pivotal tool in supporting informed decision-making during the prolonged and challenging period of the energy transition.

In the current paper, the developed methodology has been applied in the context of CCS retrofitting operations onto existing infrastructures. Specifically, CCS has been considered to capture CO_2 emissions from the stacks of a natural gas combined cycle power plant, with the aim of lowering carbon footprints without major disruptions. The application of the methodology to the case study demonstrated the versatility of the RCAI, revealing critical vulnerabilities within the capture stage of the CCS value chain and highlighting the negligible risks associated with the transport stage. These insights pinpoint the stages requiring more intensive risk management. Furthermore, the findings advocate for robust safety measures, stringent regulations, and continuous monitoring protocols to address specific risks, thereby ensuring the responsible implementation of CCS and similar green technologies.

Overall, this comprehensive risk–benefit analysis fosters a deeper understanding of the true success of green technologies, promoting sustainable advancements in the fight against global warming and aiding policymakers, engineers, and stakeholders in their strategic planning.

AUTHOR CONTRIBUTIONS

Federica Tamburini: Conceptualization; methodology; formal analysis; writing – original draft. **Valerio Cozzani:** Supervision. **Nicola Paltrinieri:** Writing – review and editing; funding acquisition; supervision. **Thomas Alan Adams II:** Conceptualization; methodology; writing – review and editing; Supervision.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX A

TABLE A1 Details of the process streams constituting the carbon capture and storage (CCS) value chain (refer to Figure 2).

Stream	Mass flow rate (kg/h)	Purity (mol.% CO_2)
1	2,819,610	0.050
2	2,819,610	0.050
3	2,680,219	0.005
4	2,680,219	0.005
5	2,819,610	0.050
6	2,819,610	0.050
7	3,979,934	2.8×10^{-6}
8	3,979,944	2.8×10^{-6}
9	3,659,760	1.1×10^{-7}
10	3,659,688	3.7×10^{-8}
11	3,839,220	4.2×10^{-8}
12	3,979,944	0.003
13	3,659,760	2.4×10^{-5}
14	3,659,760	5.4×10^{-8}
15	3,659,770	0
16	372,164	0
17	320,164	0.399
18	116,421	0.001
19	116,421	0.001
20	203,744	0.929
21	203,744	0.929
22	203,744	0.929
23	199,442	0.977
24	199,442	0.977
25	199,442	0.977
26	198,585	0.987
27	198,585	0.987
28	198,585	0.987
29	198,171	0.992
30	198,171	0.992
31	198,171	0.992
32	198,171	0.997
33	197,976	0.997
34	197,976	0.997
35	197,976	0.997
36	197,976	0.997
37	198,000	0.997