

## Compendium of Hazards of Carbon Capture Chain

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### ABSTRACT

Capturing and storing CO<sub>2</sub> (carbon dioxide) from concentrated industrial sources (e.g., cement industries and coal power plants) is a promising technology, as part of a mix of measures, for mitigating global warming. However, the implementation of Carbon Capture and Storage (CCS) also involves potential hazards and their impacts that must be addressed to ensure its safe operation. This paper aims to produce a compendium of major hazards that a CCS operation could create. The main hazards of the CCS chain include the leakage of stored CO<sub>2</sub>, accidents during transportation, the possibility of induced seismicity, and a lot more. The hazards associated with CCS encompass not only technical aspects but also factors related to human or organizational behaviour. The hazards associated with CCS may impact humans as well as the environment and may cause economic loss associated losses CCS infrastructure and liability for potential accidents. A compendium of hazards is needed to address the hazards, risks, and safety of CCS installations is presented.

### 1. Introduction

Carbon Capture and Storage (CCS) is an effective technology for reducing greenhouse gas emissions (GHG) by capturing high amounts of CO<sub>2</sub> at the source. It is a crucial technology in the effort to actively reduce industrial emissions of greenhouse gas emissions. Apart from renewable energy which can help in carbon emissions reduction, CCS or direct air capture (DAC) can also help in carbon emissions drops. CCS offers a solution for reducing emissions at the source, particularly in energy production and industrial processes, by capturing CO<sub>2</sub> and capturing it in geological formations. This is a significant advantage compared to direct air capture (DAC), which can be costly because of the low concentration of CO<sub>2</sub> in the atmosphere [1].

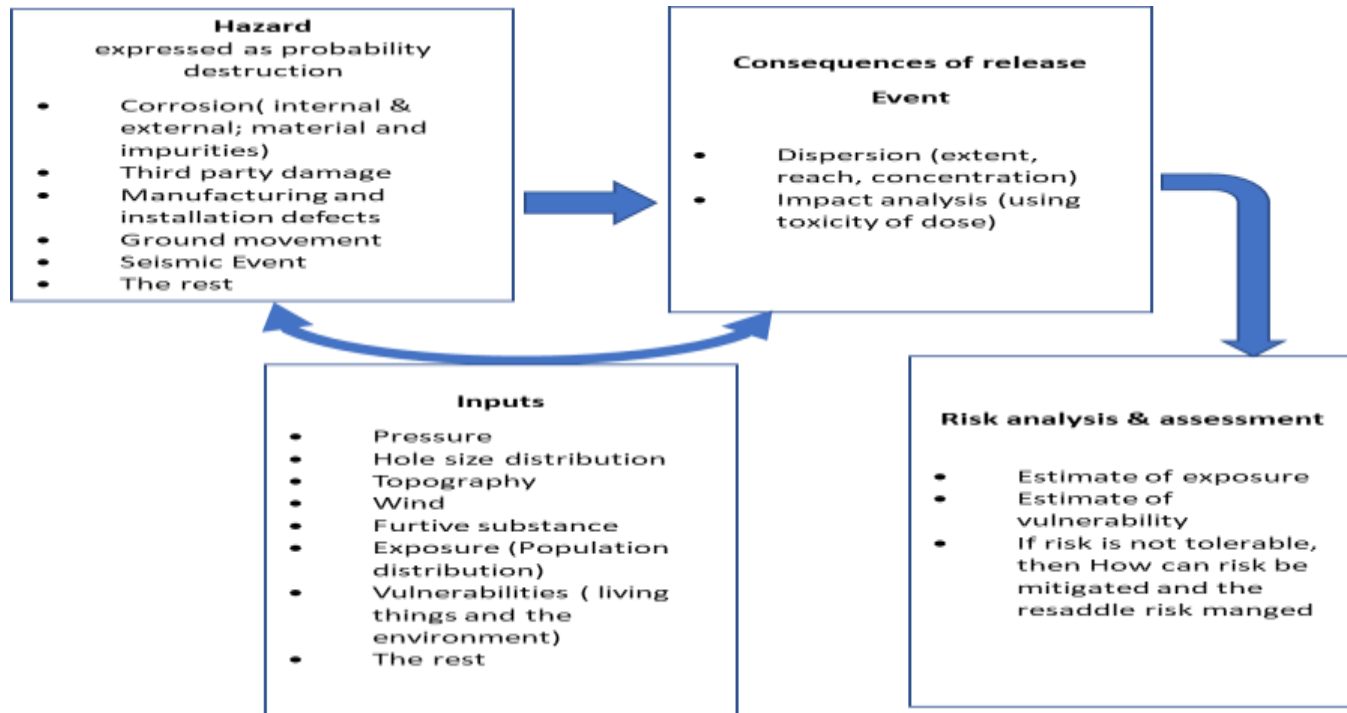
Despite the projected fast growth of renewable energy sources, the US Energy Information Administration (EIA) predicts that fossil fuels still make up to 77% of energy consumption by 2040 [2]. Large-scale CCS involves a variety of technologies, but they have three major steps in common, namely capturing carbon dioxide, compressing it for transportation, and injecting it deep underground for permanent storage [3].

At the start of a risk analysis, a list of known hazards is compiled, and the probability of occurrence for each

hazard is assessed. The next step is determining the vulnerability of workers, communities, and the environment to evaluate the consequences of a hazard if it occurs. A compendium of all CCS's known hazards reported in technical literature is compiled. CCS installation is a socio-technical system, thus hazards due to human errors, weak safety culture, and poor leadership should be considered as well.

**Table 1 Examples of risk review papers**

Reference	Synopsis (Quoted)
[4]	Review of Factors affecting the integrity and accurate hazard assessment of CO <sub>2</sub> pipelines, such as corrosion, hydrate formation, hydrogen embrittlement, and fast-running fractures.
[5]	Offers a sketch of how risk management is undertaken, using what is termed an "integrated risk management framework".
[6]	Discusses the usefulness of spatial planning for carbon captured, and injected for long-term, storage with minimal geo-hazards
[7]	Present a review of gas-hydrate hazards in various operational scenarios.
[8]	Presents a review of hazards posed to dense-phase CO <sub>2</sub> pipelines in the form of internal corrosion.
[9]	Presents a review of risk, liability, and economic issues with long-term CO <sub>2</sub> Storage



[10] Presents a review of many challenges that delay the deployment of CO2 transport by pipelines.

[11] Presents a review of necessary for the site selection, discussing geological, geothermal, geohazards, hydrodynamic, basin maturity, and economic, societal, and environmental factors.

[12] The objective of the paper is to discuss corrosion inhibitors for CO2 pipelines.

[13] Presents the design of CO2 pipelines including route selection, right of way, flow rates, and velocities, for pipelines

[14] Presents a risk management framework for environmental and human health risks and management

[15] Discuss the application and characteristics of three states of CO2 (i.e., gas phase, liquid phase, dense phase, and supercritical) for transmission pipelines.

[16] Discusses developments of CO2 storage from the point of view of improving economics as well as safety.

[17] Presents a review of various processes, technology, and materials used for the separation and capturing of CO2 from point sources.

[18] A review of four aspects of the CO2 pipeline, i.e., design, process, safety, standard & specification

[19] Review of storage leak risk.

[20] An overview of common organic corrosion inhibitors commonly used for CO2 equipment.

[21] A review of publications regarding public acceptance and social impacts of Carbon Capture projects.

[22] A comprehensive overview of all subsystems involved in the deployment of CCS technology, encompassing both technical and non-technical aspects, such as economic, social, and technical challenges.

[23] An overview of model-based CCS deployment pathways and the related risks financial, technical, environmental, health, and safety risks.

[24] The focus is on carbon steel substrate behaviour as a widely used material in various industrial applications.

[25] A review of methods used for carbon capture such as absorption-based, adsorption-based, cryogenic, and membrane-based technologies.

[26] Geological storage reservoir integrity and leakage potential and the common monitoring methods are reviewed.

Prior case studies, (See the supplementary data Table S1), examining CCS projects hold significant importance for several key reasons, such as:

- Showing feasibility
- Learning from past incidents
- Developing business cases
- Updating policy and regulations
- Enhancing public awareness

**2. Materials and Methods**

**2.1 Hazards and Risk**

A hazard is an undesirable event, which is a source the potential harm to living beings in terms of fatality, injuries, health, financial loss, property damage, and destruction of the environment but generally a combination of them. A hazard is the chance of occurrence that could have (generally) a negative effect. The intensity of the hazard reflects: the likelihood of a hazard occurring.

Exposure to the hazard

The vulnerability

Often, vulnerability and consequence are lumped together and termed impact.

In common usage, “hazard refers to 'the chance of danger, loss, injury or other adverse consequence” (Oxford English Dictionary) – a health hazard and so

Figure 1 Risk assessment process for a pipeline release.

on. Sometimes the word ‘Hazard’ is used to mean threat or the amalgamation of the probability of a hazard and the probability of its impact.

In Quantitative Risk Assessment (QRA), the risk is defined using the above factors; all expressed in probability terms. This a convenient way to combine the probability of harm due to various types of hazards with different probabilities of occurrence, consequences, and the level of exposure and vulnerability. Since harm may be a result of high-impact events but low probability (rare events) or by low-impact with high-probability events (commonplace events). Risks are ranked by the probability’s presence of hazards and their impacts in the ‘Risk Matix’ application.

According to this definition, it is not the presence of a hazard that indicates a risk rather, a hazard becomes a menace when something or somebody is exposed to its presence and is vulnerable; thus, ‘hazard is a function of circumstance. For these reasons, the notions of vulnerability and exposure must be introduced to capture these nuances – since the probability of a hazard causing harm may be mitigated by guarding against vulnerability. In QRA the following definition is adapted to determine the hazard.

$$\text{Risk} = \text{Likelihood of a Hazard} * \text{Exposure} * \text{Vulnerability} \quad (1)$$

All the parameters on the right-hand side of this relationship are used to mitigate risks. The focus of this paper is on computing hazards. Because exposure and vulnerability are situation-dependent, the risk depends on the circumstances, i.e., it is case-specific. Figure 1 shows the above relationship for a CO<sub>2</sub> pipeline release as shown in **Error! Reference source not found.**

Figure 1 Shows the process of risk assessment for a pipeline release.

This definition allows adding consequences of several hazards together from various sources. However, this definition does not differentiate between hazards with high probability but low consequence (everyday common hazards) and hazards with low probability but high impact (catastrophic event).

The papers that are reviewed in this article do not differentiate between hazard and risk, and use ‘hazard’ to mean risks. Some attempt is made to change the original authors’ use of the word ‘Risk’ to hazard as defined here. The above definitions of hazard and risk are adhered to in the article.

CCS poses both global and local hazards, with safety concerns dominating the last. These hazards can be divided into four categories: human health, environment, property, and financial. Government regulations play a role in each of these categories, but the extent of their involvement varies depending on the

type of hazard. The CCS chain is a complex installation with many interconnections between the components requiring careful consideration [27, 28]. A primary concern in managing hazards in complex systems, especially safety systems, is to recognize and evaluate potential hazards that may compromise the system's reliability and performance [29].

### 2.1.1 Capture Hazards

CCS carries health hazards associated with any carbon dioxide leakage at any stage of the process which could cause asphyxiation for both humans and animals if the dosage is high as it displaces the air [30, 31]. CO<sub>2</sub> leakage may occur suddenly or gradually, with each scenario leading to different outcomes. For instance, gradual leakage results in CO<sub>2</sub> returning to the atmosphere, while a severe and abrupt leak can cause harm to animals and humans [14]. In severe cases where CO<sub>2</sub> is more than 25% of the air, it may cause death if the level is maintained for some time [32, 33]- See the supplementary data Table S2. Apart from the hazard of suffocation caused by the displacement of the air due to the release of CO<sub>2</sub>, breathing in high levels of CO<sub>2</sub> can also raise the acidity of the blood, resulting in negative consequences on the respiratory, cardiovascular, and central nervous systems [34, 35].

One of the biggest CCS hazards comes from hydrogen sulphide (H<sub>2</sub>S), which is co-generated at the same time. The high concentration of H<sub>2</sub>S can be toxic, so it is crucial to prevent gas leaks during the capture process to ensure the safety of workers [36].

In the post-combustion process, amine-based chemicals, particularly monoethanolamine (MEA), are widely utilized for absorption. It's important to note that MEA is corrosive [37]. The most common failures in the CO<sub>2</sub> capture process are often attributed to corrosion issues [37]. In an accidental event, CO<sub>2</sub> leakage potentially may continuously be released into the atmosphere, or it may be present in the water droplets which eventually could contaminate the lakes and nearby water supplies, thus exposing the public [38]. Amine degradation within CO<sub>2</sub> capture installations can cause corrosion, although such a mechanism can also be reversed [39]. Three distinct types of amine degradation have been identified which are [40]:

1. carbamate polymerization, which can occur around the desorber and reboiler with the presence of CO<sub>2</sub> and high temperatures exceeding 100 °C.

2. Oxidative degradation can appear in the absorber when the concentration of O<sub>2</sub> in the flue gas is over 5% or because of heat-stable solids formation.

3. Thermal degradation is limited to the desorber, cross-heat exchanger, or reboiler, occurring only if the temperature exceeds 120 °C, which is the recommended maximum [37, 41].

Moreover, At the upper sections of both the absorber and regenerator, there is a significant hazard of corrosion that is caused by wet acid gases. Corrosion in the pipes can also increase the level of impurities [42]. The fire hazard can always be present due to the following three factors [43]:

- Oxygen combustion can cause an explosion.
- Amine leakage can cause a fire.
- Uncontrolled leakage of syngas can cause a fire.

Not having enough space for mixing pure oxygen with flue gas may cause an explosion [44]. During the process of separating amine, the solvent, from the gas, a fire can occur due to low water concentration and the presence of organic compounds [45]. Synthesis gas is toxic and could always cause health problems. It can also pose a fire hazard if pipework fails or due to fire.

Depending on the source of ignition, a fire may occur either immediately or after some time has passed [46]. This is due to low oxygen temperature which causes the primary flux to cool down. When liquid or dense phase CO<sub>2</sub> is kept in pressure above the thermodynamic critical pressure, but below the critical temperature, it can diffuse in various plastics and elastomers. If the pressure is lost, the CO<sub>2</sub> may rapidly come out of the solution, leading to explosive decompression [35]. Hazards associated with compressing CO<sub>2</sub> include the possibility of failing to achieve the necessary pressure, consuming too much power, and operating below the intended capacity. These issues can lead to project delays, impaired functionality of facilities, and lower than anticipated return on investment [47]. The release of CO<sub>2</sub> can cause electrostatic discharges that could ignite pyrolysis gases, leading to an explosion. Several serious accidents have been attributed to the ignition of flammable fuel/air mixtures, which was caused by the energy of electrostatic discharges resulting from the CO<sub>2</sub> release [48]. Despite the unlikelihood of CO<sub>2</sub> and flammable gases mixing, it may be necessary to consider this possibility during hazardous area classification studies [49, 50]. Inadequate control of the reactor temperature and impurities in the feed may have

a hazard of hot spots, reduced permeance, and selectivity [51]. There will be some energy loss due to heat produced and the inability to recover this heat, makes it a lot less efficient [52]. In the case of adsorption separation, there is always a need for the gas collected from the flue treatment before the adsorption. The reason for the treatment is that impurities lower the efficiency of the adsorbent [53]. There is a hazard of amine entering into the environment, which may happen through the produced wastewater by the absorber-scrubber systems [54, 55]. In membrane separation technology, the membrane may malfunction due to various factors such as fatigue under humidity, vibrations, or shocks, which results in membrane degradation, this shows as thickness reduction, membrane delamination, pinhole formation, and membrane cracking [56]. The hazard of membrane fouling is always present; for example, when gas molecules obstruct the pores of the membrane, either partially or completely, leading to a reduction in capture efficiency [57, 58]. At the same time, the hazard of reduction in the membrane efficiency is a function of the amount of gas that passes through the membrane to accelerate the degradation process [59]. To prepare CO<sub>2</sub> for transmission, it can be either compressed to reach its dense or supercritical phase or cooled to become a liquid. Failure or breakdowns during this stage could result in significant disruptions to the operations. The inability to transport captured CO<sub>2</sub> may also have negative implications for meeting emissions targets and adhering to carbon credit commitments [60]. The CO<sub>2</sub> separation process involves inherent technical risks associated with compressing and cooling gases flowing through pipes [60].

### 2.1.2 Transportation Hazards

Expenses involved in both building and maintaining a transportation system, and the potential dangers to life, property, and ecosystems, pipelines are deemed to be a more reliable and cost-effective option than other modes of transportation for high quantities of CO<sub>2</sub> [61]. Accidents that might happen during truck or ship transportation can lead to CO<sub>2</sub> escaping into the atmosphere [62]. The escape of carbon dioxide from a pipeline or intermediate storage is a risk to individuals due to its low temperature and toxicity [63]. The carbon dioxide is conveyed in a supercritical state, which means that it possesses the properties of both a gas and a liquid. In this state, CO<sub>2</sub> has a density like that of a liquid, but its viscosity is like that of a gas which makes it more economical to transport [64]. The density of CO<sub>2</sub> increases with decreasing temperature. The

supercritical phase is ideal for transporting to longer distances and is more cost-effective, but it is also regarded as more hazardous. Thus, pipelines are better suited for areas with lower population densities [15, 65].

There is always a pipeline leakage hazard. Faulty equipment, poor maintenance, and human error can cause overflow [41]. The process of releasing high-pressure CO<sub>2</sub> is a multifaceted event that involves several phenomena, including the sudden discharge and expansion of CO<sub>2</sub>, the dispersion of a dense CO<sub>2</sub> cloud, the descent of solid CO<sub>2</sub>, the sublimation of dry ice banks, and fluctuations in temperature and pressure within the pipelines [66]. Table shows that the failure of transportation pipelines can range from minor leakage through small holes to major leakage due to ruptures. The table provides rough information on the probability of such failures occurring each year. In addition to these factors, other causes of leakage include valve failure and external forces, such as accidents, support collapse, and seismic activity [67]. The leakage from a crack or pinhole has the highest frequency of 0.088 per 1000 km per year followed by hole and rupture with frequencies of 0.022 and 0.013 per 1000 km per year [68].

**Table 2 Average failure rate per year per module [67]**

Module	Expected failure rate (events per module per year)	Leaks every x year
1 CO <sub>2</sub> recovery at the source	$1.5 \times 10^{-1}$	7
2 Converging pipelines	$4.6 \times 10^{-3}$	217
3 Booster station	$4.0 \times 10^{-2}$	25
4 10 km pipeline	$3.4 \times 10^{-4}$	2,941
5 Injection well	$1.8 \times 10^{-1}$	6

To fully comprehend the practical implications of pipeline safety requirements, especially regarding impurities, at each stage of CCS, it is essential to involve all stages, that is capture, transport, and storage site operators. This is because the transportation of CO<sub>2</sub> cannot be viewed in isolation from the rest of the CCS chain [69]. Transportation pipelines are typically manufactured using carbon steel due to their ability to resist corrosion. The presence of free water in the pipeline promotes the formation of carbonic acid, which is highly corrosive to carbon steel [70]. Even with lower concentrations of impurities such as Sulphur dioxide (SO<sub>2</sub>), nitrogen dioxide (NO<sub>2</sub>), oxygen (O<sub>2</sub>), and water (HO<sub>2</sub>), nitric and sulfuric acid

can form. This may cause the pipeline to lose its wall-thickness and eventually to failure, hence releasing CO<sub>2</sub> into the atmosphere [71]. The presence of impurities in the CO<sub>2</sub> stream has a notable impact on the ability to halt ductile fractures in pipelines that carry dense-phase carbon dioxide at pressures higher than 80 bar and temperatures below around 15 degrees Celsius [72]. The reason for this is believed to be the effect of impurities on the fluid bubble-point pressure and the speed at which decompression occurs [73]. The scarcity of information and regulations on the maximum level of impurities that can be present in the pipelines makes it harder to have one enveloping solution for corrosion hazards [74, 75]. Researchers reported that as the concentration of SO<sub>2</sub> in the supercritical CO<sub>2</sub> phase decreased, there was a corresponding decrease in the corrosion rate. Furthermore, the presence of the liquid CO<sub>2</sub> phase resulted in notable localized corrosion [76, 77]. Pipeline blockage can decrease or stop the flow rate [41]. Assessing the detrimental effect of impurities on the operation, failure rates, and Health, Safety, and Environmental (HSE) impacts poses several challenges that need to be overcome [78].

According to studies done by EGIG from the year 1970 to 2019, it shows that pipeline failure due to the material has become a less significant cause of pipeline failure over time since material quality is continually improving. However, ground movement (landslides, unstable land, seismic shaking and displacements, debris flow, and so on), which is beyond human control, continues to affect pipeline failure [68]

The CO<sub>2</sub> is heavier higher than air density. Releasing a large quantity of CO<sub>2</sub> at the lower-level ground can pose a significant danger, thus it is crucial to consider the site elevation and topography [11, 79]. The dissipation of the denser-than-air vapor cloud was considerably delayed by the distinctive topographical features and atmospheric conditions present at the accident site [80]. Factors such as soil temperature, groundwater level, pipeline crossing a military-restricted area, passing through protected habitats, and heavily populated areas can all lead to health hazards depending on the rate of CO<sub>2</sub> leakage [81]. The available information on the most suitable pipe materials is not adequate [82]. Most of the data is derived from the petroleum industry, as indicated in Table 3 which deals with the flow at a lower pressure than that of CO<sub>2</sub>. As a result, the figures may not be entirely accurate [82].

**Table 3 Natural gas pipeline failure frequency [82]**

Pipeline Failure	Reported Values		
Cumulative failure frequency (incidents per km per year)	$6.1 \times 10^{-4}$	$1.55 \times 10^{-4}$	$1.1 \times 10^{-4}$

Establishing failure rates for CO<sub>2</sub> pipelines proves to be a complex task, given the absence of uniform standards or HSE thresholds for key indicators like CO<sub>2</sub> concentration, which adds another layer of complexity to the situation. Moreover, the absence of a universally recognized dose-response model for CO<sub>2</sub> hinders the assessment of impact indicators, highlighting the need for prompt resolution of this issue [78]. The severity of a failure in CCS activities can be indicated by the level of CO<sub>2</sub> leakage, which varies depending on the specific failure scenario. If the leakage is high and localized, it can pose an immediate threat to human safety. On the other hand, if the leakage is low and dispersed, it may result in long-term chronic exposure. [34].

### 2.1.3 Storage Hazards

Globally, geological formations have the potential to store over 12,000 Gt of CO<sub>2</sub>, with more than 300 Mt of CO<sub>2</sub> already sequestered through various methods[83]. Inadequate storage capacity to store or inject CO<sub>2</sub> during the assessment and injection stages at the site can lead to a risk [14]. **Error! Reference source not found.** shows the life cycle hazard profile for CO<sub>2</sub> storage [84]. Over time, the security of the storage increases as CO<sub>2</sub> is immobilised through capillary trapping, dissolution, and mineral trapping[85]. In the scenario of offshore storage, any unintentional discharge of carbon dioxide gas from an offshore reservoir could have a detrimental impact on the marine ecosystem. The elevated absorption of CO<sub>2</sub> can result in a decrease in seawater pH, leading to increased acidity. Both low pH levels and high CO<sub>2</sub> concentrations can have adverse effects on deep-sea organisms [86]. Although ocean currents and mixing can dilute CO<sub>2</sub> in the water column, the extent of the impact would depend on the rate of leakage [87]. A small leakage could cause a drop in pH levels in the sediments. This reduction in pH may increase the availability of toxic substances, which could harm infauna [87].

Storing substances underground carries extra hazards, including the possibility of seepage, pollution of freshwater sources, and triggering of seismic events

[88]. The potential hazards associated with CO<sub>2</sub> leakage underground include the following [89]:

- The possibility of the substances accumulating in geological formations above the storage site, while remaining separate from other subsurface processes.
- The potential for interference with other subsurface processes, such as natural gas reserves or injection of wastewater into deep wells.
- The hazard of groundwater contamination.
- The chance that the substances could reach the surface and get back to the atmosphere.

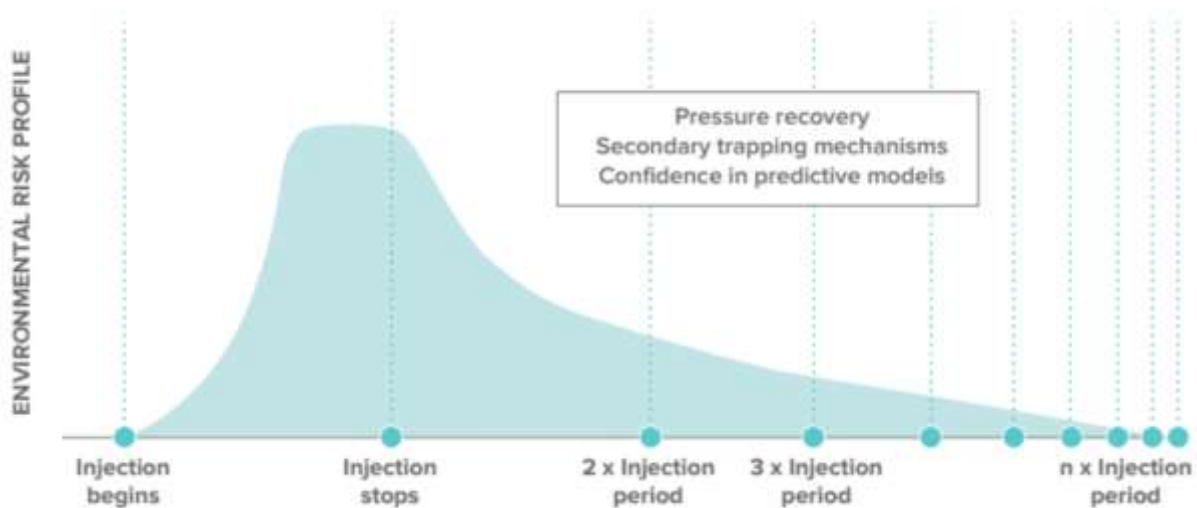
Other potential hazards include groundwater displacement, earthquake-induced leakage, and lack of capacity [5]. The main hazard factor linked to the storage of CO<sub>2</sub> is anticipated to be the accumulation of pressure in the storage reservoir [9, 16]. Fluid flow through fault zones in caprocks is dependent on various factors such as the internal geometry and connectivity of the fault/fracture damage zone, the local state of stress, and the level of cataclasis. These factors determine whether the fault zones control fluid flow or not. Therefore, minimizing the hazard of potential leakage rates along fault/fracture zones that are seismically invisible and may exist is crucial [61]. There are three ways that Caprock can fail [9,14].

**Figure 2 Life cycle hazard profile for CO<sub>2</sub> storage [84]**

- Caprocks can fail due to hydraulic fracturing causing damage to the integrity of the caprock which has a low probability of occurring but if it happens it will have a high impact.
- The diffusive loss is very small. It takes more than 500 thousand years for CO<sub>2</sub> to travel 700m above the reservoir.
- Capillary sealing, which is the main mechanism to stop the upward flow of CO<sub>2</sub> might be a source of possible failure. The capillary leakage can be high and quite fast compared to diffusive failure if it is over-pressured.

Generally, most data originate from the gas industry. It is essential to keep in mind that CO<sub>2</sub> behaves distinctively from natural gas, meaning that data on natural gas may not directly apply to CO<sub>2</sub>. Caprocks typically exhibit lower trapping efficiency for CO<sub>2</sub> when compared to hydrocarbon gases. [90].

The



generation of a flow recirculation region around the vortex structure causes the cold fluids in the core region to be pushed toward the hot wall, causing a high-temperature gradient close to the wall. This steep temperature gradient leads to a higher heat transfer rate in that area [91]. Site characterization is very important and needs a deep study before choosing it as a storage. If any of the criteria are not met, then it may put the storage site at hazard. The criteria include the following:[19, 92].

- Adequate capacity and injectivity
- Sufficient depth of storage
- The adequate thickness of aquifers or reservoirs
- Adequate porosity
- Sufficient permeability

- Low temperature
- Optimal flow conditions
- Separated hydraulically from safeguarded underground water sources.
- Low well density in the storage's 'area of influence.'
- Multiple layers of overlying aquifers and intervening aquitards or caprocks
- Reduces the impact of leaked CO<sub>2</sub> in the vicinity of or on the surface.
- Accessibility of the site and the facilities available
- Economics of Transportation
- Economics of storage
- Population density

1. When CO<sub>2</sub> is injected into deep saline formations, the

pressure changes are influenced by the properties of the underground formation. This displacement of saline waters and minerals by the injected carbon dioxide is dependent on the existing pressure levels [93]. Pressure buildup might cause caprock to fracture and induce seismic activity [94]. CO<sub>2</sub> storage underground not only might cause earthquakes but also any natural ground movement can hazard leaking the stored CO<sub>2</sub> into the atmosphere [95, 96]. Injecting CO<sub>2</sub> into saline aquifers on a large scale will have the hazard of physical and chemical changes. These changes include the flow of fluids in multiple phases, the movement of dissolved substances, and the interaction between the fluids and minerals in the geological formation [97]. CO<sub>2</sub> may also alter the underground pressure which can potentially lead to

- leakage of brine into shallower water, resulting in contamination by lowering the PH and increasing dissolved metals and other components [89, 98, 99, 100].
2. It can be injected into deep un-mineable coal, to replace methane with CO<sub>2</sub>. The hazard of reducing the permeability of the surrounding soil causes the structure of the rocks to change. Changes in the mechanical properties of coal seams can cause difficulties in assessing the integrity and safety of CO<sub>2</sub> storage [101]. Injecting carbon dioxide into deep coal seams can extract polycyclic aromatic hydrocarbons (PAHs) from the coal matrix and cause them to move within the coal seam. The injection of CO<sub>2</sub> into coal seams can cause the organic constituents of the coal matrix to move, which can lead to environmental problems. When CO<sub>2</sub> is injected and adsorbed into the coal mass, it causes the coal to expand. This expansion can result in significant changes to the internal structure of the coal mass, which can greatly affect its flow and strength properties [102]. The swelling of coal caused by CO<sub>2</sub> adsorption significantly reduces the permeability of the coal [103]. Some concerns associated with CO<sub>2</sub> storage in coal seams include the potential for leakage to the surface, the possibility of induced seismic activity, and the need for long-term monitoring to ensure the integrity of the storage [104,105].
  3. Stored CO<sub>2</sub> can also be reused for enhanced oil recovery (EOR). The notably low viscosity of CO<sub>2</sub> can result in potential leakage into production wells. [106]. CO<sub>2</sub> is commonly employed in a continuous flooding technique for EOR. Nonetheless, this method may pose challenges due to the poor mobility of CO<sub>2</sub>, issues with viscous fingering/channeling, and premature breakthrough, especially in reservoirs with varying characteristics. [107]. The term "toxic scale" refers to the formation of scales that can be harmful when CO<sub>2</sub> is injected for enhanced oil recovery (EOR), there is a hazard that a portion of the CO<sub>2</sub> will resurface along with the extracted oil [35]. Moreover, CO<sub>2</sub> poor mobility control may result in large parts of the reservoir remaining unswept.
- Blowouts of CO<sub>2</sub> injection wells.
  - Blowouts of active oil production wells that are part of the CO<sub>2</sub>-EOR project.
4. The captured CO<sub>2</sub> can also be injected into the oil and gas reservoirs that are no longer in use. When CO<sub>2</sub> in its high-density state is injected into a low-pressure reservoir, it can vaporize either in the wellbore or the subsurface reservoir formation. This vaporization process is accompanied by a temperature drop resulting from the Joule-Thomson phenomenon, abrupt changes in the thermodynamic properties of CO<sub>2</sub> phases, and an increase in flow velocity due to CO<sub>2</sub> expansion.

Moreover, three types of blowouts can happen with CO<sub>2</sub>-EOR activities [108]:

- Blowouts of production wells that are drilled into natural CO<sub>2</sub> reservoirs.

These

**Table 4 Leakage and blowout probability over time and their hazarded cost [113]**

Scenario	Probability over 500 years including the lifetime of the project and post-closure (%)	Peak leakage rate (t/d)	Duration of leak	Total mass leaked (tones)	Risked leaked mass (tones)	Total remediation cost (including ETS cost) (€m)	Risked cost (€)
Minor leakage, fault and fracture	0.2	100	50 years	1,825,000	3,800	97	194,000
Moderate leakage, fault and fracture	0.05	700	12 years	3,066,000	1,550	178	89,000
Severe leakage, fault and fracture	0.005	5,000	4 years	7,300,000	365	589	29,450
Active well leakage	0.5	50	250 days	12,500	62.5	10.4	52,000
Active well blowout	0.15	5,000	250 days	1,250,000	1,875	93	139,500
Abandoned well blowout	0.1	3,000	1 year	1,095,000	1,100	88	88,000
Seepage in abandoned wells	0.5	7	100 years	255,500	1,250	34	170,000
Severe well problem, no repair successful	0.005	6,000	2 years	4,380,000	215	524	26,200
Leak from installation	0.25	100	5 days	500	1.25	15	37,500
Undesired plume spread	0.03	0	N/A	N/A	N/A	110	15,000
<b>Total</b>					<b>10,219</b>	<b>1,838</b>	<b>840,650</b>

cause flow assurance problems such as hydrate formation, loss of pressure control, and compromised wellbore integrity [109].

Fractures and faults always present potential risks of failure, while blowouts can constitute a significant hazard. A well blowout happens when the pressure in the well is not controlled, causing fluid to flow out. The biggest hazard of CO<sub>2</sub> injection deep underground is a well failure. This can happen because of mechanical failures or an external event that affects the well, causing a loss of control temporarily, as a result of

There will be two main conclusions derived from Table 4 which were produced in the year 2019 [113].

- The likelihood of any one of these scenarios happening is remote.
- If all these unlikely scenarios happen at the same time then the total cost for one storage project would be £731.5 thousand, i.e. less than £1 million.

To ensure the success of subsea CO<sub>2</sub> storage projects, it is crucial to include marine environment monitoring to identify any possible leaks or indications of leaks. The monitoring plan is comprised of two main components: planned and triggered monitoring. The planned component continually monitors the well and nearby areas through down-hole monitoring, as well as

which CO<sub>2</sub> and other fluids would be driven out of the well [110]. Whenever there is a leakage and the pressure in the wells is not stabilized, a blowout can happen; however, CO<sub>2</sub> is not

a flammable gas and up to now there is no record of fatal accidents with CCS wells and injection processes. However, this can affect the workers' health and safety. A low level of CO<sub>2</sub> release is not fatal, but it can be very harmful to the human body [108]. When drilling a well, one of the geotechnical problems that may arise is wellbore instability. This instability can lead to rock failure and hence movement, which can also create paths for potential leakage [111]. Moreover, the cement lining in older or abandoned wells that might have degraded over time could pose a potential issue [112].

conducting active and passive seismic monitoring of the greater subsurface zone [114] However, creating a monitoring program that can accurately measure the likelihood of detecting the presence of a leak is a significant risk, necessitating a customized program design [114, 115].

#### 2.1.4 Human and Organizational Hazards

These are also referred to as human and organisational factors. Human and organizational hazards must be an essential component of the overall hazard management process, [116]. Although the technical knowledge of CCS is considered to be fully developed, the cost of its implementation is a significant factor in deterring its widespread adoption [117, 118]. The total cost of building a CCS facility is 1,200 to 1,519 million pounds where 15 % of the total cost is dedicated to

hazard and contingency. This is done to protect the business from potential hazards and unexpected events; thus, it is important to develop a comprehensive contingency and hazard assessment plan for financial losses [119]. The average capital expenditure and operational cost ranged between £35-80/ tCO<sub>2</sub> in the past (2010 prices) and it must be high enough to bring a reasonable return on investment [120]. Relying solely on public funding as the primary source of investment is not sufficient to sustain the required level of investment in CCS. CCS facilities require significant capital investments, which leads to high material costs, ultimately reducing their economic viability [84, 121, 122]. Because CCS projects often require significant infrastructure and capital investment, they typically have a long investment timeframe. This means that investors who are interested in CCS projects should be willing to commit to a long-term investment and face financial risks [123]. The absence of clearly defined regulations and scant technical knowledge could also pose financial risks and hence discourage the private sector [124, 125]. To create an adequate CO<sub>2</sub> specification for a CCS hub network, several considerations and requirements must be taken into account throughout the CCS chain. It is crucial to balance these factors to avoid creating an overly restrictive or burdensome CO<sub>2</sub> specification that may discourage potential users from connecting to the network, thus causing losses [126].

The process of acquiring permits for CCS projects is anticipated to be a major challenge and risk to encourage the growth of the CCS industry [127, 128]. Potential investors in CCS face uncertainties due to the legal framework, which does not provide the stability and certainty that these companies seek [129]. CCS liability is typically categorized as either operational or post-injection. Operational liability pertains to health, safety, and environmental hazards associated with capture, transportation, and injection. According to the International Hazard Governance Council (IRGC), post-injection liability covers health, safety, environmental, and climate hazards caused by CO<sub>2</sub> that would migrate from the intended storage site to another subsurface unit or back to the atmosphere [85]. This potentially places a hazard on whoever takes the liability during different processes [9].

Public acceptance is a hazard by itself which greatly influences the development and progress of CCS [128]. Acceptance of carbon capture by the public is a major reason for discouraging CCS technology [130]. Additionally, the lack of widespread use of CCS has

resulted in a scarcity of information, and an absence of knowledge management where information sharing is practiced, leading to increased hazards and barriers to CCS adoption [131, 132]. The entire technological chain is under scrutiny from a social perspective. To gain public acceptance, this new technology must prove its safety and minimal impact on the environment [28].

A significant hazard to the CCS chain is the uncertainty surrounding policies [128]. This may implement local or regional hazards [125]. Investors' reaction to the apparent level of policy commitment of the chain is substantial, since they are liable to policy hazards, especially in the case of long-lived assets like CCS, which rely heavily on government support. The absence of incentives, political will, and public support are among the primary hazard factors [133]. Regulators expect investors to exhibit their commitment to mitigating potential incidents and hazards by producing an environmental impact study proving the collective hazards are below a tolerable level. This expectation is placed on the investors not only by the public, customers, and governments but also by plant personnel [134]. With numerous projects involving collaboration between the government and the industry, it can be difficult to determine the appropriate party to lead the communication plan. This is because the duty holder is tasked with developing a safety case for the installation, rather than the design team. [135, 136]. A CCS project must deal with numerous knowledge-related hazards that can be broadly categorized into three groups: human hazards, operational hazards, and technological hazards [137].

### 3. Results and Discussions

Although CCS is a proven technology for controlling CO<sub>2</sub> emissions, its adoption is not yet widespread. The lack of widespread adaptation of CCS has affected knowledge generation, which potentially can lead to enhanced hazards, which in turn affects its adoption. There is a possibility that CO<sub>2</sub> leakage to occur at any point along the chain and at any time [23]. The accidental release of CO<sub>2</sub> poses a threat to living organisms and marine ecosystems and harms the environment. This paper summarizes hazards associated with the CCS chain by categorizing them into four distinct classes, which are described separately. The four categories are related to the capture process, transmission process, storage process, and non-technical factors (soft issues). Each of these categories is studied separately to understand the

associated hazards. The non-technical category includes human and organizational behavior and culture (corporate and operation management) within the system, which adds to the overall hazard of implementing the technology. Tables 5, 6,7, and 8 show a summary of major hazards in each of the subsystems.

**Table 5 A summary of major capture hazards**

Capture	
Hazards	References
Health	[14, 30, 31, 32, 33, 34, 35]
Energy consumption	[52, 138]
Amine degradation	[39, 40, 53]
Explosion due to oxygen combustion	[43,44]
Fire due to amine leakage can cause fire	[43, 45]
Fire due to uncontrolled leakage of syngas	[43, 46]
Pressure and phase change	[35, 60]
Flammable air mixtures	[48, 49, 50]
Amine leakage	[54, 55]
CO2 compression	[47]

**Table 6 A summary of major Transportation hazards**

Transportation	
Hazards	References
Corrosion (In all stages of CCS)	[37, 42, 71, 74, 75], . ,
Hydrate formation	[139, 140]
Population density consideration	[15, 65]
Carbonic acid formation	[70]
Impurities	[71, 72, 73, 78]
Pipeline blockage	[41]
Site elevation and topography	[11, 79]
Site conditions	[81]
Lack of information on pipelines' characteristics	[78, 82]
Ship or truck tank leakage	[62]

**Table 7 A summary of major storage hazards**

Storage	
Hazards	References
Leakage (In all stages of CCS)	[38, 41, 63, 67]

Contamination of water due to acid formation	[139, 141, 142]
Hydrate formation during storage	[143]
Inadequate storage capacity	[5, 14]
Threat to marine living creatures	[87, 142]
Groundwater Contamination	[88, 89, 98, 99, 100, 144]
Triggering seismic activity	[11, 88, 89, 94]
Interference with other subsurface activity	[89]
Pressure accumulation	[9, 16, 145]
Caprock fail	[9, 14]
Site characterization	[19, 92]
Natural groundwater movement	[95, 96]
Changing soil characteristics	[101]
Toxic scale	[35]
Blowouts	[108]
Well Integrity	[106, 109, 110, 111, 112]
Monitoring	[114, 115]

**Table 8 A summary of major non-technical hazards**

Non- Technical (Human elements, legal, financial)	
Hazards	References
Investment hazard	[84, 121, 122, 134, 147]
Public acceptance	[21, 28, 128, 130, 146]
Liability	([9, 85, 93]
Regulations	[27, 28 63]
Environmental	[148]
Lack of political support	[133]
Project Permitting	[127, 128]
Lack of technical knowledge	[124, 125]
Legal uncertainties	[129, 147]
High facility cost	[120]
Restrictive CO2 specification	[126]
Knowledge Management	([131, 132, 137, 149]
Absence of Incentives	[133]
Communication hazards	[135, 136]

#### 4. Conclusion

In conclusion, the compendium of hazards associated with carbon capture and storage (CCS) technology assists in understanding and mitigating risks throughout the entire CCS chain. The potential for CO2 leakage and associated environmental, health, and safety risks requires addressing all hazards listed in this

paper and hazards that are specific to the installation. By categorizing hazards into capture, transmission, storage processes, and non-technical factors, this paper aims to provide a comprehensive examination of the various hazards associated with CCS technology. Moving forward, continued research, constant monitoring, and strict regulatory standards are essential to ensure the safe and effective deployment of CCS technology as a vital tool in mitigating climate change.

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