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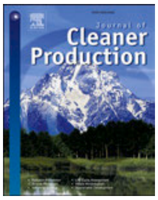

Review

Analysis of CO_2 pipeline regulations from a safety perspective for offshore carbon capture, utilization, and storage (CCUS)

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ABSTRACT

Offshore carbon capture, utilization, and storage (CCUS) is emerging as an essential option for decarbonization. Pipelines are an efficient and cost-effective way to transport large volumes of CO_2. Safe transportation of carbon dioxide (CO_2) to offshore storage and injection facilities is one of the prerequisites to ensuring safe CCUS operation. The current work first examines offshore CO_2 pipeline hazards in CCUS projects based on existing literature. Then, it compares pipeline safety regulations in the USA, Europe, Australia, China, and the Middle East, aiming to identify how these regulations have covered these hazards and potential areas for improvement. Lastly, it provides recommendations to enhance CO_2 pipelines' safety within CCUS projects. The results suggest that although the examined jurisdictions share a holistic commitment towards safety and environmental protection, notable differences exist. The existing regulations in the USA and Australia do not sufficiently account for the challenges faced in offshore CCUS operations, particularly those posed by CO_2 impurities. In Europe, the distinct hazards of CO_2 streams from CCUS are acknowledged. However, the required directives and guidelines for pipeline design and operation have not adequately addressed these hazards. Bridging these regulatory gaps requires measures including international harmonization, establishing guidelines for repurposing pipelines, and the implementation of Safety Case legislations. Furthermore, the existing regulatory frameworks can be improved by integrating with standardizing organizations' operating standards and recommended practices (e.g., Det Norske Veritas and International Organization for Standardization). This paper will be a valuable resource for policymakers, researchers, and industrial stakeholders in understanding the regulatory landscape for offshore CO_2 pipelines for CCUS purposes.

1. Introduction

Climate change, a pressing global issue, is primarily driven by anthropogenic activities such as the combustion of fossil fuels, deforestation, and certain agricultural practices (Wei et al., 2022). These activities contribute to the release of greenhouse gases into the atmosphere, with carbon dioxide (CO_2) being the most significant among them (Ritchie et al., 2020). In recent years, the concentration of CO_2 in the atmosphere has been constantly increasing, amplifying the greenhouse effect. The consequences of climate change are far-reaching, leading to rising global temperatures, ocean-level rise, more frequent and intense weather events, and biodiversity loss (EPA, 2022; European Commission, 2023; Wuebbles et al., 2017). To mitigate global warming and limit average global temperature increase, negative emissions technologies (NETs) including but are not limited to afforestation and reforestation, enhanced weathering, and carbon capture, utilization, and storage (CCUS) (Feng and Hicks, 2023; Minx et al., 2017; Sinha and Chaturvedi, 2019; Zheng et al., 2023b).

Carbon capture encompasses a range of technologies designed to reduce CO_2 emissions from significant point sources like power plants and energy systems (d'Amore et al., 2021; Guo et al., 2023; Han et al., 2023; Kotagodahetti et al., 2022; Turgut et al., 2021; Win et al., 2023; Xue et al., 2023), petrochemical and process industries (Gielen et al., 2002; Olabi et al., 2022; Zheng et al., 2023a), cement plants (Antzaras et al., 2023; Benhelal et al., 2013; Gallego Dávila et al., 2023; Izumi et al., 2021; Jakobsen et al., 2017), steel plants (Harpprecht et al., 2022), residential areas and transportation (Zuo et al., 2022) and other industrial facilities (Korczak et al., 2022; Zhang et al., 2023) or the removal of existing CO_2 from the atmosphere (IEA, 2022a). According to the International Energy Agency (IEA), the current generation of CCUS-equipped power and industrial plants is specifically designed to capture approximately 85–90% of their total CO_2 emissions. CO_2 capture methods include post-combustion (Aghaie et al., 2018; Chao et al.,

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List of abbreviations

AS/NZS	Australian/New Zealand Standard
BSEE	Bureau of Safety and Environmental Enforcement
CCS	Carbon capture and storage
CCUS:	Carbon capture, utilization, and storage
CFR	Code of Federal Regulations
COP	Conference of Parties
CO_2	Carbon dioxide
DAC	Direct air capture
DNV	Det Norske Veritas
DOI	Department of Interior
DOT	Department of Transportation
EC	European Commission
EU	European Union
FYP	Five-year Plan
GHG	Greenhouse gas
HAZOP	Hazard and operability studies
IEA	International Energy Agency
IIJA	Infrastructure Investment and Jobs Act
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
ISO	International Organization for Standardization
MAOP	Maximum allowable operating pressure
NET	Negative emissions technology
NGERA	National Greenhouse and Energy Reporting Act
NOPSEMA	National Offshore Petroleum Safety and Environmental Management Authority
NTEL:	National Energy Technology Laboratory
OCS	Outer continental shelf
OPGGSA	Offshore Petroleum and Greenhouse Gas Storage Act
PHMSA	Pipeline and Hazardous Materials Safety Administration
PHA	Process hazard analysis
SEMS	Safety and Environmental Management System
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change

2021; Khalilpour et al., 2015; Man et al., 2014), where CO_2 is separated from flue gas after fuel combustion, pre-combustion (Bailera et al., 2017; Petrescu and Cormos, 2017), which converts fuel into a hydrogen and CO_2 gas mixture before combustion, oxy-fuel combustion, where fuel is burned in pure oxygen to produce CO_2 and water vapor, and direct air capture (DAC), which captures CO_2 directly from the air using chemical processes (Fasihi et al., 2019; Markewitz et al., 2012; McLaughlin et al., 2023). Once captured, the CO_2 can be (i) utilized to provide renewable clean energy or yield useful products that can be incorporated into industrial processes (Arning et al., 2021; Challiwala et al., 2021; Elbashir et al., 2023; Galimova et al., 2022; Jarvis and Samsatli, 2018; Mikulčić et al., 2019; Ostovari et al., 2022; Rahman et al., 2017; Ryu et al., 2022; Thonemann et al., 2022; Wu et al., 2023; Zhang et al., 2020b; Zhi et al., 2023), (ii) used for enhanced oil recovery (EOR) (currently, most widely used and most economical) (Li et al., 2022; McLaughlin et al., 2023; Qiu et al., 2020; Seddighi, 2017; Zhang et al., 2020b), or (iii) securely stored in various geological formations, including depleted oil and gas reservoirs, deep saline formations, or unminable coal seams (Chen et al., 2015; Zhang et al., 2021, 2023). Offshore geologic storage offers several advantages for CO_2 storage, including potential ease, safety, and cost-effectiveness compared to onshore methods (Schrag, 2009). This is due to avoiding challenges such as land acquisition costs, proximity to population centers, hazards to underground drinking water sources, and public perception concerns (Federico et al., 2020). Offshore storage also benefits from streamlined processes as offshore leases typically involve single licensing authorities, simplifying project planning and execution (Eide et al., 2019).

CO_2 transportation plays a crucial role in CCUS, enabling the movement of captured CO_2 from the capture point to the storage site (Mualim et al., 2021; Sun and Chen, 2022). Hence, effective CO_2 transportation is vital for successfully implementing CCUS projects. Transportation involves various means for offshore deployments, such as pipelines or ships, depending on the distance and volume of CO_2 to be transported (IEA, 2022a). Pipelines are the predominant and cost-effective means of transporting large volumes of CO_2 over long distances in CCUS projects (Lu et al., 2020b; Onyebuchi et al., 2018; Zhang et al., 2006). For shorter distances or when pipelines are impractical, ships are utilized which raises concerns about managing emissions from the ships themselves (Bjerketvedt et al., 2022; Hoang et al., 2022). The transportation process necessitates meticulous planning and oversight to ensure public and environmental safety (Zanobetti et al., 2023).

International climate agreements and provisions to mitigate carbon emissions through supporting technologies, such as CCUS, have emerged from the United Nations (UN) efforts. The United Nations Framework Convention on Climate Change (UNFCCC), established in 1992 during the Earth Summit, is an international treaty requiring parties to convene regularly at the Conference of Parties (COP) to tackle climate change. Additionally, the Paris Agreement, a legally binding treaty adopted in 2015 at the UN Climate Change Conference (COP21), involves 196 Parties and focuses on the crucial goal of limiting global warming to below 2 °C, with efforts to further restrict it to 1.5 °C. Complementing these agreements, the UN Intergovernmental Panel on Climate Change (IPCC), a scientific body, plays a vital role in assessing climate change, its impacts, and future risks. By providing policymakers with invaluable information, the IPCC aids in formulating effective adaptation and mitigation strategies.

Through these efforts, the UN recognizes the significance of CCUS as a key technology for reducing greenhouse gas emissions and urges its development and implementation (IEA, 2020a). There has been a significant growth in the CCUS industry, with over 78 new projects announced in the USA between 2021 and 2022. Furthermore, according to a 2022 report by McKinsey, the adoption of CCUS technology needs to increase by 120 times by 2050 for countries to fulfill their net-zero commitments (Biniek et al., 2022). CCUS' economical deployment is currently dependent on the presence of policy incentives and carbon trading mechanisms (Fikru, 2022; Kegl et al., 2021; Lin and Tan, 2021; Lu et al., 2020a; Zhang et al., 2020a). In the United States, CCUS is growing exponentially in light of the current policies, including the Infrastructure Investment and Jobs Act (IIJA) of 2021 and the Inflation Reduction Act (IRA) of 2022, with billions of funding and tax credits for CCUS-related projects (IEA, 2022b).

This widespread deployment of CCUS relies heavily on the presence of CO_2 pipelines to transport captured CO_2 from various sources. The first offshore CO_2 pipeline, the Snohvit project in Norway, has been in operation since 2008, covering about 100 miles between Hammerfest and the Snohvit field under the Barents Sea (Eiken et al., 2011). Norway's Northern Lights project also aims to transport CO_2 from industrial emitters in Norway and the Netherlands to an offshore storage site in the North Sea, spanning approximately 780 miles (IEA, 2021). Other ongoing and planned offshore CO_2 pipeline projects in the North Sea include the Porthos project in the Netherlands, the Viking CCUS project in the United Kingdom, and the Bifrost project in Denmark. The USA has 50 operational pipelines spanning over 5000 miles, carrying approximately 77 million tons of CO_2 annually (IEA, 2022b). Recently, the US Gulf of Mexico Carbon Capture and Sequestration Partnership Hub has taken initiatives to transport CO_2 from onshore industrial emitters on the Gulf Coast to offshore fields in the Gulf of Mexico (Sachde et al., 2022).

CO_2 pipelines are regulated by the same authorities that oversee natural gas or hydrogen pipelines, such as the Pipeline and Hazardous Materials Safety Administration (PHMSA) and Bureau of Safety and Environmental Enforcement (BSEE) in the USA. Despite some shared guidelines, significant differences in regulations are expected due to the nature of the transported medium (Lu et al., 2020b). CO_2 presents a unique set of distinct hazards, which are thoroughly discussed in this study.

The safety hazards posed by CO_2 pipelines are evidenced by past incidents (Vitali et al., 2022b). On February 22, 2020, a CO_2 pipeline belonging to Denbury Enterprises ruptured suddenly near Satartia, Mississippi, resulting in the release of CO_2 gas. The pipeline was constructed in challenging, hilly terrain, and the soil surrounding the pipeline became saturated from two months of rain, leading to a pipe weld failure and the release of an explosion of ice and CO_2. Nearby individuals experienced difficulty breathing, with some collapsing in their homes. Approximately 200 residents from the village and surrounding areas were evacuated by emergency personnel (Eller, 2022). The rupture resulted in 49 people being hospitalized and approximately 300 residents being evacuated from their homes (Mathews, 2022). Incidents involving CO_2 can lead to casualties when a substantial release occurs, as seen in the case of Lake Nyos, Cameroon, in 1986. A limnic eruption caused a sudden and massive discharge of CO_2, estimated to be between 100,000 and 300,000 tons (Baxter et al., 1989). It resulted in a significant loss of life, with over 1700 people and 3500 livestock fatalities (Kling et al., 1987). The released gas formed a fast-moving cloud that descended onto nearby villages, displacing the air and suffocating individuals and animals within a radius of 25 km. This 1986 incident serves as a clear indication of the dangers linked to CO_2 emissions. However, it was not until the 2020 Startia incident and the widespread proposals for an extensive network of CO_2 pipelines for CCUS purposes that the US PHMSA was prompted to introduce enhanced measures to strengthen safety oversight of CO_2 pipelines nationwide and ensure the protection of communities from hazardous pipeline incidents (PHMSA, 2022).

While there is widespread support for CCUS to reduce CO_2 emissions, there are reservations regarding pipelines' extensive and large-scale deployment due to the questionable readiness of the involved technologies and the absence of comprehensive safety regulatory frameworks that promote responsible operation (Chen et al., 2022; Ding et al., 2020; Lu et al., 2020b; Onyebuchi et al., 2018; Zhang, 2021). Several countries and jurisdictions have demonstrated policy backing for CCUS. However, multiple studies emphasize the need for improved regulatory frameworks for CO_2 pipelines (Chrysostomidis et al., 2009; Dixon et al., 2015; IEA, 2022c; Zhang, 2021). For instance, the US government has recently leased a vast Gulf of Mexico (GoM) area, where offshore CCUS-related functions are heavily anticipated. However, any operation is yet to start. Lack of regulations is one of the major reasons behind this delay, as the industries are unsure about the detailed guidelines –essential for safe and sustainable operation. The literature also addresses environmental, health, and safety regulatory issues associated with CCUS operations, highlighting the necessity of establishing specific standards for CO_2 transportation technologies with explicit CO_2 purity specifications (Koornneef et al., 2012; Sleiti and Al-Ammari, 2022; Zakkour and Haines, 2007).

The current study analyzes CO_2 pipeline regulations from a safety perspective for offshore CCUS. This topic has received limited attention in previous research. In their reviews, Lu et al. (2020b) and Sleiti et al. (2022) highlighted the limited safety standards for CO_2 pipelines and the significance of considering impurities' impact on phase equilibrium and corrosion mechanisms. The latter study suggested utilizing digital twins (DT) as a means to enhance reliability and safety in CO_2 transport. Mace et al. (2007) examined the regulatory gaps regarding CO_2 capture and storage in Europe, emphasizing the importance of explicitly incorporating CCUS activities within legal frameworks. Dixon et al. (2015) examined the regulatory changes that occurred in Europe, the USA, and Australia from 2005 to 2015, specifically focusing on international laws related to greenhouse gas (GHG) emissions. Zhang (2021) examined the legal and regulatory frameworks governing CCUS in Europe, China, and the Middle East, revealing that regulatory clarity posed a significant challenge across all three jurisdictions, with the additional finding that China and the Middle East lack specific laws or regulations dedicated to CCUS. In a more recent report in 2022 (IEA, 2022c), the International Energy Agency (IEA) investigated how different jurisdictions have addressed issues related to frameworks concerning CCUS, with particular emphasis on the storage aspect.

Notably, most research has primarily focused on safety regulations concerning the capture and storage components of CCUS, overlooking the critical aspect of CO_2 transportation. Furthermore, offshore pipeline transport, an important aspect of the overall CCUS process, has received limited attention in the literature. To address these limitations, this work has evaluated the available regulations for CO_2 transportation through pipelines from a safety perspective. We have identified the hazards to understand what can go wrong with CO_2 pipeline transportation during offshore CCUS operations. We have studied the relevant global safety regulations and compared how robustly these regulations address the safety concerns stemming from identified hazards. We have also identified the regulatory gaps and provided recommendations to bridge these gaps.

The remainder of this manuscript has been organized as follows. Section 2 exhaustively explains the hazards associated with offshore CO_2 pipelines in the context of CCUS initiatives. Section 3 discusses the existing regulatory developments concerning offshore CO_2 pipeline transportation safety in the United States, Europe, Australia, China, and the Middle East. A detailed discussion of how these regulations address the identified hazards, regulatory gaps, and potential scope of improvements is presented in Section 4. The available recommended practices by classification and standardization societies (e.g., Det Norske Veritas and the International Organization for Standardization) are discussed in Section 5. Finally, Section 6 concludes the manuscript by providing recommendations to address and bridge these regulatory gaps for improved safety and effectiveness in CO_2 pipeline operations within CCUS projects.

2. Hazards associated with CO_2 pipelines

The CCUS industry has considerably less experience than hydrocarbon services (e.g., natural gas). For instance, the USA, which leads the world in the mileage of CO_2 pipelines, has over 300,000 miles of natural gas transmission pipelines, transporting around 100 Bcf/day of natural gas over thousands of miles from production areas to local utility delivery points, in contrast to only 5000 miles of CO_2 pipelines (FECM, 2020). Reasonably, the current offshore CCUS industries have less experience with safety-related risks (e.g., disruption in the aquatic environment due to a pipeline leakage or leaking to the atmosphere causing shortness of breath to humans and other animals) that can be faced during CO_2 transportation through pipelines. However, these scenarios can happen and result in unwanted outcomes.

One of the key aspects of safety management is identifying what can go wrong in an operation, which is popularly known as hazard identification. It is a crucial step as it helps determine what situation will lead to unwanted scenarios. Although CO_2 does not pose the same flammability hazards as natural gas, it presents its own set of challenges and concerns (Oosterkamp and Ramsen, 2008; Wang et al., 2023). These include operating at higher pressures and facing increased risks of corrosion and ductile running fractures. Another relevant difference between CO_2 and natural gas is that CO_2 is an odorless gas and heavier than air. It is of paramount importance to identify these hazards. In the current work, we have studied the available literature to find such hazards associated with offshore CCUS operations. Alternatively, techniques like process hazard analysis (PHA) and hazard and operability studies (HAZOP) could be employed to get a complete list of hazards worth considering. It should be noted that we have focused solely on safety-related hazards; the security-related hazards (e.g., bomb threat and sabotage, just to name a few) are out of the scope of the current work. Fig. 1 shows a summary of system boundaries and identified hazards. The detailed descriptions of these hazards can be found in the sub-sections 2.1-2.5.

2.1. Dense CO_2 phase hazards

Depending on the application, CO_2 transportation involves handling it either as a gas or a dense phase, with the term "dense phase" referring to CO_2 pipelines operating in a supercritical or liquid state. The supercritical state (sCO_2) occurs at temperatures and pressures exceeding critical values, $T_c = 304.2$ K and $P_c = 7.4$ MPa, where CO_2 exhibits characteristics between a liquid and a gas. Pipelines transporting sCO_2 have a higher susceptibility to ductile fractures, which can lead to significant pipeline damage (Wang et al., 2016). On the other hand, liquid CO_2 (lCO_2) is maintained in a subcooled or subcritical state by cooling to temperatures well below ambient temperature, ensuring it remains in a liquid phase throughout the operation. It is crucial to keep the pipeline above the carbon steel brittle temperature to prevent catastrophic ruptures (Kuprewicz, 2022). It is worth noting that regulations for pipelines transporting liquid CO_2 are currently absent. In contrast, gaseous CO_2 (gCO_2) is not technically preferable since pipelines require larger diameter pipes to move the same gCO_2 tonnage pipeline capacity compared to dense phase. For instance, at $T = 450$ K, more than three times the pipeline diameter is needed to transport gCO_2 at $P = 1$ MPa compared to sCO_2 at $P = 10$ MPa (The Engineering ToolBox, 2023).

Potential hazards of dense CO_2 include.

A. CO_2 liquid-gas expansion

The expansion ratio of CO_2 is large (1 volume of liquid CO_2 at $T = 277$ K and $P = 20$ MPa yields approximately 520 vol of gas at the same temperature and atmospheric pressure), and, consequently, high pressures can rapidly build up in confined spaces (EI, 2013). It is important to design systems with sufficient capacity to accommodate CO_2 expansion and identify areas where liquid CO_2 may become trapped. Inadequate pressure protection (e.g., no relief devices) can result in an uncontrolled release, leading to additional hazards such as propelling debris.

B. Ductile fracture propagation

CO_2 pipelines are considered more vulnerable to fast-propagating ductile fractures, which are fractures that can travel over long distances along the pipeline (Barnett and Cooper, 2016; Martynov et al., 2017; Mohammed Nor et al., 2023; Skarsvåg et al., 2023). This vulnerability arises from factors, including the high operating pressure and temperature as well as the solving ability of supercritical CO_2, which can generate a weak layer and enhance the likelihood of cracking. Fracture propagation occurs when the decompression speed of the fluid is less than the fracture propagation speed of the pipe wall. Compared to natural gas, as vapor starts to form, the decompression speed of the CO_2 stream decreases substantially (DNV, 2017). Consequently, the risk of running ductile fractures is more pronounced in CO_2 pipelines. To address this issue, it is crucial to regulate the toughness of the pipeline material and carefully manage the operating temperature and pressure, or through the installation of suitable fracture arrestors (ISO, 2016). Common pipe material for CO_2 pipelines can be carbon, carbon-manganese, or corrosion-resistant alloys (CRA) steels. All are vulnerable to ductile fractures, but they have different fracture toughness requirements (ISO, 2016).

C. Temperature-drop and potential solid phase formation during rapid depressurization

In transient scenarios involving rapid depressurization in CO_2 pipelines, the material may experience temperature drops below ductile/

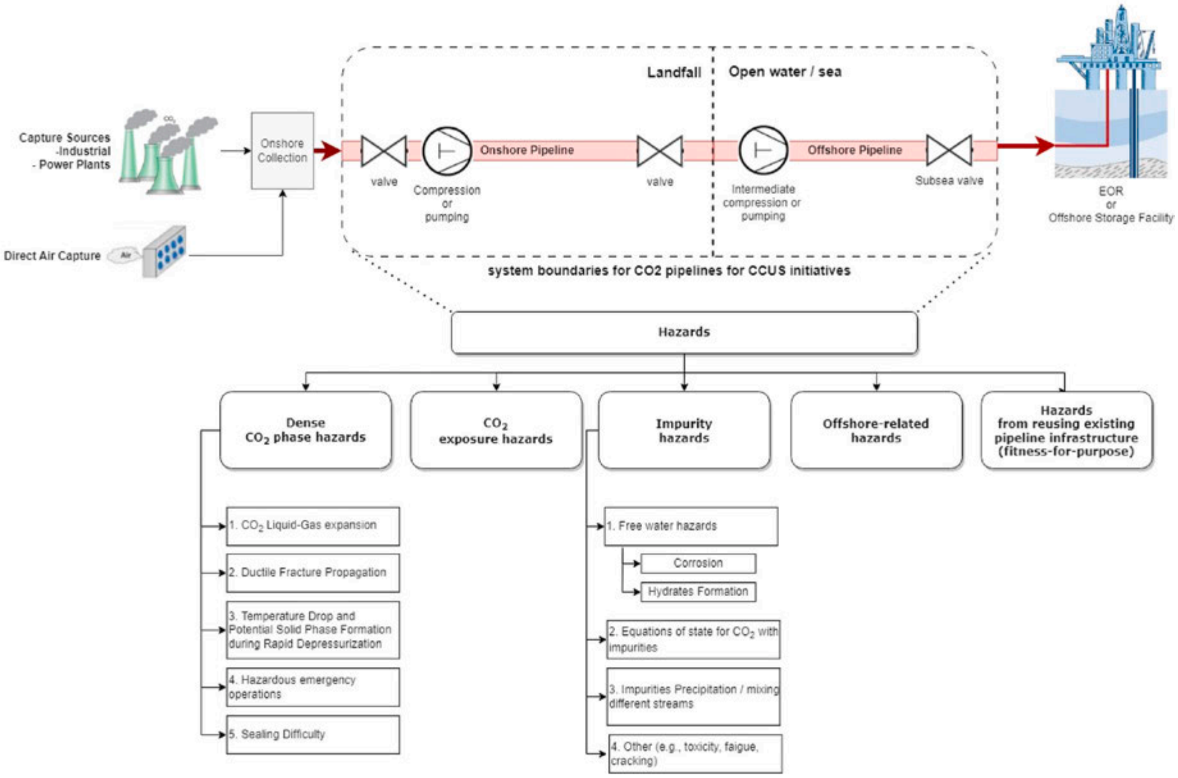

Fig. 1. Schematic illustration of the system boundaries and identified hazards for pipelines transporting CO_2 for offshore CCUS initiatives.

brittle transition temperature (DBTT), causing a substantial reduction in the material's fracture toughness, increasing the risk of brittle fracture and potentially causing catastrophic ruptures (Bilio et al., 2009; Martynov et al., 2013). Similarly, the release of high-pressure CO_2 into the atmosphere can result in significant cooling below the triple point (−56.6 °C), leading to the formation of solid CO_2 particles (dry ice) at −79 °C (Hulsbosh-Dam et al., 2012; Teng et al., 2018).

Consequently, unlike the decompression of hydrocarbons, the release of CO_2 can involve a mixture of gaseous and solid states. Solid CO_2 particles released during decompression should be considered, as they are erosive and can pose a risk to critical equipment nearby. The quantity of solid CO_2 produced during the decompression process is influenced by factors such as the pressure and temperature of the CO_2 stream, as well as the rate at which the decompression occurs (Meleshkin et al., 2019; Munkejord et al., 2020). Therefore, all of these factors as well as pipeline material DBTT must be regulated to ensure the safety of pipeline transportation as well as its surroundings.

D. Hazardous emergency operations

If the temperature of the released CO_2 plume is below the dew point temperature of the surrounding air, water vapor will condense, forming a visible fog cloud that can make it difficult for emergency operations to distinguish between CO_2 solids and condensed water within the cloud (Mathews, 2022). The size and opacity of the water vapor cloud depend on the temperature within the cloud and the humidity level of the air.

E. Sealing difficulty

The unique properties of supercritical CO_2, such as its lack of surface tension and extremely low viscosity, can pose challenges to effective sealing (Connolly and Cusco, 2007). Regulations based on the sealing capabilities of valves used for hydrocarbon liquids and gases may not hold for CO_2 and need to be thoroughly tested. This becomes especially critical when considering that CO_2 streams often contain significant impurities, as discussed in the following section. Explosive decompression, a phenomenon where elastomer seals absorb gas at high pressure, swell and harden in the presence of supercritical CO_2, needs to be considered.

2.2. *CO_2 exposure hazards*

CO_2 possesses toxicity and acts as an asphyxiant. Exposure to elevated levels of CO_2 can result in various health effects, including headaches, dizziness, difficulty breathing, increased heart rate, and even asphyxiation due to its displacement of oxygen in the bloodstream (OSHA, 2022a). In high concentrations, CO_2 can function as a toxic substance, leading to hypercapnia, heightened respiratory rate, tachycardia, cardiac arrhythmias, impaired consciousness, convulsions, coma, and potential fatality (Permentier et al., 2017). Solid CO_2 has the potential to cause burns upon direct contact, and rapid warming of solid CO_2 can generate large quantities of CO_2, posing hazards, particularly in confined spaces (Langford, 2005).

When regulating material selection, commissioning, and operation of CO_2 pipelines, it is crucial to consider all of these parameters.

2.3. *Impurity hazards*

The composition of CO_2 can differ based on its source, specifically the method used for CO_2 capture. The solving ability of CO_2 can also introduce additional impurities during its transportation through pipelines. Moreover, the composition of the CO_2 stream can be altered due to various factors, including changes in pressure and temperature during compression and conditioning, intentional removal of impurities through purification, interactions between different impurities, and reactions with the surrounding environment, like pipeline walls or underground water (ISO/TC, 2020). Additionally, tracer substances can be added to the CO_2 stream for monitoring its movement and locating potential leaks (European Commission, 2012b). These processes can result in the presence of diverse chemical components in the CO_2 flow, including but not limited to CH_4, H_2O, H_2S, SO_x, NO_x, N_2, O_2, glycol, and other substances (Paschke and Kather, 2012).

The presence of different combinations of impurities can lead to.

A Free water hazards

Water-related issues become particularly prominent during upset or shutdown scenarios. Moreover, impurities like non-condensable gases, SO_x and NO_x, can also affect the solubility of water in CO_2 (Hajiw et al., 2018; Sun et al., 2023). Hazards from free water include.

- ***Corrosion***

The presence of liquid water in CO_2 environments can lead to the partial dissolution of CO_2 and the formation of carbonic acid, resulting in corrosion issues with the steel alloys typically employed in long pipelines (Choi and Nešic, 2011). The corrosion caused by carbonic acid can pose challenges and necessitate appropriate regulations for corrosion protection measures to maintain the integrity and longevity of the pipeline system.

- ***Hydrates formation***

Hydrates are generated when CO_2 molecules interact with water under specific conditions, typically at temperatures below 300K and pressures exceeding 600 kPa (Wang et al., 2012). The formation of hydrates within the pipeline can result in blockages, leading to significant operational and safety concerns (Rao et al., 2022).

B Equations of state (EOS) for CO_2 with impurities

Accurately characterizing the thermodynamic properties of CO_2 is of paramount importance in the design and operation of CCUS pipelines. The presence of impurities in CO_2 significantly alters its properties, deviating from those of pure CO_2, including phase behavior, density, speed of sound, viscosity, thermal conductivity, and heat capacity (McKay et al., 2022). Most impurities affect the critical and saturation pressure in the pipeline (Peletiri et al., 2017). Therefore, it is essential to regulate the necessary modifications to the pure CO_2 equation of state (EOS) in order to accurately represent CO_2/impurities systems.

C Impurities precipitation

Supercritical CO_2 is known for its excellent solvent efficiency. However, when exposed to a significant pressure reduction, such as during a leak, it undergoes a transition into a gaseous state and loses its solvent capability nearly completely (Vitali et al., 2022a). Additionally, as mentioned earlier, impurities can influence the critical point of the transported medium, leading to the possibility of transforming into a gaseous phase during transportation (Lu et al., 2020b; Sleiti et al., 2022). As a result, there is a potential for any substance present within the transported medium (impurities or tracer substances) in the pipeline to precipitate out of solution.

Table 1 presents other hazards and associated concerns regarding impurities in CO_2 transported through pipelines for CCUS purposes. Establishing safety regulations requires careful consideration of all these concerns, as their presence underscores the need for stringent regulatory scrutiny throughout actual operations. In addition to safety and pipeline integrity hazards, impurities implications on the vapor-liquid and phase equilibria of CO_2, and overall density should be carefully considered (Al Baroudi et al., 2021; Peletiri et al., 2019).

Table 1
Impurities, composition ranges depending on capture process, and associated hazards.

Impurity	Composition ranges (Adu et al., 2019)			Hazards
	Post-combustion	Pre-combustion	Oxy-combustion	
H_2O	100–640 ppmv	0.1–600 ppmv	0–1000 ppmv	1 Corrosion, also known as sweet corrosion 2 Hydrates formation
O_2	0.0035–0.03 vol%	0.03–1.3 vol%	0.001–6.0 vol%	1 Corrosion: Oxygen exacerbates CO_2 corrosion of pipeline carbon steels, even against chromium-doped steel, despite its corrosion-resistant properties (Jayasinghe, 2021; Wang, 2009; Xia et al., 2020). O_2 may combine with H_2 in the stream to form free water (Brown et al., 2017). 2 Oxygen promotes the formation of elemental sulfur and sulfuric/nitric acid, in the presence of SO_x and NO_x compounds (Halseid et al., 2014).
H_2S	Trace	100–34 000 ppmv	Trace	1 Toxicity: a highly toxic gas, and accidental releases of H_2S can pose significant health risks (OSHA, 2023). 2 Deposition: H_2S reacts with O_2, resulting in the formation of elemental sulfur, which can deposit and cause blockages within the pipeline (Halseid et al., 2014). This deposition of sulfur increases pressure drop and can result in operational issues. 3 Corrosion: presence of H_2S in the CO_2 pipeline dramatically increases the corrosion rate (Choi et al., 2016). 4 Fatigue in the presence of water (DNV, 2017) 5 Sulfide stress cracking (SSC): The presence of H_2S lowers the pH, causing it to drop below the depassivation pH of the alloy, leading to an accelerated rate of proton discharge. SSC occurs when atomic hydrogen diffuses into the metal, reducing the ductility and deformability of the metal, also known as hydrogen embrittlement (Iannuzzi, 2011).
SO_x	0–100 ppmv	25 ppmv	0.1–25 000 ppmv	Corrosion: Cross-chemical reactions results in the formation of sulfuric/nitric acid, highly corrosive chemicals (Halseid et al., 2014). SO_2 may cause Fatigue in the presence of water (DNV, 2017)
NO_x	20–50 ppmv	400 ppmv	0–2500 ppmv	
CO	1.2–20 ppmv	300–4000 ppmv	0–162 ppmv	1 Toxicity: Accidental release of CO can pose a toxicity hazard (OSHA, 2022b). 2 CO–CO_2 cracking: Stress corrosion cracking occurs in CO/CO_2 environments containing water (Kowaka and Nagata, 2013)
N_2	0.01–0.29 vol %	0.0195–1.3 vol%	0.01–16.6 vol%	1. N_2 reduces the decompression velocity, which introduces hazards such as fractures, explosive decompression, and the formation of solid CO_2 or hydrates (Brown et al., 2017). 2. Affects the bubble point of the CO_2, causing pumping issues (Brown et al., 2017).
H_2	Trace	0.002–3.0 vol%	Trace	1. Hydrogen-Induced Stress Corrosion Cracking (HISCC) can result in rapid crack growth and eventual failure of the pipeline, including duplex stainless steel (Brown et al., 2017). 2. Hydrogen embrittlement of

(continued on next page)

Table 1 (*continued*)

Impurity	Composition ranges (Adu et al., 2019)			Hazards
	Post-combustion	Pre-combustion	Oxy-combustion	
				the pipeline (Elkady et al. 2024). 3. Free water formation: H_2 may combine with O_2 to form free water (Brown et al., 2017). 4. Affects the bubble point of the CO_2, causing pumping issues (Brown et al., 2017).
Ar	0.0011–0.045 vol%	0.0001–1.3 vol%	0.01–5.0 vol%	–
CH_4	<100 ppmv	0–20000 ppmv	–	Fire and Explosion: CO_2 is heavier than air, while methane is lighter than air, so methane can accumulate in pockets and pose a risk of explosion or fire, following a leak.
Amines	–	–	–	Traces of amines utilized in the CO_2 capture process (post-combustion) may undergo reactions with CO_2 and other impurities (O_2, NO_x, SO_x, etc.) to produce degradation products, some of which may pose potential risks to humans and the environment based on their toxicity and concentration levels (Rey et al., 2013).
Glycol	–	–	–	Glycol readily dissolves in water and forms a corrosive aqueous phase at significantly lower water concentrations compared to the solubility limits observed for pure CO_2 (Dugstad et al., 2011).

2.4. Offshore-related hazards

Offshore pipelines span from the first valve, flange, or connection above water on a platform to the first valve, flange, connection, or insulation joint at a landfall unless otherwise specified by the legislation. When transporting CO_2 via offshore pipelines, there are several important considerations for ensuring safety. Firstly, the pipelines must be designed and constructed to withstand the challenging marine environment, including corrosive saltwater and potential damage from storms, waves, and currents. Secondly, careful routing is crucial to avoid sensitive marine habitats, shipping lanes, and areas with high currents or other environmental hazards. Additionally, burying the pipelines at an adequate depth is necessary to protect them from damage caused by ships or fishing gear and minimize the potential impact on marine life. Lastly, safe CO_2 transport requires specialized equipment like subsea isolation valves, subsea pigging launchers and receivers, and subsea control systems.

During the construction of CO_2 offshore pipelines, the environmental hazards are similar to those of conventional hydrocarbon installations. However, operational pitfalls, particularly accidental leakage, present unique environmental hazards, including pH reduction, carbonate dissolution, and direct toxic effects associated with CO_2 in marine conditions. The release of CO_2 into seawater can lead to a reduction in pH levels, causing potential impacts on marine organisms. Acidification can affect the tissues and body fluids of marine organisms, leading to acute and chronic effects on survival, metabolism, and reproduction. Marine animals with calcium carbonate shells or skeletal structures may be vulnerable to softening or dissolution due to the reaction with CO_2. High concentrations of CO_2 can also have direct toxic effects on marine organisms by reducing the oxygen affinity of hemoglobin, affecting oxygen uptake in fish and other aquatic animals. Moreover, release from a subsea CO_2 pipeline, particularly in near-shore areas or near offshore facilities, may also pose toxic hazards to humans nearby.

2.5. Hazards from reusing existing pipeline infrastructure (fitness-for-purpose)

Using existing pipelines for CO_2 transportation requires a thorough investigation into their suitability and assessment of degradation, considering the unique hazards and operating conditions of CO_2 compared to conventional hydrocarbons. While the overwhelming majority of existing pipelines worldwide are constructed from carbon steel, it is important to note that these pipelines may not have been originally designed for the high pressures required or the corrosion rates expected for CO_2 transport. While existing CRA pipelines may offer the advantage of higher corrosion resistance, they are susceptible to stress corrosion cracking (SCC) as well as de-passivation in the presence of water (Sonke et al., 2022). Despite these challenges, utilizing existing infrastructure can greatly reduce the overall cost of CO_2 transportation; therefore, safety regulations need to be established, considering appropriate measures to ensure the feasibility and safety of such reuse.

3. Offshore CO_2 pipelines regulatory system

3.1. The United States

3.1.1. Federal laws

The Pipeline Safety Act (PSA) (1968) is a federal law that provides the regulatory framework for the safe transportation of hazardous materials through pipelines and grants PHMSA the authority to enforce these regulations. The PSA has evolved over the years, with key milestones including ***the Hazardous Liquid Pipeline Safety Act of 1979 (HLPSA)***, which established safety standards for the transportation of hazardous liquids, including CO_2, by pipeline, ***the Pipeline Safety Reauthorization Act of 1992 (PSRA)*** which highlighted safety management system requirements, ***the Pipeline Safety Improvement Act (PSIA) of 2002*** with new inspection and reporting requirements, ***the Pipeline Inspection, Protection, Enforcement, and Safety Act (PIPES Act) of 2006*** with integrity management and reporting requirements, and finally ***the Pipeline Safety, Regulatory Certainty, and Job Creation Act (PSRCJCA) of 2011*** which included new requirements to improve emergency response planning and enhance public awareness of pipeline safety risks. PHMSA is granted the authority to enforce all these requirements. PSRCJCA specifically addressed the need for enhanced safety regulations for CO_2 pipelines and required PHMSA to issue new regulations for the transportation of CO_2 by pipeline.

On the Outer Continental Shelf (OCS), PHMSA shares the authority with the Bureau of Safety and Environmental Enforcement (BSEE) according to ***the Outer Continental Shelf Lands Act (OCSLA) of 1953***. OCSLA grants BSEE the authority to regulate exploration, development, and production activities on the OCS, including offshore pipeline construction, operation, and maintenance. To sum up, the Department of Transportation (DOT)'s PHMSA has jurisdiction over transportation-related facilities, including pipelines, located landward of the coastline, deep-water ports, and their associated seaward pipelines. In contrast, the Department of Interior (DOI)'s BSEE retains jurisdiction over facilities, including pipelines, located seaward off the coast. In August 2020, PHMSA and BSEE signed a Memorandum of Understanding (MOU) to clarify the roles and responsibilities of the two agencies and facilitate collaboration for regulating offshore pipelines on the Outer Continental Shelf (OCS) (US DOT & US DOI, 2020).

3.1.2. Department of Transportation (DOT)'s Pipeline and Hazardous Materials Safety Administration (PHMSA)

The regulations for CO_2 pipelines issued by the Pipeline and Hazardous Materials Safety Administration (PHMSA) are.

1. ***Title 49 of the Code of Federal Regulations (CFR), Part 195***: "**Transportation of Hazardous Liquids by Pipeline**" - This regulation outlines the requirements for the transportation of hazardous liquids, including CO_2, by pipeline. It was first issued in the 1970s and has been updated several times since then, with the most recent updates occurring in the early 2010s (US DOT, 1970). The code is structured to address safety and reliability standards in steel pipeline design (Subpart C), construction (Subpart D), and operation and maintenance (Subpart F). It also covers topics such as Record keeping and Reporting Obligations (Subpart B) and Corrosion Control (Subpart H). Originally focused on hydrocarbons, the code has been updated to incorporate CO_2 following incidents like Startia's and the growing number of CCUS projects. PHMSA is actively enhancing its safety oversight of CO_2 pipelines and continues to work on implementing additional measures (PHMSA, 2022). Moreover, in 49 CFR Part 198, financial responsibility requirements are discussed to ensure that pipeline operators have sufficient resources to address incidents, including cleanup and compensation for damages. Details of the topics discussed under relevant Subparts are discussed in Table 2.

2. ***Emergency Response Guidebook (ERG)*** - This guidebook provides emergency response personnel with the information they need to respond effectively to incidents involving CO_2 pipelines, including information on the physical and health hazards associated with CO_2 and the proper response procedures. The Emergency Response Guidebook is updated periodically, with the most recent update occurring in 2020 (PHMSA, 2020). It provides information on the release of CO_2 in various forms, including pure (ID 1013-120) and mixture (IDs 1014-122, 1015-126, and 1041-115) states, as well as compressed gas, liquified (ID 1058-120), refrigerated liquid (ID 2187-120), and solid (dry ice) (ID, 1845-120) states. Mixtures of CO_2 with other substances such as oxygen (ID 1014-122), nitrogen (ID 1058-120), air (ID 1058-120), and nitrous oxide (ID 1015-126) are also covered. The ERG offers guidelines on spill isolation criteria and protective measures for the public, which are determined by the spill's size.

3. ***PHMSA's Pipeline Safety Compliance and Enforcement Program*** - This program is responsible for ensuring that pipeline operators comply with federal regulations for the transportation of CO_2 and other hazardous liquids by pipeline, including conducting inspections and taking enforcement actions as necessary (PHMSA, 2023a). The enforcement measures taken by PHMSA against pipeline operators for violations of federal pipeline safety regulations can include issuing warning letters and notices of probable violation, imposing civil penalties, initiating administrative proceedings, revoking or suspending operating authority, requiring corrective actions, conducting inspections and audits, initiating legal actions,

Table 2
49 CFR Part 195 subparts' focus and regulatory details.

Subpart (Focus)	Topic	Details
Subpart B (Records Keeping)	Maps and Records	Pipeline operators must maintain maps and records: - Their pipeline systems, design parameters (T, P, etc.), pressure testing/ protection, and corrosion control. - Inspections and tests for at least 2 years or until the next inspection/test. - Training
Subpart C (Minimum design requirements)	Design Temperature	Pipelines may be subject to low temperatures either during the initial fill of the line or due to rapid pressure reduction; hence, ensuring that components are made of appropriate materials is essential.
	Design Pressure (Internal)	The internal design pressure of the pipeline is determined using Barlow's formula as modified in ASME/ANSI B31 to consider: - Specified minimum yield strength (determined by performing tests of ANSI/ API Spec 5L), - Nominal wall thickness, - Nominal outside diameter, - Design safety factor (0.6 for offshore) and - Seam joint factor (in accordance with ASTM or ANSI/API Specs).
	Design Pressure (External)	Following ASME/ANSI B31, external pressure and anticipated external loads must be considered in the design to ensure the pipeline's structural integrity
	Fracture Propagation	System must be designed to mitigate the effects of fracture propagation.
	Pipe Material (New/ Used)	• Steel that can withstand the anticipated internal pressures and external loads of the pipeline system. • Manufactured according to a written specification that outlines the chemical requirements and mechanical tests. • For used, surface defects, such as cracks or corrosion, must not exceed the maximum allowed depth specified in the pipe's manufacturing specification.
	Valve/Fittings	• Valves in accordance with ANSI/API Spec 6D, • Fittings in accordance ASME/ANSI B16.9 or MSS SP-75
	Other	Accommodate the passage of instrumented internal inspection devices in accordance with NACE SP0102.
Subpart D (Minimum construction requirements)	Installation/Pipe Inspection	Inspection by trained and qualified personnel must be provided to ensure: - Installation is compliant,

(continued on next page)

Table 2 (*continued*)

Subpart (Focus)	Topic	Details
		and - Pipe components are not damaged or weakened (visual)
	Offshore Pipeline Installation, Cover, & Clearance	• Pipes in water depths of 12–200 feet are to be installed below the natural bottom of the underwater environment unless supported by stanchions or concrete coating. • Minimum cover depths for buried pipes, including 48 inches for deep-water port safety zones, 36 inches for the Gulf of Mexico and its inlets in waters less than 15 feet deep, and 36 inches for other offshore areas under water less than 12 feet deep. • Clearance between pipes and underground structures is at least 12 inches.
	Other	Transportation of pipes via ship must comply with API RP 5LW.
Subpart E (Pressure Testing)	Pressure Testing	• Pipelines must be pressure tested (for at least 4 continuous hours at a pressure equal to 125 percent, or more, of the maximum operating pressure) without leakage before operation and after replacement, relocation, or changes. • Operators can choose a risk-based alternative program for testing older pipelines. The program assigns risk classifications based on location, product, volume, and probability of failure indicators. • May use inert gas or CO_2 as the test medium.
Subpart F (Minimum Operation and Maintenance requirements)	Procedural Manual	An operator's manual is required for each pipeline system, which should be reviewed and updated annually. The manual must include procedures for: - Normal operations (start-up & shutdown) - Maintenance, - Responding to abnormal operations, and - Checking variations (in pressure, temperature, flow, etc.) from normal operations.
	Emergency Response Training	Training should cover emergency procedures, hazardous materials characteristics, recognizing emergency conditions, and controlling accidental releases. The training program should be reviewed annually and updated if necessary.
	Maximum Operating Pressure	The maximum operating pressure for a pipeline is determined by the internal design pressure of the pipe, design pressure of other components, and testing pressures. Pressure cannot exceed 80% of test pressure or the highest operating pressure for 4 or more continuous hours. During surges, pressure cannot exceed 110% of operating pressure limit. Adequate controls and protective equipment must be provided to control pressure within the limit.
	Overpressure Safety Devices and Overfill Protection Systems	Pipeline operators must inspect and test pressure limiting devices, relief valves, pressure regulators, or other item of pressure control equipment as well as overfill protection systems annually (every 15 months at maximum).
	Underwater Inspection (Gulf of Mexico)	Periodic inspections must be conducted, and if a pipeline poses a hazard, (1) the National Response Center must be notified within 24 h, and (2) the location must be marked in accordance with 33 CFR Part 64 no later than 7 days after discovery.
	Inspections of Pipelines in Areas Affected by Extreme Weather and Natural Disasters	Pipeline operators must inspect affected facilities within 72 h to detect any safety issues. If unable to inspect, they must notify the appropriate authority.
	Public awareness	In alignment with API RP 1162, develop and implement a written program for ongoing public education on attributes and characteristics of the pipeline, possible hazards, and reporting and emergency procedures.
	Leak Detection	An effective leak detection system is required. Operators must evaluate the system's capability and modify it as needed considering factors such as pipeline length and size, nearest response personnel, leak history, etc. Computational pipeline monitoring (CPM) leak detection system must be designed in accordance with the requirements in API RP 1130.
Subpart H (Minimum Corrosion Control Requirements)	External Corrosion	• All buried or submerged pipelines must have external coatings and cathodic protection for corrosion control. • External coating: designed to mitigate corrosion, have sufficient adhesion, be ductile, strong, and support cathodic protection. • Cathodic protection: performed in compliance with NACE SP 0169. Buried or submerged pipelines must be

(*continued on next page*)

Table 2 (*continued*)

Subpart (Focus)	Topic	Details
		electrically isolated from other metallic structures unless they are cathodically protected as a single unit. • Protected pipelines must be tested at least once a year, while unprotected pipes must be reevaluated for corrosion every three to five years.
	Internal Corrosion	Pipeline must be mitigated against internal corrosion by investigating the corrosive effect and using corrosion inhibitors in sufficient quantities. Monitor the effectiveness of inhibitors using coupons, examining them at least twice a year.
	Atmospheric Corrosion	Offshore pipeline operators must inspect pipelines that are exposed to the atmosphere for evidence of atmospheric corrosion at least once every calendar year. If atmospheric corrosion is found during an inspection, the operator must provide protection against it.
	Procedures Against Corroded Popes	• Replace the pipe in case of: - General Corrosion with remaining wall thickness less than required for the maximum operating pressure. - Localized corrosion pitting that might result in leakage. unless the operator reduces maximum operating pressure or repairs the pipe using a reliable method. • If pipe wall is not penetrated, two procedures can be used to determine the strength of corroded pipe based on actual remaining wall thickness, which are ASME/ANSI B31G and PRCI PR-3-805 (R-STRENG). • **For onshore pipelines,** if direct assessment is used to evaluate the effects of external corrosion or stress corrosion cracking, NACE SP0502 and NACE SP0204–2008, respectively, must be followed.

requiring compliance plans, and placing additional safety requirements on operators (PHMSA, 2023b).

3.1.3. *Department of Interior (DOI)'s Bureau of Safety and Environmental Enforcement (BSEE)*

Considering the IIJA, the Bureau of Safety and Environmental Enforcement (BSEE) is currently developing regulations pertaining to offshore CO_2 pipeline transport for carbon capture and storage (CCS) purposes. While BSEE does not currently possess specific codes or standards for this purpose, it is actively working to establish them in accordance with the IIJA (Grauberger et al., 2022). Moreover, the BSEE does have regulations and guidelines for the design, construction, and operation of offshore pipelines in the Outer Continental Shelf (OCS) that would apply to CO_2 pipelines for CCS, including 30 CFR Part 250 Subpart J - Pipelines and Pipeline Rights-of-Way and Subpart S - Safety and Environmental Management Systems (SEMS).

Subpart J establishes the minimum criteria governing the design, installation, testing, inspection, and operation of pipelines located on the OCS. Meanwhile, Subpart S mandates the implementation of a Safety and Environmental Management System (SEMS) program to effectively address safety and environmental hazards in both new and existing facilities, including offshore pipelines. Details of the topics and guidelines discussed under these subparts are discussed in Table 3.

3.2. *Europe*

3.2.1. *The European Union (EU) directives*

EU has established several directives for the transportation of CO_2 through pipelines, which set out specific requirements for the design, construction, operation, and maintenance of pipelines. These directives also include provisions for emergency response planning and risk management.

Directive 2003/87/EC of the European Parliament, also known as ***EU Emissions Trading System (ETS) Directive***, establishes a scheme for greenhouse gas emission allowance trading within the European Community. This directive applies to CO_2 pipeline transport as it establishes rules for emissions trading, including the issuing of emissions allowances and the reporting of emissions data.

The Gas Directive (2009/73/EC) and the Offshore Directive 2013/30/EU set out specific requirements for the safe operation of offshore oil and gas installations, covering a range of areas, including the design, construction, operation, maintenance, and emergency response planning. Similar guidelines may apply to CO_2 pipelines; however, as discussed earlier, there are distinct differences between natural gas and CO_2 that require specific treatment and guidance to ensure their safe transport and handling.

The CCS Directive (2009/31/EC) establishes a legal framework for the safe and environmentally sound geological storage of CO_2 (European Union, 2009). It requires that CCS projects undergo a comprehensive risk assessment, including an assessment of potential impacts on human health and the environment. The directive also sets out requirements for monitoring, reporting, and verification of CO_2 storage sites, as well as liability and financial assurance provisions. The CCS directive specifies that the composition of the CO_2 stream must predominantly comprise CO_2, without any inclusion of waste or other materials for disposal. While there may be incidental substances related to the CO_2 source or capture process and trace substances for monitoring purposes, their concentrations must remain below levels that could cause harm to the storage site, transport infrastructure, environment, or human health.

3.2.2. *The European Commission guidance documents*

The European Commission has released four Guidance Documents to provide stakeholders with information on the implementation of the CCS Directive (2009/31/EC) (European Commission, 2011, 2012a–c). Of particular relevance to offshore CO_2 pipeline transport are sections 3.3, 3.4, 3.6, 3.8 and 4.3 of Guidance Document 2. These sections specifically address the impacts on pipelines, as well as the potential health and environmental hazards associated with the CO_2 stream with focus on its composition. They conclude that the Competent Authority (CA) should carefully manage composition of the CO_2 stream to ensure the following.

1. The integrity of the storage site and the pipeline infrastructure is not compromised.
2. There is no significant risk to the environment or human health.
3. Compliance with the relevant EU legislation is upheld.

Table 3
30 CFR Part 250 subparts J and S focus and regulatory details.

Subpart (Focus)	Topic	Details
Subpart J (Pipelines and Pipeline Rights-of-Way)	Design	• Internal pressure: same as required by PHMSA's Subpart C Title 49 of the CFR, Part 195 • Valves/flanges/fittings: same as required by PHMSA's Subpart C Title 49 of the CFR, Part 195. • Risers: governed by API RP 2RD. • Corrosion protection (for at least 20 years): - External protective coating, and - Cathodic protection system • Consider environmental factors such as water currents, storm or ice scouring, soft bottoms, mudslides, earthquakes, subfreezing temperatures, and others. • Maximum allowable operating pressure (MAOP): same as required by PHMSA's Subpart F Title 49 of the CFR, Part 195
	Installation	• Burial: in water depths of less than 200 feet, must be buried to a depth of at least 3 feet. • Cover: valves, taps, tie-ins, capped lines, and repaired sections that could be obstructive must have at least 3 feet of cover. • Separation from obstructions: minimum of 18 inches.
	Pressure Testing	• At least 8 h for installation, relocation, uprating, and reactivation after being out-of-service for more than 1 year, and at least 2 h after repairs. • At a pressure of at least 1.25 times the MAOP. • Must not exceed 95% of the specified minimum-yield strength of the pipeline. • Temperature and pressure recorders, along with deadweight test readings, must be used, and no observable leakage is allowed during testing
	Safety Equipment	• Flow Safety Valve (FSV): - Incoming pipelines to a platform/ subsea tie-in • Automatic Shutdown Valves (SDV) - Incoming/Crossing pipelines boarding a platform, • High- and Low-Pressure Sensors (PSHL) - Set not to exceed 15 percent or 5 psi, whichever is greater, above and below the normal operating pressure range. - Connected to the automatic- and remote-emergency shut-in systems. - Departing/Bidirectional pipelines • Block Valves: - Incoming/Bidirectional pipelines to a subsea tie-in, • Comply with API RP 14C
	Inspection	• For signs of leakage as prescribed by the Regional Supervisor (at least every 2 years). • Pipelines with a less than 20 years (or unknown) life expectancy must be inspected annually.
Subpart S	Safety and Environmental Management Systems (SEMS)	The program must comply with API RP 75 standards and ensure personnel adherence to policies and procedures. SEMS should include general safety instructions for the following: 1. Hazards Analysis (facility level) and a job safety analysis (JSA) (operations/task level) 2. Management of Change 3. Operating Procedures 4. Safe Work Practices 5. Training 6. Mechanical Integrity 7. Pre-startup Review 8. Emergency Response and Control 9. Investigation of Incidents 10. Auditing in accordance with Center for Offshore Safety requirements COS–2–01, COS-2-03 and COS–2–04 11. Recordkeeping 12. Stop Work Authority (SWA) 13. Ultimate Work Authority (UWA) 14. Employee Participation Plan (EPP) 15. Reporting Unsafe Working Conditions

These sections also discuss pipeline leakage and recommended detection/monitoring approaches. Some details of the instructions discussed under these sections are summarized in Table 4.

3.3. *Australia*

3.3.1. *Regulatory authority*

In Australia, Commonwealth CCUS laws exclusively pertain to offshore areas under the Commonwealth's jurisdiction. Conversely, state and territory CCUS laws govern both onshore and offshore projects within their respective jurisdictions. Hence, offshore CO_2 pipeline operations are typically conducted collaboratively with both the Commonwealth and state/territory governments, ensuring coordination between the two levels of government. In this article, we will focus on the regulations set forth by the Commonwealth.

3.3.2. *Commonwealth laws*

The Environment Protection and Biodiversity Conservation Act of 1999 (EPBC Act) applies nationwide and requires companies to undertake environmental assessments before undertaking CO_2 pipeline transport for CCUS purposes. This assessment must identify and address potential environmental impacts on land, water, and biodiversity. It also applies to Commonwealth waters (i.e., the waters outside of state and territory jurisdiction). In Commonwealth waters, companies must also comply with ***the Offshore Petroleum and Greenhouse Gas Storage Act (OPGGSA) of 2006***, which regulates offshore petroleum and greenhouse gas storage activities. In addition to regulating storage, the OPGGSA requires companies to prepare safety cases, environmental plans, and other documents to demonstrate that their pipeline operations are safe and environmentally responsible. The OPGGS Act established the National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA), which is responsible for administering this act. Moreover, under ***the National Greenhouse and Energy Reporting Act (NGERA) of 2007***, certain corporations are required to report their greenhouse gas emissions, including CO_2 emissions, to the government. Finally, ***the Clean Energy Regulator Act (CERA) of 2011*** was enacted by the Australian Government to establish the Clean Energy Regulator (CER) as a statutory authority responsible for administering NGERA and enforcing various programs and regulations related to clean energy and carbon reduction. This includes monitoring and reporting CO_2 emissions and ensuring compliance with safety and environmental standards for CO_2 pipelines used in CCUS projects.

Table 4
European Commission's guidance document 2's foci and details to comply with the CCS Directive.

Section (Numbered from source)	Topic	Details to comply with the CCS Directive
3.3/3.4/3.8 CO_2 Streams Composition	Composition Evaluation	• Establish composition standards for CO_2 streams, subject to approval by the CA. • Assess impurities hazards on: - Pipeline safety: corrosion, hydrate formation, and flow assurance difficulties. - Human/Environmental safety: leakages • Evaluate impact of tracer/monitoring substances. • Optimize stream composition. • Conduct risk assessments, considering start-up and shut-down periods. • Modify pipeline materials selection and possibly its thickness. • In cases of significant irregularities in stream composition, take corrective actions.
	Streams from Different Processes	• Assess the hazards of blending streams from different sources.
3.6 Pipeline Impacts	Corrosion Impacts Hydrate Formation•	• Water content limit: - Literature value varies: 50–640 ppm (by mol) −250 ppm, in the presence of moderate levels of other impurities, as they lower the solubility limit. −160 ppm, under choke conditions (-2 °C & 50 bar). - Have safety margins (2 for normal operations) between the maximum allowable water content and the calculated minimum water content that may cause water droplets. - If lower temperatures and pressures are foreseen or high concentrations of impurities, the safe level may need to be further reduced. - Maintain the CO_2 stream well below the critical temperature of 31 °C during compression using intercoolers. • Control: - Dewatering and continuous water-monitoring. - Do not use ammonia for hydrate prevention due to the potential for corrosion and for forming solid ammonium carbonate when reacting with CO_2. • Consider pressure and temperature variations, especially during commissioning, re-start, or upset conditions.
4.3 Monitoring Methods	Pipeline Leakage	• Leak detection: computational pipeline monitoring (CPM) • Use a risk-based approach to decide on gas detectors. • Monitoring water content: use a moisture analyzer instead of a dew point measurement.

3.3.3. *Regulatory guiding principles*

The Australian Regulatory Guiding Principles establish a unified and consistent regulatory framework for CCUS at the national level (MCMPR, 2005). Section 5.3 of the document addresses CO_2 pipeline transportation and provides recommendations, including.

1. Utilizing the Australian Standard for oil and gas pipelines Australian/New Zealand Standard (AS/NZS) 2885, which is endorsed by all Australian governments and applies nationwide since 1994, for the transportation of CCUS streams via pipelines. This Standard outlines requirements for the design and construction of steel pipelines.
2. Modifying and expanding existing government regulations concerning environmental protection and occupational health and safety (OH&S) for pipelines operating in similar conditions to those used in CCS projects. These amendments should explicitly extend the current pipeline regulatory framework to encompass CCS pipelines, ensuring comprehensive coverage.

3.3.4. *Safety case legislation*

As previously mentioned, under the OPGGSA, CO_2 pipeline operators are required to prepare a safety case and submit it to NOPSEMA for evaluation. The safety case is a systematic and structured approach that outlines the hazards associated with the company's activities and the measures that have been put in place to manage those hazards and ensure the safety of workers, the public, and the environment. NOPSEMA assesses the safety case against the requirements outlined in the OPGGSA and applicable validation criteria to determine acceptance or rejection. Upon acceptance, the operator assumes responsibility for operating the facility in accordance with the safety case, conducting periodic reviews, and updating the safety case as necessary.

3.3.5. *Australian/New Zealand standard (AS/NZS) 2885*

The AS/NZS 2885 "Pipelines - Gas and liquid petroleum" is a mandated Australian standard that provides guidelines for the design, construction, testing, operation, and maintenance of pipelines transporting hydrocarbons. The standard was tailored to be used for transporting CO_2 for CCUS purposes in Australia (Australian Limited, 2015). Although the AS/NZS 2885 is effective in the planning and early design stages, it falls short when it comes to detailed design and operation due to its omission of a crucial aspect: risk management for CO_2.

3.4. *Other jurisdictions*

3.4.1. *China*

China is the largest emitter of CO_2 in the world, accounting for approximately 30% of global emissions, which has pressured it to transition into a low-carbon economy (Shan et al., 2020). In China, it is evident that government intervention plays a paramount role in driving the development of CCUS initiatives (Jiang and Ashworth, 2021). The country's fundamental policy framework is the Five-year Plan (FYP), which serves as a comprehensive roadmap for economic and social development over a five-year period. The integration of CCUS technology into the FYPs began with the 12th FYP for National CCUS Technology Development in 2013 (MOST, 2013). China's government has issued guidance documents promoting CCUS development, including the Notice on Promoting CCUS Demonstration, the Industrial Green Development Plan (2016–2020) and the 13th Five-Year Work Scheme on Greenhouse Gas Emissions Reduction (IEA, 2020b). In May 2019, China released an updated roadmap for CCUS technology development (Sandalow et al., 2022). By 2030, they aim for industrial applications and long-distance onshore pipelines. By 2050, extensive deployment of CCUS technology is targeted, with multiple industrial hubs across the country.

In China, CO_2 is currently primarily transported via tanks rather than pipelines in most projects. The Ministry of Industry and Information Technology (MIIT) of China has issued a standard, SH/T3202, which provides recommended specifications for engineering CO_2 pipeline transportation. This standard applies to the design of new, rebuilt, or expanded onshore CO_2 pipeline projects (MIIT, 2018). However, China's current regulatory framework for CCUS is considered inadequate as it lacks enforceable legal provisions such as dedicated laws or regulations specifically addressing CCUS (Jiang et al., 2020; Zhang, 2021). In

September 2023, China adopted the GB/T 42797-2023 standard for pipeline transportation systems. This standard, largely derived from ISO 27913:2016, has been tailored to align with Chinese standard system requirements and local technical terminology. Section 6.2 delves into the discussion of relevant ISO standards.

3.4.2. *The Middle East*

In the Middle East, demand for CO_2 for EOR and efforts to decarbonize the refining and petrochemical sectors drive CCUS adoption. Two large-scale CCUS facilities operate in Saudi Arabia and the United Arab Emirates, linked to natural gas processing and steel production, with CO_2 used for EOR. Supporting these facilities, there are two CO_2 pipeline systems in the region, one in the United Arab Emirates (45 km) and another in Saudi Arabia (85 km) (IEA, 2020b).

After a thorough examination of the legal and regulatory frameworks concerning CCUS in the Middle East, it becomes evident that there is a lack of clarity, as no specific laws or regulations are dedicated to CCUS (Zhang, 2021). This lack of clarity extends to aspects such as specifications for CO_2 impurities transported through pipelines. Furthermore, the sensitive nature of regional cooperation in the Middle East presents a significant challenge, particularly in regard to regulations that govern the potential transboundary transport of CO2 through pipelines (Tsai, 2014, 2017).

4. CCUS regulatory gaps

Regulatory gaps regarding the safety aspects are summarized in Table 5 and discussed in the following sections.

4.1. *United States*

PHMSA and BSEE incorporate CO_2 into the pipeline CFR code by including the term "or carbon dioxide" within the definition of "hazardous liquids." However, it is important to note, as stated in Section 2, that while CO_2 does not present the same flammability hazards as conventionally transported hazardous liquids, it still introduces its own distinct challenges and concerns due to its unique characteristics. These characteristics include operating at higher pressures and facing elevated risks of corrosion and ductile running fractures. As a result, the mere extension of existing pipeline regulations to encompass CO_2 pipelines exposes a significant gap in the US regulatory system.

Table 5

Summary of regulatory gaps* in the USA, Europe, Australia, China, and the Middle East (**x**: major gap; **o**: minor gap; √: no gap). A major gap signifies hazards or concerns that remain unaddressed, whereas a minor gap suggests that existing regulations do not adequately cover them (partial coverage of the hazard). No gaps indicates that the regulators have sufficiently addressed the respective concerns or hazards.

*As of August 2023.

Hazards/Concerns		USA	EU	AU	China	ME
CO_2 specific hazards vs oil & gas (hydrocarbons) pipeline		o	o	o	x	x
Dense CO_2 phase hazards	1. CO_2 Liquid-Gas expansion	✓	x	o	x	x
	2. Ductile Fracture Propagation	✓	x	o	x	x
	3. Temperature Drop and Potential Solid Phase Formation during Rapid Depressurization	✓	x	o	x	x
	4. Hazardous emergency operations	✓	x	o	x	x
	5. Sealing Difficulty	✓	x	o	x	x
CO_2 exposure hazards		o	✓	✓	x	x
Impurities hazards	1. Free water hazards - Corrosion	✓	✓	x	x	x
	- Hydrates Formation	x	✓	x	x	x
	2. Equations of state for CO_2 with impurities	x	✓	x	x	x
	3. Impurities Precipitation/mixing different streams	x	✓	x	x	x
	4. Other (toxicity, fatigue, cracking, and others)	x	✓	x	x	x
Offshore-related hazards		o	o	o	x	x
Hazards in reuse of existing pipeline infrastructure (fitness-for-purpose)		✓	x	✓	x	x

Additionally, the prevalent belief that the extensive experience in transporting CO_2 in the United States implies a seamless transition for CCUS initiatives requires a critical examination. This viewpoint necessitates scrutiny due to the presence of impurities in CO_2 captured from fossil-fueled power plants and industrial sources, which have not been previously transported at the expected scale. Although PHMSA and BSEE regulations address the hazards associated with CO_2, they fall short of adequately considering the hazards posed by commonly found impurities, except for corrosion. Not enough consideration is given to potential issues, such as the formation of hydrates, the precipitation of impurities, consequences of mixing different CO_2 streams, the need to modify the EOS to accommodate impurities, and other associated hazards.

4.2. *Europe*

Unlike the US regulations, European directives have acknowledged the significance of considering the unique hazards associated with the composition of CO_2 streams derived from CCUS initiatives. Similar to the directives established for CO_2 storage and composition monitoring/control, there is a pressing need for the EU to develop directives that focus on creating tailored design and operation guidelines, as well as emergency response protocols, specifically catered to CO_2 streams from CCUS sources. Furthermore, the EU currently lacks explicit guidance on the reuse of existing pipeline networks for CO_2 transportation and the associated hazards.

Additionally, the development of CO_2 pipeline policies in the EU faces significant challenges that directly impact the advancement of CCUS projects. Two primary concerns in this regard are the limited availability of public funding and the need for complementary policy instruments to incentivize low-carbon investments (Zhang, 2021). Public funding plays a critical role in supporting the development and deployment of CO2 pipelines. However, the availability of such funding is often constrained, posing a challenge to the implementation of these projects. Moreover, the EU's policy landscape should include complementary instruments that induce low-carbon investment in CO_2 pipelines. While the EU ETS is an important policy instrument for reducing greenhouse gas emissions, its ability to mobilize private investment in CCUS projects may be uncertain due to carbon price volatility. By addressing funding constraints and establishing stable policy mechanisms, the EU can overcome these challenges and create an enabling environment for the successful implementation of CO2 pipeline policies. This, in turn, will support the growth of CCUS projects and contribute to achieving the EU's climate targets.

4.3. *Australia*

Australia, like the USA, advocates for extending the guidelines for transporting hydrocarbons through pipelines to encompass CO_2 transport. In this context, the Australian/New Zealand Standard AS/NZS 2885 serves as a reference. Although this standard provides guidance for pipeline design, installation, operation, and monitoring, it is essential to recognize that CO_2-specific regulations and measures addressing impurities and associated hazards are vital for ensuring the safe and effective transportation of CO_2 in support of CCUS initiatives. Simply adapting existing guidelines may not fully account for the unique characteristics and challenges posed by CO_2, necessitating the development of tailored regulations to guarantee the success of CCUS projects in Australia.

4.4. Other jurisdictions (China and the Middle East)

Despite receiving government support, the regulatory gaps in China and the Middle East regarding CO_2 pipeline transport for CCUS initiatives are significant. There is a notable absence of enforceable legal provisions, including specific laws or regulations dedicated to CCUS. On a positive note, China has recently taken a step forward by adopting a modified version of ISO 27913 in September 2023 to ensure the safe and efficient handling of pipeline transportation systems. In the Middle East, there is still a lack of domestic standards for operating offshore CO_2 pipelines in CCUS projects. Additionally, regulating the transboundary transport of CO_2 through pipelines poses challenges, particularly in the Middle East region.

4.5. Summary of the gaps

Globally, challenges in the regulatory landscape for CO_2 pipelines for CCUS purposes are evident across various regions. In the USA, while efforts have been made to incorporate CO_2 into hazardous liquids' pipeline regulations (PHMSA's 49 CFR Parts 195 and BSEE's 30 CFR Part 250), there is a shortfall in addressing impurities-related hazards expected from capture activities. Australia follows a similar trajectory, advocating for the extension of guidelines designed for hydrocarbon transport, AS/NZS 2885, to cover CO_2, neglecting several CO_2-specific hazards. In Europe, while there's recognition of the unique hazards tied to CO_2 from CCUS projects (EU's CCS Directive, 2009/31/EC), there's a pressing need for dedicated directives and guidelines. In China, the existing regulatory framework for CCUS is considered inadequate, especially lacking specific laws and regulations for CCUS and offshore CO_2 pipelines. Nevertheless, there has been a recent initiative in China to integrate international standards to offer essential guidance for pipeline transportation. The Middle East faces a significant challenge as it lacks relevant and enforceable regulatory frameworks and standards for the safe transport of CO_2 through pipelines, both locally and transboundary. Addressing these regulatory gaps is imperative for fostering safe, secure, and effective CCUS implementation worldwide.

5. International standards and recommended practices for CO_2 pipelines

To address the existing regulatory gaps discussed in the previous sections, relevant standards and recommended practices from renowned organizations like Det Norske Veritas (DNV) and International Organization for Standardization (ISO) are investigated.

5.1. DNV

DNV-ST-F101 "Submarine pipeline systems" is an industry standard that outlines a comprehensive set of requirements and recommendations for the entire lifecycle of submarine pipeline systems. Its primary objective is to ensure a consistent and adequate level of safety through structural assessment. The standard encompasses various key aspects such as safety philosophy framework, target failure probabilities, design basis, design criteria, material selection, corrosion control, line pipe specification, component manufacturing specifications, corrosion prevention, insulation, and more. While DNV-ST-F101 provides a comprehensive set of guidelines for marine and submarine pipelines, it may not address the unique challenges and considerations associated with CO_2 pipelines. Specific guidance on the design and operation of CO_2 pipelines is given through DNV-RP-F104, as discussed below.

DNV-RP-F104 "Design and operation of carbon dioxide pipelines" is a comprehensive recommended practice for the design and operation of CO_2 pipelines (DNV, 2017). The recommended practice is based on international standards and best practices, and it takes into consideration the unique characteristics of CO_2 as a pipeline transport medium.

The guidelines in DNV-RP-F104 cover a wide range of topics, as illustrated in Table 6.

5.2. ISO

ISO has established international standards for pipeline transportation of CO_2, including requirements for pipeline design, construction, and operation. These standards are recognized globally and are used as the basis for many national regulations.

ISO 13623:2017(en) "Petroleum and natural gas industries — Pipeline transportation systems", similar to AS/NZS 2885, can potentially apply to CO_2 pipelines, as it provides guidelines for the design, construction, and operation of control and communication systems for pipelines used in the petroleum and natural gas industries. The standard covers a range of topics related to pipeline control and communication systems, including system design, construction and installation, and operation and maintenance. However, the applicability of ISO 13623 to CO_2 pipelines will depend on the specific requirements of the CO_2 pipeline project and the characteristics of the CO_2 transport medium. While some aspects of the standard may be directly applicable, others may need to be adapted or modified to take into account the unique characteristics of CO_2 as a pipeline transport medium.

ISO 27913:2016 "Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems" outlines further requirements and suggestions beyond existing pipeline standards to account for the transport of CO_2 streams from the capture location to the storage site (ISO, 2017). The main purpose of the standard is to ensure the safe and reliable design, construction, and operation of pipeline transportation systems for CO_2 streams.

It covers metallic pipelines, onshore and offshore pipelines, conversion of pipelines for CO_2 transportation, and transport of both gaseous and dense phases (ISO, 2016). Additionally, it addresses areas including establishing a safety philosophy framework, determining failure probabilities, design criteria, materials selection, addressing concerns regarding corrosion and insulation, and providing guidelines for the installation, testing, operation, and abandonment of pipeline transportation systems. It is designed to complement existing pipeline standards like ISO 13623 and ISO 14692. This standard recognized the lack of data to define a safe operation window for impurities concentration in CO_2 transport (ISO/TC, 2020). It recommends consulting the most up-to-date research during pipeline design.

ISO/TR 27921:2020, entitled "Carbon dioxide capture, transportation, and geological storage — Cross-Cutting Issues — CO2 stream composition," is a technical report developed by ISO/TC 265's Technical Committee (ISO/TC, 2020). Its objective is to provide a comprehensive depiction of the fundamental characteristics of the CO_2 stream post-capture, considering common purification methods. The primary goal of this report is to assess the potential effects of impurities on all elements of the Carbon Capture and Storage (CCS) chain. Special attention is given to the crucial role of monitoring the composition of the CO_2 stream in effectively managing the entire CCS process. Moreover, the report tackles the topic of combining CO_2 streams from different sources prior to transportation or storage, presenting the main benefits, hazards, and operational constraints associated with this practice while offering valuable insights for its efficient and safe implementation. Recommendations from the report include.

1. Online continuous or semi-continuous monitoring: It is crucial to monitor the composition, mass flow rate (as per ISO 27919), temperature, and pressure of the CO_2 stream in real-time. This monitoring should be carried out by knowledgeable operators following standardized operating procedures (SOPs) to mitigate impacts and minimize risks. SOPs ensure reliable and comparable results, considering factors like level of validation, uncertainty, and available alternatives. Accurate monitoring of the CO_2 stream composition plays a vital role in ensuring the proper operation of CCUS activities, reducing the risks of adverse impacts, quantifying

Table 6
DNV-RP-F104 focus and recommended practices details.

Subpart (Focus)	Topic (Numbered from source)	Details
Section 3 (Safety Philosophy)	3.2 Systematic Review of Risks	• Safety evaluations: ISO 13623-Annex A • Hazard identification and risk assessment: ISO 17776, ISO 31000, and NORSOK Z-013. • Risk reduction: ISO 17776 and CO_2 RISKMAN Guidance • Uncertainty due to lack of relevant knowledge/experience shall also be qualified, i.e., overlooking potential hazards or identifying non-credible hazards. • Assess and manage risk to an acceptable level.
	3.3 Risk Basis for Design	• Categorization: DNVGL-ST-F101 recommends classifying CO_2 as category E unless the operator has significant operational experience, in which case it is classified as category C. • Location classes: DNVGL-ST-F101
	3.4 Safety Assessments	• Release: Consider hazards of: - Solid CO_2 particles released should be considered. - Temperature reduction at the leak point. - Foggy cloud formation & consider transient thermos-hydraulic behavior. • Dispersion: - Validate empirical underwater release models and water surface dispersion models for CO_2 in CCUS-scale. - Best compared to an equivalent release of propane (C3H8) due to their similar physical properties.
Section 4 (Concept Development and Design Premises)	4.2 Concept development	• Stream Composition: - Hazards from mixing different CO_2 streams: water dropout due to decreased solubility in the combined stream or detrimental cross chemical reactions. - Water Content: a minimum safety factor of two (2) between the maximum allowable water content and the minimum calculated water content that could cause water-drop under normal conditions. Major source of water entrainment is from the intermediate compressor stages. - Toxic/Hazardous Content: consider combined hazardous effects. - Hydrocarbons: no condensation to occur within the operational envelope of the pipeline.
	4.3 Design premises	• Thermo-hydraulic modelling: - Ensure that the pipeline safely operates at a reduced rate. - Enable pressure surge analysis, water drop-out analysis, simulation of controlled and accidental release scenarios, pipeline shut-in and start-up analysis, pipeline depressurization, and simulation of heat transfer to and from surroundings. - At a minimum, accounts for two-phase single and multi-component fluid behavior under steady-state conditions. - Consider seasonal variations in ambient temperature, as these variations affect the mass density of the CO_2 stream. • Flow assurance: - Heat ingress and pipeline insulation impact the minimum temperature during depressurization. - Hydrate formation for both gaseous and liquid CO_2, considering water content (& dewatering) and the presence of non-condensable components. Do not use ammonia for hydrate prevention due to the potential for forming solid ammonium carbonate when reacting with CO_2. - Consider transient operation and line packing. • Flow coating is not recommended. Proper qualification of coating materials for CO_2 compatibility and decompression scenarios is essential if flow coating is utilized.
	4.4 System Design Principles	• Design/Incidental pressure: ISO 13623 and DNVGL-ST-F101 • Yield strength utilization factor: ISO 13623 for category E fluids or DNVGL-ST-F101. • Pipeline control system: automatically control operating parameters, including P, T, water content, etc., to ensure safe dense phase operation. • Maximum allowable operating pressure (MAOP): design pressure minus the pipeline control system operating tolerance. • Maximum allowable incidental pressure (MAIP): incidental pressure minus the pipeline control system operating tolerance. • Dewatering: - Control hydrate formation and corrosion. - A safety integrity level (SIL) should be defined for the water monitoring system (IEC 61508). • Submerged vent stations: consider pertinent safety and environmental hazards, including high concentrations of CO_2 on the sea surface and the potential acidification of the water column.
Section 5 (Materials and Pipeline Design)	5.2/5.3 Materials selection	• Select materials that are compatible with: - all states of the CO_2 stream.

(*continued on next page*)

Table 6 (*continued*)

Subpart (Focus)	Topic (Numbered from source)	Details
		- Expected impurities (sour service assessment in case of H2S) - low temperatures during depressurization. • Carbon–Manganese steel is suitable for pipelines with controlled water content, while corrosion-resistant alloys (CRA) or internally lined PE liners may be considered for shorter sections or when water content control is insufficient. • Non-metallic materials (Internal and external coatings, seals, lubricants, etc.) should be: - qualified for low-temperature conditions, - resistant to Swelling and explosive decompression. - chemically compatible with CO_2. • Material testing and qualification standards and recommended practices, such as NORSOK M-710, NACE TM 0297–2008 and DNVGL-RP-A203 should be followed.
	5.4 Corrosion	• Internal corrosion: - Consider the presence of by-products. If H2S presents, do sour service assessment based on ISO 15156 and DNVGL-ST-F10 - Control: (1) effective dewatering. (2) Internal polyethylene (PE) liners, considering potential collapse of the PE liner during pressure reduction. (Note) No indication that pH stabilization or corrosion inhibitor mitigate it. - Type 13Cr martensitic stainless steels are typically regarded as highly resistant to CO_2 corrosion as long as the welds undergo proper post-weld heat treatment (PWHT). • External corrosion protection: external coating (qualified for low temperatures) and cathodic protection.
	5.6 Running ductile fracture	• Ensure resistance through fracture control plan: - Consider pipe wall thickness, material properties (fracture toughness and yield strength, transition temperature), and physical properties of the CO_2 composition (saturation pressure and rapid decompression speed). - Reduce stress level. - Use mechanical crack arrestors. • Validate two-curve model (TCM), such as the Battelle TCM, for estimating the arrest pressure for CO_2.
Section 6 (Construction)	6.2 Pre-commissioning	• Pressure testing: strength and leak testing per DNVGL-ST-F101, ensure effective drying after. • Drying: to a dew point of −40 °C to −45 °C (at ambient pressure).
Section 7 (Operation)	7.2 Commissioning	• Consider low CO_2 temperatures and solid CO_2 formation during initial filling.
	7.4 Contingency Plans	• Establishing contingency plans and emergency response procedures that consider CO_2 characteristics. • Monitor CO_2 and O_2 levels during pipeline repair.
	7.5 Operational Controls and Procedures	• Sudden increase/decrease of rate must be performed manually, considering the thermo-hydraulic model. • Shut-in: maintain high pressure to prevent free water or vapor formation. • Depressurization: - avoid it as possible. - ensure the temperature is above the design temperature, and pressure is above the triple point pressure. - Reintroducing dense CO_2 into a pipeline with substantial solid CO_2 should be avoided to prevent rapid sublimation and the resulting significant increase in volume (750 times), which could lead to over pressurization.
	7.7 Inspection	• In-line inspection tool: compatible with pressures and CO_2 phases and impurities.
Section 8 (Re-qualification of Existing Pipelines)	8.3 Re-qualification process	• Must adhere to the same requirements outlined in Sections 3 to 7, similar to those for a pipeline designed exclusively for the transportation of CO_2.

greenhouse gas storage (or emissions) correctly, and facilitating knowledge sharing among CCUS stakeholders and the public.

2. Impurity concentration thresholds: It is cautioned that no general recommendations for impurity contents should be used as guidance. According to ISO 27913:2016, the maximum concentration of a single impurity is dependent on the presence and concentration of other impurities. Therefore, concentration thresholds are case-specific and require optimization for the entire CCUS process, taking into account safety, environmental protection, costs, and energy demands.
3. Mixing of CO_2 streams: When combining or mixing CO_2 streams, it is important to consider that additional or different chemical reactions may occur based on the composition and flow rates of the combined CO_2 streams. Specific assessments are necessary to identify potential hazards, especially during modifications in mass flow rate or CO_2 stream composition that can arise from intended or unintended (re-)start or shutdown of CO_2 emitters and CO_2 stream flows.
4. Predictive modeling: Developing predictive models that can anticipate relevant geo-technical reactions would be beneficial. This would allow for potential adjustments to the CO_2 stream composition if necessary.

6. Conclusions and recommendations

This study performed a comprehensive examination to analyze the existing regulations for CO_2 transportation pipelines for offshore CCUS purposes in the United States, Europe, Australia, China, and the Middle

East from a safety perspective. The evaluation has been made considering distinct hazards (e.g., dense phase of CO_2, exposure risks, impurities, and repurposing existing pipelines) that can be faced during offshore CCUS CO_2 transportation. Throughout the investigation, significant regulatory gaps were noticed. The current regulations in the United States and Australia inadequately address the specific challenges posed by CO_2 pipelines. Both countries primarily advocate for extending existing hydrocarbon guidelines with minor modifications to encompass CO_2 transport. In Europe, while there is recognition of the unique hazards associated with CO_2 streams from CCUS, there is a pressing need for dedicated directives and guidelines pertaining to pipeline design, operation, and addressing funding constraints while stimulating low-carbon investments. Other jurisdictions, China and the Middle East, lack relevant enforceable regulatory framework, that control safe CO_2 pipeline local or transboundary transport.

Based on our previous discussions, we recommend the following to bridge regulatory gaps.

- International harmonization: promote international harmonization and coordination in regulations to ensure responsible deployment of CCUS projects. Collaborative efforts will help establish consistent and effective standards for the safe implementation of CCUS initiatives worldwide.
- Utilizing US experience with caution: leverage the United States' experience with CO_2 pipelines, primarily focused on Enhanced Oil Recovery (EOR), to gain valuable insights for developing CO_2-CCUS specific regulations. These regulations should address all the hazards associated with CO_2 pipelines for CCUS initiatives, as outlined in Section 2.
- Repurposing existing pipelines: establish guidelines that provide appropriate measures to ensure the feasibility (fitness for service) and safety of repurposing existing pipelines for CO_2 transport. Such guidelines should consider the unique characteristics and challenges posed by CO_2, including impurities and associated hazards.
- Appropriate CO_2 quality: To ensure the durability and integrity of the transport infrastructure for CO_2 projects, it is recommended to incorporate regulatory frameworks guidelines from initiatives like DYNAMIS (De Visser et al., 2008), IMPACT (Lilliestråle et al., 2014), or NTEL (Shirley and Myles, 2019) that provide appropriate CO_2 quality recommendations.
- Effective monitoring and modelling: regulations should require continuous monitoring of CO_2 pipelines, including composition, flow rate, temperature, and pressure, through standardized procedures (e.g., ISO 27919, ISO 27913, DNV-ST-F101) to ensure reliability and risk management and mitigation. These monitoring results can be used to assess dynamic quantitative risk, which can be further utilized to assess dynamic safety. The regulations should ensure validation of available models for CO_2, including pipeline flow capacity, impurity interactions (such as free water phase formation, solid deposition, or corrosion), and release rate and dispersion, as a prerequisite to operation. Finally, supporting the application of digital twins (DT) for predicting the dynamic behavior of CO_2 pipelines through monitoring and predictive modelling can help achieve high reliability, availability, and maintainability of the system.
- Safety Case legislation: introduce safety case legislation, similar to the requirements in Australia, in all jurisdictions, including the USA. This legislation will help outline the hazards associated with CO_2 pipelines and detail the measures implemented to manage those hazards, ensuring the safety of workers, the public, and the environment.
- Incorporating established standards: incorporate internationally recognized standards such as ISO 27913 and recommended practices such as DNV-RP-F104 into the regulations. These standards provide valuable guidance on various aspects of CO_2 pipeline design, operation, and safety and can enhance the effectiveness and consistency of regulatory frameworks. It is noteworthy to mention that China has recently adopted the GB/T 42797-2023 standard, a modification of ISO 27913, to guide Chinese pipeline transportation systems.
- Transboundary CO_2 transit: develop intergovernmental regulations that deal with CO_2 pipelines crossing different jurisdictions.

Implementing these recommendations can strengthen the regulatory framework for offshore CO_2 pipelines, promote safe practices, and support the successful deployment of CCUS projects on a global scale.

CRediT authorship contribution statement

Ahmed Hamdy El-Kady: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Md Tanjin Amin:** Data curation, Formal analysis, Methodology, Supervision, Writing – review & editing. **Faisal Khan:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – review & editing, Funding acquisition. **Mahmoud M. El-Halwagi:** Formal analysis, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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