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A systematic review of key challenges of CO_2 transport via pipelines

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A B S T R A C T

Transport of carbon dioxide (CO_2) via pipeline from the point of capture to a geologically suitable location for either sequestration or enhanced hydrocarbon recovery is a vital aspect of the carbon capture and storage (CCS) chain. This means of CO_2 transport has a number of advantages over other means of CO_2 transport, such as truck, rail, and ship. Pipelines ensure continuous transport of CO_2 from the capture point to the storage site, which is essential to transport the amount of CO_2 captured from the source facilities, such as fossil fuel power plants, operating in a continuous manner. Furthermore, using pipelines is regarded as more economical than other means of CO_2 transport

The greatest challenges of CO_2 transport via pipelines are related to integrity, flow assurance, capital and operating costs, and health, safety and environmental factors. Deployment of CCS pipeline projects is based either on point-to-point transport, in which case a specific source matches a specific storage point, or through the development of pipeline networks with a backbone CO_2 pipeline. In the latter case, the CO_2 streams, which are characterised by a varying impurity level and handled by the individual operators, are linked to the backbone CO_2 pipeline for further compression and transport. This may pose some additional challenges.

This review involves a systematic evaluation of various challenges that delay the deployment of CO_2 pipeline transport and is based on an extensive survey of the literature. It is aimed at confidence-building in the technology and improving economics in the long run. Moreover, the knowledge gaps were identified, including lack of analyses on a holistic assessment of component impurities, corrosion consideration at the conceptual stage, the effect of elevation on CO_2 dense phase characteristics, permissible water levels in liquefied CO_2, and commercial risks associated with project abandonment or cancellation resulting from high project capital and operating costs.

1. Introduction

1.1. Background

The latest Intergovernmental Panel on Climate Change (IPCC) report revealed that anthropogenic greenhouse gas emissions have remained the dominant cause of global warming and climate change since the 1950s, and warned that this trend will continue to intensify if anthropogenic CO_2 emissions are not abated [1]. Similarly, one of the key outcomes of the COP21 agreement is to keep the mean earth temperature below 2 °C above pre-industrial levels and a further commitment to decrease it to below 1.5 °C by 2050 [2]. Knoope et al. [3] reported that to mitigate drastic climate change, global CO_2 emissions should be cut by 50–85% compared to 2000 emission levels. Yet, the worldwide emissions from combustion of fossil fuels climbed to an all-time high of 34 $GtCO_2$ in 2011 [4]. Furthermore, 32 $GtCO_2$ was emitted in 2015, as reported by Kennedy et al. [5], showing a partial decoupling between the growth in global CO_2 emissions and that of the global economy [6]. It has been also reported that reduction in the CO_2 emission will put a ceiling on the mean earth temperature increase of between 2 and 2.4 °C [7–9].

Importantly, the power sector of 2050 is expected to rely primarily on renewable energy sources (RES), with support from fossil fuel power generation with CO_2 capture and storage (CCS), and nuclear power plants [10]. However, differences in operating patterns, and hence interaction between these technologies, will affect the operation of the energy network [11,12]. Although CCS is expected to impose significant efficiency and economic penalties [13], and cannot be perceived as an ultimate solution to climate change, its integration to the fossil fuel power plant fleet will act, at least, as a bridge to a clean, reliable and sustainable energy supply [14].

Different countries continue to strike a balance between the need to mitigate climate change by reducing CO_2 emission and utilisation of fossil fuels for power generation and industrial processes. For this

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reason, fossil fuels constitute a substantial share in the global energy mix [15–19]. Obviously, there is some tension between the two views on the future shape of the global energy system. One is advocating the necessity to cut CO_2 emissions and the other promotes continued operation of fossil fuel power plants and carbon-intensive industrial processes. In the latter case, it is considered that these carbon-intensive processes are imperative for the maintenance of both the competitive economies and a high living standard [20–26].

With the continued consumption of fossil fuels, considerable and continuous reduction in the amount of CO_2 emission from power and industrial plants can be achieved through CCS technology [27–30]. The CCS chain has been applied for enhanced oil recovery (EOR) for many years, but its application for climate change mitigation has only been considered recently [31]. In the CCS chain, CO_2 is captured from large-scale emitters, such as fossil fuel power plants, using various CO_2 capture and separation technologies, compressed and purified, and finally transported to a storage site, where it is injected underground and usually stored in a depleted oil and gas reservoir or deep saline aquifer for a long period of time. Depending on the CO_2 phase, its transport can be carried out via a pipeline (dense phase) or by trucks, rail, and ships (liquid phase) (Fig. 1).

The approach employed in most CCS demonstration projects to date, such as the Boundary Dam, Petra Nova, and ROAD projects, is mainly based on point-to-point transport. The exceptions are the projects that utilise existing pipelines, including in oil and gas or EOR pipelines. EOR is a process that has been in use for decades to improve hydrocarbon recovery from oil reservoirs. In this process, high-pressure CO_2 is injected into the reservoir to increase its pressure, thereby improving its hydrocarbon yield.

Importantly, transport of CO_2 via pipelines has a number of advantages over other means of CO_2 transport, including transport by trucks, rail, and ships. CO_2 transport to a suitable place for sequestration, in terms of space and secure storage, usually requires the use of pipelines, especially where continuous flow from the CO_2 capture facility is required [33]. Furthermore, pipelines allow transporting a larger amount of CO_2, which could have been captured from a number of point sources, over long distances in a more economic manner compared to other means of CO_2 transport. There are, however, a number of challenges for CO_2 transport via pipelines that must be resolved for successful deployment of CCS systems. Although these challenges are unlikely to prevent complete deployment of the system [21], this means of transport is regarded as a high-risk component of the CCC chain [34,35] (Fig. 2).

1.2. Overview of CO_2 transport via pipelines

Pipeline engineering with reference to hydrocarbon transport has a long history. Namely, there is considerable experience in the field of oil and gas transport, including EOR enhanced oil recovery [16,32,36]. However, transporting CO_2 streams containing impurities, as opposed to pure CO_2 streams, imposes additional challanges. Several studies highlighted that various issues should be considered when it comes to the transport of captured CO_2 containing impurities, such as operating pressure, repressurisation intervals and pipe integrity. This is irrespective of the mode of transport, whether in gaseous, liquid or supercritical phases across a difficult terrain [15,16,32,36–40].

In the US, pure CO_2 is regularly transported via onshore pipelines over long distances [41]. Most of these CO_2 pipelines were designed purposely for EOR [40]. Although some CCS projects consider CO_2 transport from fossil fuel power plants or other industrial sources, the majority of CO_2 that is being transported comes from natural sources [37,42–46]. It has been reported that CO_2 with impurities is transported via pipeline systems in the US and Canada. An example of such system is the 325 km pipeline transporting CO_2 that contains ~0.9% hydrogen sulphide (H_2S) from a North Dakota, US, gasification plant to Saskatchewan, Canada for EOR. Importantly, such onshore CO_2 pipeline systems have been operational for more than 30 years without any significant incidents caused by corrosion [47,48]. However, there is a lack of extensive experience of CO_2 transport via offshore pipelines over long distances.

Over the last decade, there has been slow but steady progress in the development of large scale industrial processes (LSIP) CCS projects. Several authors have shown insights into the design of pipelines and the operational philosophy for CO_2 streams from some of the first

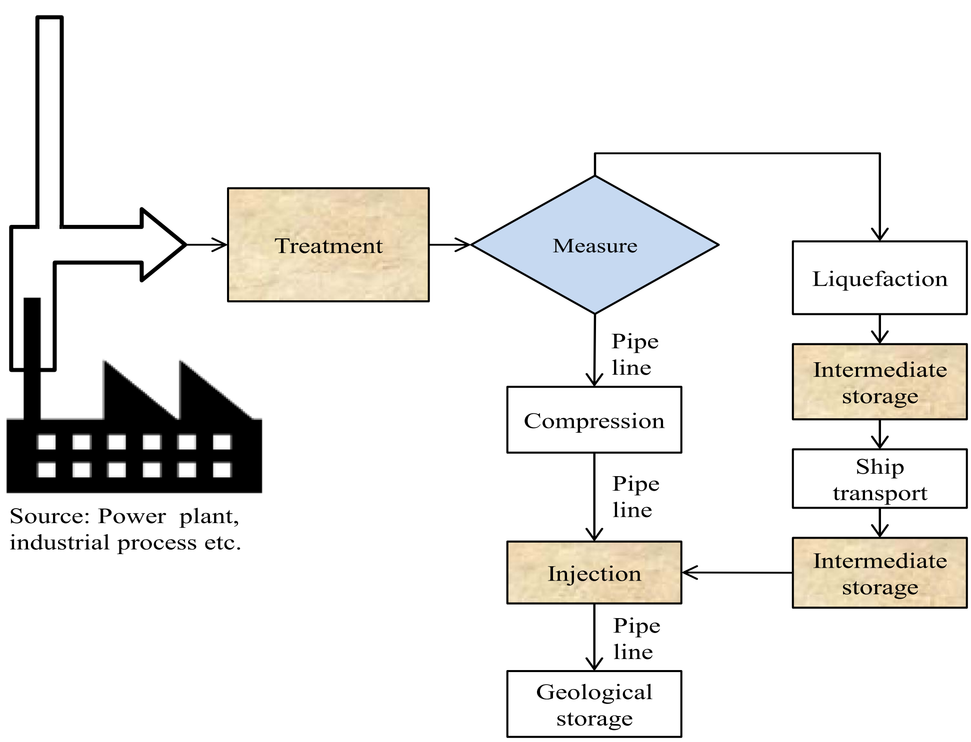

Fig. 1. Liquefaction and compression transport schemes (Adapted from Spinelli et al. [32]. Copyright 2012 The International Society of Offshore and Polar Engineers).

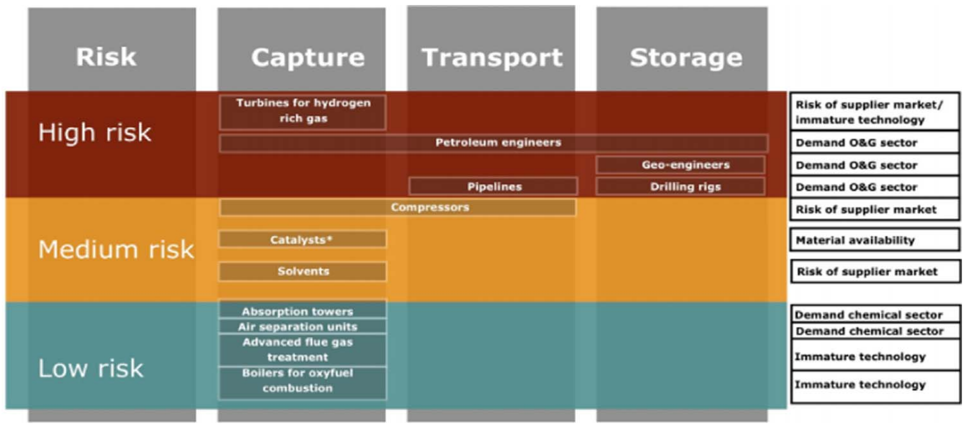

Fig. 2. Potential supply chain constraints (Adapted from International Energy Agency Greenhouse Gas Programme [35]. Copyright 2012 The International Energy Agency).

generation LSIP at active and planned stages [49,50]. There exist seventeen operational industrial-scale CCS projects (Table 1). These projects have the capacity for capturing, transporting and storing 31.2 Mtpa of CO_2. Additionally, it is expected that by 2018, five more LSIP CCS projects will become operational, resulting in a total of 22 CCS projects in operation with the capacity of 40.6 Mtpa of CO_2 [49].

Out of the seventeen LSIP CCS projects currently in operation, two are for power generation, nine are for gas processing, and six are for production of iron and steel, chemicals (fertilisers and ethanol) and fuels (hydrogen). Regarding the type of CO_2 capture process, the power generation projects apply a post-combustion technology, while the gas processing plants use the pre-combustion technology. Also, the separation of CO_2 from industrial processes is applied to the iron and steel, chemical, and hydrogen plants. It is important to mention that none of the LSIPs in operation utilises oxy-fuel combustion technology. Finally, fifteen LSIPs use pipeline as the mode of CO_2 transport.

1.3. Challenges of CO_2 transport via pipelines

Transportation of CO_2 via pipeline faces several technical and economic challenges that range from techno-economic, pipeline design, flow assurance, pipeline integrity, through to safeguarding and safety.

A large amount of CO_2 can be efficiently transported via pipeline if it is in the supercritical (dense) phase. CO_2 in the dense phase is particularly sensitive to the existence of steep elevations and impurities. This does not only impact on the repressurisation distance in the pipeline system, but also affects the fluid dynamics and thermodynamic behaviour of the CO_2 stream, resulting in different flow regimes that alter the pipeline operating conditions [38,51–59]. Detailed consideration is required to get the optimal pipeline sizing, distance before repressurisation, and the number of pumps/size of pumping or compressor stations, as well as their energy requirements [27,60–63].

Presently, the overall construction cost of CO_2 pipelines is high when cost-benefit analysis is taken into consideration [64–66]. A high cost of CO_2 pipeline infrastructure development and implementation makes it necessary to develop a framework for economic evaluation of carbon capture and transport (CCT) chains in terms of total project and operating costs. This framework would be able to assess the cost of both multiple small-capacity pipelines, the single large-capacity pipeline, and the increasing-capacity pipeline [3,67–69]. Furthermore, understanding and addressing corrosion issues in terms of low pH and the effect of corrosion inhibitor in the preservation of the pipeline integrity and life extension are important in relation to the annual operating cost [70–76]. Finally, modelling and simulation of CO_2 transport via pipeline are carried out with a considered objective function to estimate a total annualised cost including investment and operating and maintenance costs [77]. Despite many publications addressing a number of challenges of CO_2 transport via pipelines, so far, there has not been one that has critically reviewed most of these aforementioned issues.

The challenges related to CO_2 transport via pipelines have been addressed by a number of publications that focused on specific subjects, such as identification of risks and estimation uncertainty, cost estimation using techno-economic models, as well as assessment of operation and design aspects of the CO_2 pipeline system [3,78–80]. This review aims at gathering the information on potential challenges of the CO_2 transport via piplelines to identify uncertainties and knowledge gaps that need to be addressed to ensure timely deployment of the complete CCS chain at large scale. The objective is to support reduction of the high level of uncertainty associated with CO_2 pipeline transport resulting from limited information availability. The review attempts to narrow the lack of understanding of what the outcome of CO_2 pipeline projects will be. Information availability enables the industry to evaluate the severity and relevance of uncertainties in order to target the high-uncertainty areas with relevant mitigation strategies. Sizable differences in the techno-economic cost models of CO_2 pipelines reviewed have shown that these differences can translate into projects costing tens of millions of pounds more than initially estimated. This review compares the most relevant techno-economics models such as MIT, Ecofys, McCoy and Rubin, and Ogden with a mathematical simulation tool, Aspen Process Economic Analyser (APEA) [77]. Furthermore, an assessment of the importance of an early introduction of mitigation measures against the risk of corrosion at the project conceptual and implementation stages is evaluated. Finally, the impact of the impurities in the CO_2 stream on the performance of the pipeline system is assessed [24,40,81–87].

2. CO_2 properties in pipeline transport

2.1. Thermodynamic properties

Impurities contained in the CO_2 stream impact on the design and operation of the pipeline system. Therefore, knowledge of the thermodynamic properties with regard to the relationship between pressure, volume, temperature and their combined effects is important. At the triple point (5.2 bar, −56 °C), CO_2 can exist as solid, liquid or gas. However, at temperatures and pressures beyond the critical point (74 bar, 31 °C), CO_2 is in the supercritical phase. Importantly, the presence of impurities in the CO_2 stream alters the cricondenbar, which is the highest pressure on the phase diagram. This affects the operating pressure range and increases the possibility of two-phase flow in the CO_2 transport pipeline [45,88–90]

Experimental data on binary mixtures of CO_2 with other impurities are widely available [91–93]. However, most of the experiments were focused on CO_2/H_2O, CO_2/CH_4, CO_2/N_2, and CO_2/H_2S, whilst only a few involved effects of O_2, SO_2 and Ar that may be present in the CO_2

Table 1
Large-scale industrial CCS projects in operation (Reproduced from Global CCS Institute [49]. Copyright Global CCS Institute 2017).

Project Name	Location	Operation date	Industry	Capture type	Capture capacity (Mtpa)	Transport type	Primary storage
Terrell Natural Gas Processing Plant (formerly Val Verde Natural Gas Plants)	United States	1972	Natural Gas Processing	Pre-combustion capture (natural gas processing)	0.4 – 0.5	Pipeline	Enhanced oil recovery
Enid Fertilizer CO_2-EOR Project	United States	1982	Fertiliser Production	Industrial Separation	0.7	Pipeline	Enhanced oil recovery
Shute Creek Gas Processing Facility	United States	1986	Natural Gas Processing	Pre-combustion capture (natural gas processing)	7	Pipeline	Enhanced oil recovery
Sleipner CO_2 Storage Project	Norway	1996	Natural Gas Processing	Pre-combustion capture (natural gas processing)	1	No transport required (direct injection)	Dedicated Geological Storage
Great Plains Synfuels Plant and Weyburn-Midale Project	Canada	2000	Synthetic Natural Gas	Pre-combustion capture (gasification)	3	Pipeline	Enhanced oil recovery
Snøhvit CO_2 Storage Project	Norway	2008	Natural Gas Processing	Pre-combustion capture (natural gas processing)	0.7	Pipeline	Dedicated Geological Storage
Century Plant	United States	2010	Natural Gas Processing	Pre-combustion capture (natural gas processing)	8.4	Pipeline	Enhanced oil recovery
Air Products Steam Methane Reformer EOR Project	United States	2013	Hydrogen Production	Industrial Separation	1	Pipeline	Enhanced oil recovery
Coffeyville Gasification Plant	United States	2013	Fertiliser Production	Industrial Separation	1	Pipeline	Enhanced oil recovery
Lost Cabin Gas Plant	United States	2013	Natural Gas Processing	Pre-combustion capture (natural gas processing)	0.9	Pipeline	Enhanced oil recovery
Petrobras Santos Basin Pre-Salt Oil Field CCS Project	Brazil	2013	Natural Gas Processing	Pre-combustion capture (natural gas processing)	1	No transport required (direct injection)	Enhanced oil recovery
Boundary Dam Carbon Capture and Storage Project	Canada	2014	Power Generation	Post-combustion capture	1	Pipeline	Enhanced oil recovery
Quest	Canada	2015	Hydrogen Production	Industrial Separation	1	Pipeline	Dedicated Geological Storage
Uthmaniyah CO_2-EOR Demonstration Project	Saudi Arabia	2015	Natural Gas Processing	Pre-combustion capture (natural gas processing)	0.8	Pipeline	Enhanced oil recovery
Abu Dhabi CCS Project (Phase 1 being Emirates Steel Industries (ESI) CCS Project)	United Arab Emirates	2016	Iron and Steel Production	Industrial Separation	0.8	Pipeline	Enhanced oil recovery
Illinois Industrial Carbon Capture and Storage Project	United States	2017	Chemical Production	Industrial Separation	1	Pipeline	Dedicated Geological Storage
Petra Nova Carbon Capture Project	United States	2017	Power Generation	Post-combustion capture	1.4	Pipeline	Enhanced oil recovery

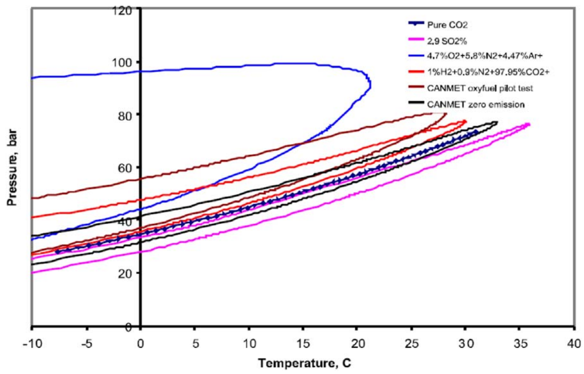

Fig. 3. Phase envelopes for pure CO $_2$ and CO_2 mixtures (Reproduced from Wang et al. [37]. Copyright Elsevier 2011).

stream captured from the fossil fuel power plants. The presence of impurities alters the critical pressure of the CO_2 stream due to the differences in the vapour pressure of various constituent species (Fig. 3), and thus affects the repressurisation distance along the CO_2 transport pipeline. To alleviate the impact of impurities on the possibility of two-phase flow, the operating pressure of the CO_2 transport pipeline needs to be increased and suitable points of repressurisation need to be identified [82,94–102].

2.2. Transport properties

As can be seen in Fig. 4, a small alteration in the working conditions close to the CO_2 critical point can result in a significant change in CO_2 density. For example, the density will double for a decrease of about 10 °C from the critical temperature.

This has both technical and cost implications on the hydraulic system of CCS pipeline systems [82,94,103–105]. To keep the CO_2 stream at the supercritical phase throughout the CO_2 transport pipeline, a pump-based system is recommended for flow repressurisation [33,106,107]. Furthermore, the variation in the pipeline depth can be expected to induce changes in the temperature and pressure of the CO_2 stream, as a result of differences in the surrounding pressure, especially in a marine environment [108].

The design and establishment of CO_2 transport pipelines are dependent on several factors such as viscosity and thermal conductivity, and these influence calculation of its hydraulic properties, as well as its ability to transfer heat [94,109]. Fig. 5 shows that the viscosity of pure CO_2 decreases with increase in temperature and reduces further with the presence of impurities. Importantly, the reduction in CO_2 viscosity increases the efficiency of transport along the pipeline, as the pressure losses throughout the pipeline are reduced.

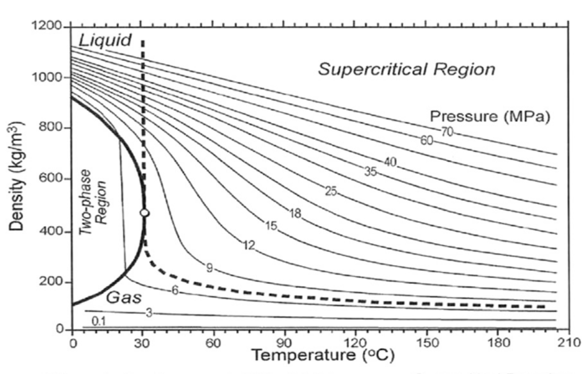

Fig. 4. Variation of carbon dioxide density with temperature (Reproduced from Global CCS Institute [15]. Copyright Global CCS Institute 2013).

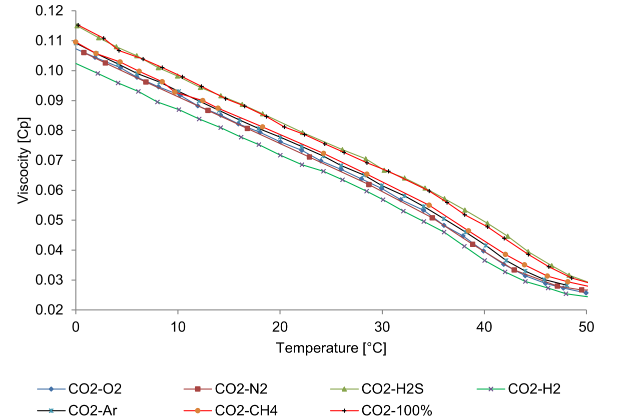

Fig. 5. Effect of impurities and temperature on CO $_2$ stream viscosity at 100bar (Reproduced from Lucci et al. [110]. Copyright International Society ofOffshore and Polar Engineers 2011).

2.3. Impurities in CO_2 streams from CCS

Flue gas is a product of fossil fuel combustion, mainly containing N_2, CO_2, H_2O and O_2 due to excess air in the combustion process. Nitrogen-containing impurities primaly include oxides, such as NO and NO_2, which are collectively known as NO_x. Other potential impurities are oxides of sulphur (SO_2, SO_3) commonly referred to as SO_x, and hydrogen sulphide (H_2S). Thus, the likely impurities in the CO_2 stream separated from coal-fired power plant flue gas are NO_x, SO_x, H_2O, O_2 and H_2S [56,111]. For example, Chapoy et al. [28], identified various gaseous impurities that exist in the CO_2 stream as N_2, O_2, SO_2, CH_4, H_2O, CO, and H_2S. Importantly, operating conditions of CO_2 transport pipelines, such as pressure, differ depending on whether the pipeline is located within the onshore or offshore environment. For this reason, these pipelines need to be managed under stringent control of contaminants [48,112,113]; for example the Dynamis project recommended levels of impurities for CO_2 transport via pipeline as shown in Table 2.

It has been shown that there are significant differences in the amounts and types of contaminants in the CO_2 stream transported by different operators [26,43,113]. Notably, the key influencing factors are the differences in CO_2 capture and separation technology, as well as fuel used at the CO_2 source as shown in Table 3 [41,115,116]. Potential impurities in CO_2 streams captured from a coal-fired power plant using the monoethanolamine (MEA) process were widely examined [43,56,117]. These studies concluded that in order to give a complete account of impurities in the CCS processes, there is need to consider various technologies employed for CO_2 separation and likely impurities to be expected from those technologies [118,119].

Free water (H_2O) in the CO_2 stream is considered as the most undesirable of impurities. This is because it can result in hydrate formation in the CO_2 transport pipeline, as well as react with most of the acidic gas impurities. As a result, the presence of free water can lead to corrosion problems under an enabling environment, for example, a suitable pressure and temperature [43]. Consequently, in the case of transporting CO_2 for EOR, Kinder Morgan adopted certain stringent conditions that help limit the level of contaminants which include: no free water, $<$ 20 ppm H_2S, $<$ 35 ppm SO_x, $<$ 4% N_2, $<$ 5% CH_4 [48,121]. Connell [19] reported a requirement to limit the free water content to $<$ 600 ppm for certain operations. Table 3 shows levels of impurities from different CO_2 capture processes employed in CCS demonstration projects. In the same vein, Thomas and Benson [121] reported that at Sleipner Vest, operated by the Norwegian-based company Statoil in the North Sea, the water content for the first compression state is 3.9%$_{mol}$ and at the third stage it is 0.3%$_{mol}$.

It has been reported that the presence of other impurities, such as CH_4, N_2, H_2O and amines in the CO_2 stream affects the solubility of H_2O [111,121]. Similarly, Yang et al. [122] noted a considerable

Table 2
CO_2 quality recommendation for transport from Dynamis project [114].

Component	Concentration	Limitation
H_2O	500 ppm	Technical: below solubility limit of H_2O in CO_2, no significant cross effect of H_2O and H_2S, cross effect of H_2O and CH_4 is significant but within limit for water solubility
H_2S	200 ppm	Health and Safety considerations
CO	200 ppm	Health and Safety considerations
O_2	Aquifer < 4 vol%. EOR 100–1000 ppm	Technical: range for EOR, because of lack of practical experiments on the effects of O_2 underground
CH_4	Aquifer < 4 vol%. EOR < 2 vol%	Health and Safety considerations
N_2	< 4 vol% (all non-condensable gases)	As proposed in ENCAP project
Ar	< 4 vol% (all non-condensable gases)	As proposed in ENCAP project
H_2	< 4 vol% (all non-condensable gases)	Further reduction of H_2 is recommended because of its energy content
SO_x	100 ppm	Health and Safety considerations
NO_x	100 ppm	Health and Safety considerations
CO_2	> 95.5%	Balance with other compounds in CO_2

Table 3
Expected Impurities from different CO_2 capture technologies [120].

Impurities	Post-Combustion	Oxy-fuel Combustion	Pre-Combustion
CO_2	> 99%	> 90%	> 95.6%
O_2	< 0.1%	< 3%	trace
H_2O	0.14%	0.14%	0.14%
H_2	trace	trace	< 3%
H_2S	trace	trace	< 3.4%
CH_4	< 0.01%	–	< 0.035%
N_2	< 0.8%	< 1.4%	balance
Ar	trace	< 5%	< 0.05%
SO_x	< 0.001%	< 0.25%	–
NO_x	< 0.001%	< 0.25%	–

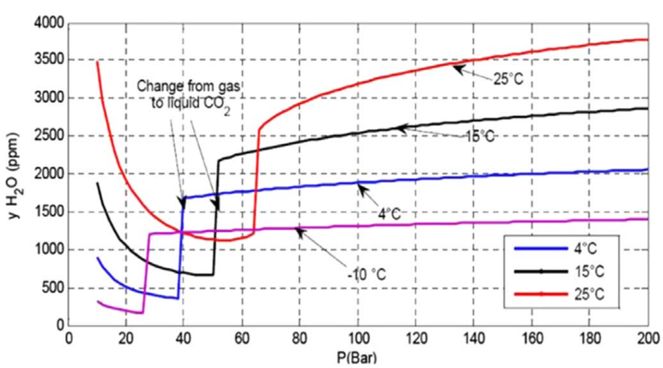

Fig. 6. Solubility of water in pure CO_2 as a function of pressure and temperature (Reproduced from de Visser et al. [126]. Copyright Elsevier 2008).

reduction in water solubility in the liquid phase when 5% CH_4 was added. The presence of free water is significant in CO_2 transport because free water may result in a phase split that, in turn, could trigger hydrate formation and pipe blockage, as well as pipeline corrosion. Moreover, Choi et al. [123] reported that water solubility in CO_2 drops sharply as pressure increases between 50–60 bar and then shows a rapid increase with stabilisation at 60–80 bar. However, it can be observed from Fig. 6 that the CO_2 solubility in water increases considerably after the change of CO_2 phase from gaseous to liquid. Yet, it is essential to understand the difference in the impurities content among different phases during pressure drop, especially when free water is readily available [124]. Unfortunately, as claimed by Ruhl and Kranzmann [125], the impurities in the CO_2 stream are a vital subject with regard to supercritical CO_2 transport that is not totally understood at present.

2.4. Preferred conditions for CO_2 transport

The amount of CO_2 transported via pipeline is highest in the supercritical phase as a result of its high density in this phase in comparison with other phases [28,99,124,127,128]. Furthermore, transport of CO_2 in the supercritical phase is regarded as the most cost effective method of transport from the CO_2 capture point to the point of its utilisation or storage via pipeline [84,96,129–131]. The amount of CO_2 transported per unit volume is maximised in this phase because the supercritical fluid possesses the density of a liquid and the viscosity of a gas (Fig. 7) [45,132].

However, for the captured CO_2 to be transported in the supercritical phase, it has to be compressed to a pressure that is higher than the critical pressure [43,133], in order to prevent two-phase flow in the CO_2 transport pipeline [134]. The condition under which CO_2 is transported to the storage site is primarily dependent upon the availability of the means of CO_2 transport, such as a ship, truck or pipeline. Yet, some authors are of the opinion that the amount of CO_2 to be transported along with the distance between the CO_2 capture facility and storage site should be considered in order to determine the most economically feasible mode of transport [64,135,136]. As identified above, the presence and type of impurities influence the properties of the CO_2 fluid. The power requirement for compression of a CO_2 stream with impurities is higher than that to that for pure CO_2. This is a result of an increase in the critical pressure of the mixture with an increase in the impurities content. In the same vein, it is believed that if the CO_2 stream with impurities reaches a two-phase situation along the pipeline, there will be a larger drop in pressure compared to the pure CO_2 stream [39,45,57,93,137]

Finally, Cole et al. [43] reported that the CO_2 transport pressure

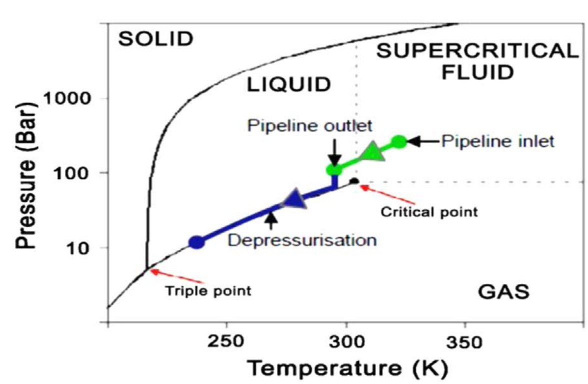

Fig. 7. Operating conditions for CO $_2$ transport pipeline (Reproduced from Cole et al. [43]. Copyright Elsevier 2011).

ranges between 50 to 100 bar. This is consistent with a study by Spycher et al. [138] who found that at the pressures of 50 tob 100 bar, water solubility limit is restricted from 0.3 $\times 10^{-2}$ to 0.4 $\times 10^{-2}$ (mole basis). Commenting on the issue of free water condensation, Thomas and Kerr [44] stated that before the transportation of CO_2 via a pipeline, effort should be made to purify, dehydrate and compress it to a supercritical pressure of 145 bar.

In summary, there has been considerable work carried out on the effect of each impurity on both critical point and pipeline repressurisation distances. Most research on the effect of impurities on the thermodynamics of transported CO_2 is largely based on mono, binary and ternary considerations. For this reason, it is essential to quantify the holistic impacts of CO_2 impurities on transport line performance. This should be conducted at different impurity contents, for example, up to 20%.

3. CO_2 pipeline design

3.1. Pipeline sizing, design and network configuration

Determination of a pipe diameter for a particular project may involve one, two or three steps, in addition to other considerations. These steps include engineering calculation using correlations available in the literature, benchmarking the results with well-tested data from a similar project, and a hydraulic analysis.

In estimating the costs of the CO_2 transport pipeline, consideration of the pipeline diameter is a critical factor [139]. This is because when considering the substantial lengths of CO_2 pipelines, a miscalculation in the optimum diameter can result in incurring an additional capital cost that could have been avoided. In this regard, several sources indicated that consideration of technical factors, such as material roughness, flow rate, pressure drop per unit length, viscosity/density of the fluid and differences in topography, are necessary for determination of the appropriate diameter [84,139–141].

To obtain all the specific requirements for CO_2 pipeline design and sizing, an integrated approach needs to be adopted [68,82,119,140,142]. A reliable method for design of the CO_2 transport pipeline in detail considers the effect of both the environment (soil or water) temperature and CO_2 flow rate on pipeline diameter and length. Furthermore, the design procedure includes hydraulic analysis to estimate the optimum pressure drop for the CO_2 transport pipeline, considering both the obstructions in the pipeline path such as roads, bridges, rails and the insulation. It is claimed that to design an efficient CO_2 transport pipeline network, the distance between the CO_2 source and utilisation or storage site, network topology and CO_2 transportation mode must be considered [16,24,32,140,143–145]. Several sources reported on the maximum distance before booster pump stations for repressurisation to both maintain the CO_2 stream in a supercritical phase and minimise the power requirement [62,86,143,146–149].

Specific issues, such as the phase and the level of impurities of the transported CO_2 stream, make it imperative to take into account the pipeline material, its specifications and pipeline code and standard. These considerations are important in the design and construction phase of the CO_2 transport pipeline [26,84,142,150]. Critical among these specifications are the mechanical properties of the pipeline, such as its toughness and strength, which are directly related to its thickness. Moreover, selection of the proper material for CO_2 transport in the pipeline under supercritical operating conditions is an important design aspect. Most of the past experience with material selection for the pipeline comes from the oil and gas industry, in which, however, the pipelines are operated at lower pressures [151]. However, little is known about the effect of impurities in the CO_2 stream in combination with a high pressure, as encountered in CO_2 transport. The MATTRAN project was commissioned to test metallic materials for CO_2 pipeline transport [76], including X grade steel (X60, X70, and X100). The strength of the materials was tested under various impurities contents. Furthermore, Hashemi et al. [152] tested the mechanical properties of a number of metallic materials subjected to corrosive environment and other non-corrosive degradation mechanisms that can be expected to occur in the CO_2 transport pipeline.

Table 4
Mechanical properties of pipeline-grade steel.

Grade	Yield strength (MPa)	Tensile strength (MPa)	Yield ratio (%)	Elongation (%)	CVN impact energy at 0 °C (J)	CVN impact energy at −50 °C (J)
X60	461	553	83	21	194	187
X80	550	658	84	20	211	200
X100	690	780	88	25	212	197
X120	827	931	89	28	287	231

Micro-alloyed steel materials applied in the advanced CO_2 transport pipeline projects are characterised by a high material strength. This is acquired through a suitable combination of thermal and mechanical treatment, as well as composition of the material resulting in its high quality. Consequently, a realistic balance between the toughness of the material and its strength was obtained. The grade of the steel used in the CO_2 transport pipeline, which can vary from X60 to X120 (Table 4), indicates the minimum required toughness and strength of the material together with Charpy-V-notch (CVN) impact test results, which are applied to the toughness specification.

X100 was used to demonstrate a typical stress-strain curve (Fig. 8). In the demonstration, stress of a round bar tensile specimen for the pipeline was measured to obtain the yield and tensile strengths in the circumferential direction, which were estimated to be 769 and 823 MPa, respectively [153]. This is in fulfilment of the X100 requirements as shown in Table 4.

For large-scale exploitation, where CO_2 is captured from different point sources and transported over long distances for storage, as shown in Fig. 9, the most economical configuration of the CO_2 transport pipeline network must be considered. Based on the experience from the oil and gas industry on the gas gathering networks, scenario C presented in Fig. 9, which assumes that CO_2 is transported via multiple diameter trunk lines, can be considered as the most credible and the least cost-intensive option [143]. It is claimed that in addition to being characterised by reduced pipeline oversizing, scenario C will have lower operating cost by ensuring that the right operating pressure is maintained throughout the pipeline. Therefore, development of the multiple-diameter trunk line is crucial to implementation of CO_2 transport pipeline networks at a relevant scale [64,143,154].

Large-scale deployment of a CCS chain requires a reliable, safe and cost-efficient solution for transport of CO_2 from the capture facility to the permanent storage site [146]. The goal is to develop a CO_2

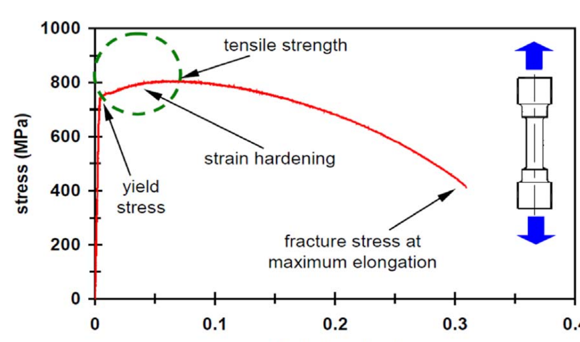

Fig. 8. A typical stress-strain plot for X100 steel (Reproduced from Hashemi et al. [153]. Copyright European Structural Integrity Society 2004).

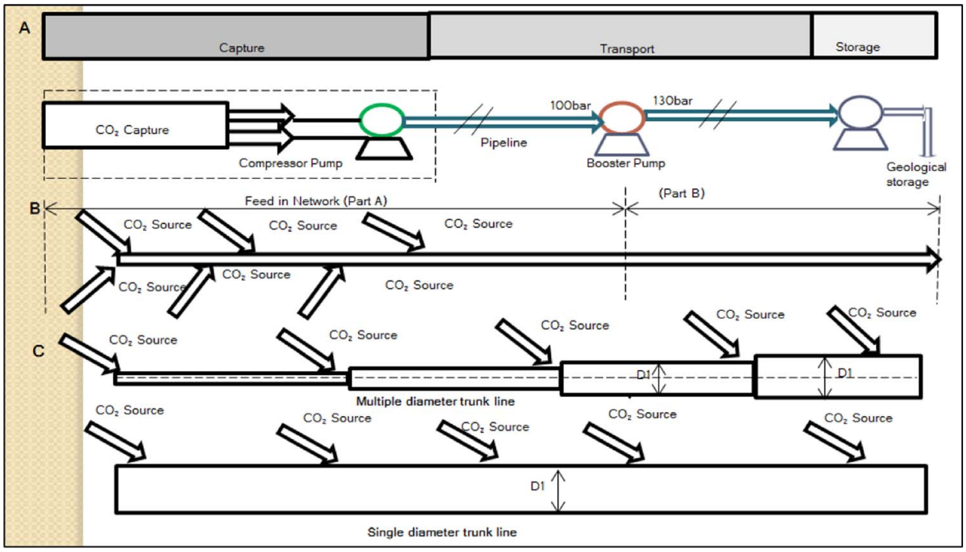

Fig. 9. Schematic of CO_2 transport network configuration (A) with a single CO_2 source connected to a storage site; (B) linking multiple supplies to a trunk line (Part A) that then to a storage site (Part B); (C) with a multi-diameter trunk line connected to a storage site or a single-diameter trunk line connected to a storage site (Reproduced from Chandel et al. [143]. Copyright Elsevier 2010).

transport pipeline that will achieve the satisfactory performance level, while reducing the cost of CO_2 transport to a level acceptable to the operators.

3.2. Construction material

3.2.1. Defect tolerance

It is necessary to consider how the material selected for the CO_2 transport pipeline will act in response to defects at the design stage [110,155]. Such defects could be in the form of ductile fracture propagation, highlighting the importance of pipeline toughness [125,155–162]. However, in the event that the pipeline material does not have adequate toughness to withstand or arrest ductile fracture propagation, there will be a requirement for crack arrestors to be installed (Fig. 10).

Pipeline infrastructure life extension is a prevailing topic in the more mature oil and gas industry and this requirement should form part of the important considerations if reuse and/or repurposing of existing pipelines is adopted for CO_2 transport [164].

3.2.2. Pipeline material fracture propagation

Transport of CO_2 via pipeline in the supercritical phase is a peculiar process. This is because, in the event of any leakage, liquid-to-gas expansion will occur as a result of the Joule-Thompson effect. This will cause deep cooling of the body of the pipeline [165]. The situation may decrease the local toughness of the pipeline material, which could initiate a fracture. Furthermore, the fractured pipe may break and the abrupt expansion of the CO_2 in the supercritical phase would result in a substantial driving force for fracture propagation. A momentum would impact on the broken part of the pipe resulting in a long propagation fracture, especially if the crack arrestors or design conditions were improperly selected [32,115]. For this reason, adequate attention should be given to the design process and the selection of the crack arrestor.

Fig. 10. Crack repair using crack arrestors [163].

3.3. CO_2 pipeline corrosion protection

3.3.1. Laboratory studies on the corrosive effect of impurities in CO_2 pipelines

The importance of corrosion in the CO_2 transport pipeline cannot be underestimated as it would affect the integrity of the pipeline infrastructure [166–169]. A number of studies have been conducted on the subject of impurities and their corrosivity in the transport of CO_2. It has been highlighted that the presence of free water in the CO_2 stream transported via the pipeline should be avoided [74,111,123,124,170–175]. Some of those studies that evaluated the effects of H_2O and other impurities on corrosion in different pipeline material are summarised in Table 5.

There is a correlation between the moisture content in the CO_2 stream and the rate at which the interior wall of the CO_2 transport pipeline corrodes [123,173,176,179]. However, the research on the allowable level of free water in the CO_2 stream that will not cause the pipeline corrosion is limited. There are two views, one saying that the free water content should be limited to as low as 50 ppm, whilst the other indicating that, in the worst case scenario, it should not exceed 600 ppm as above this level corrosion of the pipeline material may occur [121]. In practice, some of these sources recommended that in the presence of a large quantity of SO_2, lower levels of moisture must be considered [43,124,180]. SO_2 naturally was noted to be more acidic when dissolved in water and could intensify the corrosion of the pipeline.

In the same way, Ruhl and Kranzmann [181] reported that in an experiment carried out with CO_2 containing SO_2, NO_2, O_2 and H_2O, the damage resulting from corrosion of the pipeline material increases with a decrease in temperature. It was further claimed that, in accordance with the Joule-Thompson effect, a reduction in the temperature occurs along with a drop in the operating pressure or at a time of total depressurisation of parts of the pipeline. Furthermore, Ruhl and Kranzmann [181] conducted an experiment aimed at identifying

Table 5
Summary of studies evaluating the impact of impurities on the corrosion rates of the pipeline materials [176].

Material	Temperature (°C)	Pressure (bar)	Impurities	Reference
X63 steel, 13Cr Steel	49.95	80	H_2O, O_2, SO_2	Choi et al. [123]
X63 steel	9.98–49.95	100	SO_2, O_2, H_2O,	Dugstad et al. [124]
X70 steel	24	82	H_2O, H_2S,	McGrail et al. [177]
304 SS	265	93–165	Methanol	Xiang et al. [176]
304 L SS	46.85	241.38	Methanol Tetrahydrofurfuryl alcohol	Russick et al. [178]
X60 steel, AISI 4140 steel	3.3–22.22	138	H_2O, H_2S,	Xiang et al. [176]
Carbon steel	31	76	H_2O, MEA	Thodla et al. [162]

critical conditions for severe corrosion in a continuous flow of CO_2 containing SO_2 at ambient pressure. The result showed that at a humidity level of about 1700 ppm with a SO_2 concentration of 650 ppm, no significant corrosion of the material occurred at the time of contact with the continuous flow.

Apart from the formation of carbonic acid in the aqueous phase, which reduces the pH and increases the risk of corrosion, a key challenge of CO_2 transport via pipeline is the presence of impurities such as NO_x, SO_x, H_2S that segregate to the aqueous phase. The segregated aqueous phase forms in situ sulphuric and nitric acids, which cause a further drop in the pH of the solution [170]. When analysing the effect of impurities on corrosion, it was estimated that in a worst-case scenario, the fluid pH could be as low as 3.2, attributed to carbonic acid alone. Likewise, in the event of formation of an isolated water-rich aqueous phase, CO_2 saturates it, producing a pH of approximately 3. Choi et al. [123] gave a clear explanation (both theoretical and experimental) of the mutual solubility of H_2O in CO_2 as well as CO_2 in H_2O.

The manner in which low pH impacts on the pipeline material can be predicted to a degree by the Pourbaix diagram for iron (Fig. 11) [43,182]. The Pourbaix diagram is an illustration of a phase diagram outlining electrochemical stability for different redox states of an element. The water redox line (dotted) is important in the Pourbaix diagram for elements such as Fe. Water in liquid form is stable between the dotted lines. However, below the H_2 line and above the O_2 line, liquid water is unstable relative to H_2 and O_2, respectively. An active metal such as Fe can only show stability below the H_2 line. Therefore, metallic Fe displays instability when it gets in contact with water and undergoes some reactions. Under such conditions, these reactions occur irrespectively of the potential (V) and pH.

3.3.2. Corrosion and pipeline design

In the design and operation of CO_2 transport pipelines, corrosion and material selection are of significant consideration [155,159,176,184,185]. Before material selection is carried out, it is necessary to identify the full stream composition together with the whole range of operating conditions that all the system equipment will be exposed to [70,109,175,186–189]. Again, consideration should be given to the steady state as well as the dynamic excursion situations such as shut-down, start-up, and upsets [117,190,191]. In CO_2 pipeline transport, corrosion and corrosion mechanism considerations take into account: free water phase, CO_2 corrosion and O_2 corrosion of carbon steel, corrosion-resistant alloys, stress corrosion, hydrogen damage, liquid metal embrittlement and degradation of non-metallic parts [78,159,161,192].

3.3.3. Corrosion prevention procedures

There are factors militating against CO_2 pipeline corrosion prevention procedures and these include: lack of selective protection of low-grade carbon steel materials, absence of knowledge of application of correct metallurgy inhibitor test, inadequate correlation of surface monitoring procedures with internal rate of corrosion and negligence on the significance of complementing laboratory tests with field trials [129,169,182,193–201].

With the discovery of low-alloy steel (Cr steel), Guo et al. [174] maintained that the disparity between steel and corrosion-resistant alloy in terms of cost and corrosion resistance has been minimised. In a related development, ECD [120] looked at cost and resistivity when they studied the use of composite glass reinforcement plastic (GFK) or steel grade L485MB and concluded that steel was preferable because of lower capital expenditure, favourable results from corrosion tests and several references.

In summary, the future CO_2 transport pipeline will require intermingling of CO_2 fluids from different sources; monitoring levels of impurity which may inadvertently lead to corrosion is important. The following questions needs to be addressed:

- What is the best effective procedure to abate most avoidable corrosion cost (should be addressed at the conceptual phase)?
- There is a need for further research to determine the effect of elevation on the fluid properties as a result of pressure drop, how the supercritical nature of the fluid is lost temporarily and how quickly

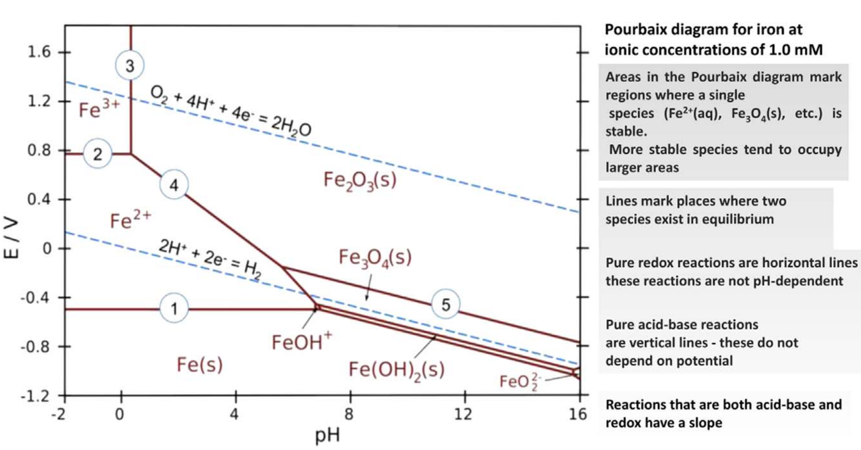

Fig. 11. Pourbaix diagram for iron (Reproduced from Western Oregon University [183]. Copyright Western Oregon University 2013).

this can recover. Again, at what height could the supercritical/dense nature fail to converge?

Moreover, it is expected that as the CCS industry grows, more power plants and industrial operators will connect to an already installed trunk pipeline. This has an obvious economic advantage over point-to-point operations as shown in some of the demonstration projects. However, work is needed to develop a method of determining the optimum pipe diameter to avoid over-specification of pipe size in anticipation of future growth in a region.

4. CO_2 pipeline operations

4.1. Energy analysis

Energy losses result from the existence of impurities which affect the thermodynamics of the CO_2 phase [202]. In an event following transport, depressurisation or fracture formation, involving rapid cooling, understanding the heat transfer characteristics of the CO_2 transport pipeline is crucial [85,124,203–205]. It is essential to accurately understand and represent the correlation between the physical properties of the CO_2 stream, such as temperature and pressure, expressed in terms of other physical-dependent properties including density, viscosity and thermal conductivity [46,94,109,206–208]. This is because there is a considerable phase difference between CO_2 and other similar fluids such as natural gas transported through the pipeline. A direct link exists between the energy requirements and the operating pressure when considering supercritical fluid flow in CO_2 pipeline transport. It has been shown that four major components of pressure drop, which include friction, acceleration, local and gravitational, can be distinguished [208,209]. In the pipeline transport of CO_2 in the supercritical phase, it is essential that the operating temperature is maintained at a desired level. If necessary, heaters and insulation need to be applied at some locations of the CO_2 transport pipeline to prevent hydrate formation. Loss of energy in the CO_2 transport pipeline can be analysed by estimating the amount of heat transferred to the environment that is proportional to the heat transfer coefficient and the temperature difference between the pipe wall and the surrounding environment. Furthermore, in the CO_2 transport pipeline, energy analysis should involve heat loss to the pipeline surroundings, depressurisation resulting from an accidental discharge, as well as planned maintenance. The energy drop along the pipeline is proportional to the length of the pipeline, though other factors such as the nature of the pipeline material, ambient temperature, and insulation, where applicable, need to be taken into account. Importantly, on an increase in the ambient temperature, the density of CO_2 reduces, causing an increase in velocity of the fluid flow. As a result a pressure drop occurs. The implication of this is that further pressure drop results in higher operating costs [26]. Importantly, determination of the maximum safe CO_2 pipeline distances to subsequent booster stations as a function of inlet pressure, environmental temperature, and ground heat transfer rate can be carried out by commercially available energy analyses [55,102].

4.2. Power requirements for CO_2 pipeline transport

The specific energy requirement for CO_2 pipeline transport depends on a number of factors, such as the inlet pressure, impurities content in the CO_2 stream, pipe diameter and length, and heat transfer coefficient. Importantly, due to the pressure loss along the pipeline, the compression or pumping stations are required to maintain the CO_2 stream in the supercritical phase. Therefore, both the cost and the energy requirement of the CO_2 transport pipeline are expected to increase for the routes located in a difficult terrain of variable altitude. Importantly, the total energy requirement for the CO_2 transport pipeline comprises the power requirement to compress the CO_2 stream to the pipeline inlet pressure and the power requirement for recompression of the CO_2 stream to compensate for the pressure losses along the pipeline. The latter is not only influenced by the efficiency of the compressor, but primarily by the temperature of the pipeline environment and the thermal insulation layer, both of which affect the operating conditions of the CO_2 transport pipeline [102,210]. Importantly, it has been shown that for a post-combustion CO_2 capture, a 20% reduction in the compression power requirement can be achieved when the CO_2 stream is only compressed to the critical pressure, under which it becomes a supercritical fluid, and then is pumped, as opposed to being further compressed, to the desired pipeline inlet pressure. In the same vein, there are different power requirements for refrigerated and non-refrigerated compression strategies in comparision to isothermal compression, which is assessed to be 30–40% higher [85,211].

4.3. Flow assurance

4.3.1. CO_2 pipeline transport flow assurance considerations

Generally, flow assurance is dependent on many factors including the allowable level of impurities in the CO_2 stream, the operating conditions of the CO_2 transport pipeline (pressure and temperature), and the potential for hydrate formation [28,212]. In a flow assurance assessment, the dynamic or non-steady state is important. This is because by their nature, it is usually difficult to determine the frequency of occurrence of various operating states, such as shut-down and start-up [50,122,213]. Several sources have described these phenomena including an initial start-up, planned shut-down, planned start-up after planned shut-down, and planned start-up after non-planned shut-down emergencies [50,120,163,214–216]. These sources have developed some understanding on several conditions including temperature, pressure, density, and viscosity, among others that affect the flow assurance of the CO_2 transport pipeline.

4.3.2. Recompression (start-up/shut-down)

Operating the CO_2 transport pipeline under a two-phase condition is not desirable, as this presents a particular difficulty during start-up. However, to overcome this difficulty, the CO_2 stream is initially compressed, and then recompressed along the pipeline, to a higher pressure than the nominal operating pressure. This not only affects the energy requirement, but also has an impact on the nominal operation pressure design for the CO_2 transport pipeline [85,191,202,204,209,216,217]. Of equal significance is an operation under a long-lasting shut-down and cool-down scenario, for example after weeks of low mass flow rate, increasing the flow rate becomes essential for a subsequent start-up procedure. Importantly, as mentioned above, recompression distance is dependent on the impurity content, as well as the pipeline diameter (Fig. 12) [86,139]. If the presence of impurities is large, the CO_2 transport pipeline will need to be operated at a higher pressure to sustain the supercritical phase [28,45,46,106,129].

4.3.3. Hydrate formation

It is important to avoid hydrate formation in the CO_2 transport pipeline. Operating away from the hydrate formation zone is essential to prevent the pipeline from blockage that will lead to a forced shut-down of the system and will increase the energy consumption required for subsequent start-up of the system. Following the results from the Dynamis project, at the temperature of approximately 10 °C lower than the system operating condition, stringent free water content specification is required to prevent hydrate formation [106,111,126,218]. There is a possibility of hydrate formation when free water is present in a significant amount, and both temperature and pressure are in the hydrate formation zone (Fig. 13). Nevertheless, hydrates may still be formed at a very low temperature, even though the amount of free water in the CO_2 stream is negligible. In that instance, the hydrate

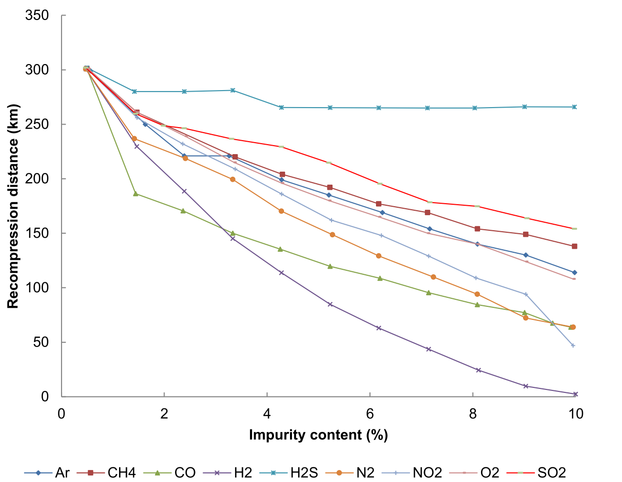

Fig. 12. Relationship between recompression and impurity (Reproduced from Lucci et al. [41]. Copyright The International Society of Offshore and Polar Engineers 2011).

curve will be moved further to the left (Fig. 13). In this sense, transport of CO_2 at a low temperature and a high pressure along a pipeline located on the sea bed increases the risk of hydrate formation [176,216].

Importantly, efforts are being made, especially at the demonstration stage, to compress and transport water-free CO_2, but this may be difficult at the project implementation stage where the mixing of the CO_2 streams from different sources is expected. Therefore, in terms of operational parameters, the specification of the drying condition of CO_2 is important. Work is required to identify the free water content that is allowable under particular operating conditions and that would pose minimal corrosion issues in the CO_2 transport pipeline

4.4. Reliability and maintenance

Reliability is the capability of an engineering system or a component to operate under a set of operating conditions for a specified period to produce a desired result. Based on this definition, a system or component can be described as unreliable when it can no longer maintain or operate under a specific set of operating conditions over time to produce a desired result. Therefore, measures need to be taken at the design stage to ensure that systems are made reliable over their useful life cycle.

A necessary consideration of reliability, availability, maintainability and operability (RAMO) characteristics of the CO_2 transport pipeline makes significant positive contribution to achieving reasonable economic life cycle costs [84,167,190,194,220–223]. Importantly, it has been claimed that there is little experience to date on the actual behaviour of anthropogenic CO_2 in the supercritical phase and this poses a number of challenges for the integrity, reliability, safety and cost-efficiency of the pipeline [123,170,173,189,224]. It is a common understanding within the industry that the CO_2 transport pipeline network should be designed and developed within the remits of that of the oil and gas industry [32].

The reliability and maintenance challenges should be mostly considered at the design phase of the CO_2 transport pipeline. At this stage, it becomes imperative to resolve the challenges related to impurities content in the CO_2 stream, material selection, corrosion and fracture prevention, as well as operation and maintenance of the entire system [124,221]. Reliable pipelines for CO_2 transport will require a well organised maintenance culture. Furthermore, the current literature has emphasised the importance of reliable means of corrosion prediction that are necessary for the prevention of leakage, accidental discharge and loss of CO_2 resulting from corrosion [84,129,188,222,225–227]. Finally, for effective control of CO_2 pipeline integrity, a management regime is required and this incorporates, among a number of other aspects, selection of material, inspection and monitoring, maintenance, operation, corrosion mitigation, evaluation of risks together with the concept of communicating these risks [114,129,167–169,193–196,220,223,224,228–232].

4.5. Environmental concerns of CO_2 release and dispersion

Transport of CO_2 takes place under a high pressure and in a supercritical phase. Depressurisation of the system may occur as a result of pipeline failure or planned maintenance [115,233]. Loss of pressure can also occur due to the length and geometry of the CO_2 transport pipeline. It have been shown that the maximum CO_2 release rate from a faulty pipeline is estimated at a range of 0.001–22 ts^{-1} [78]. However, other studies have estimated this release rate at 8.5–15 ts^{-1}. Importantly, these figures depend on the pipe diameter, puncture size and the level of impurities that may affect the CO_2 stream phase,

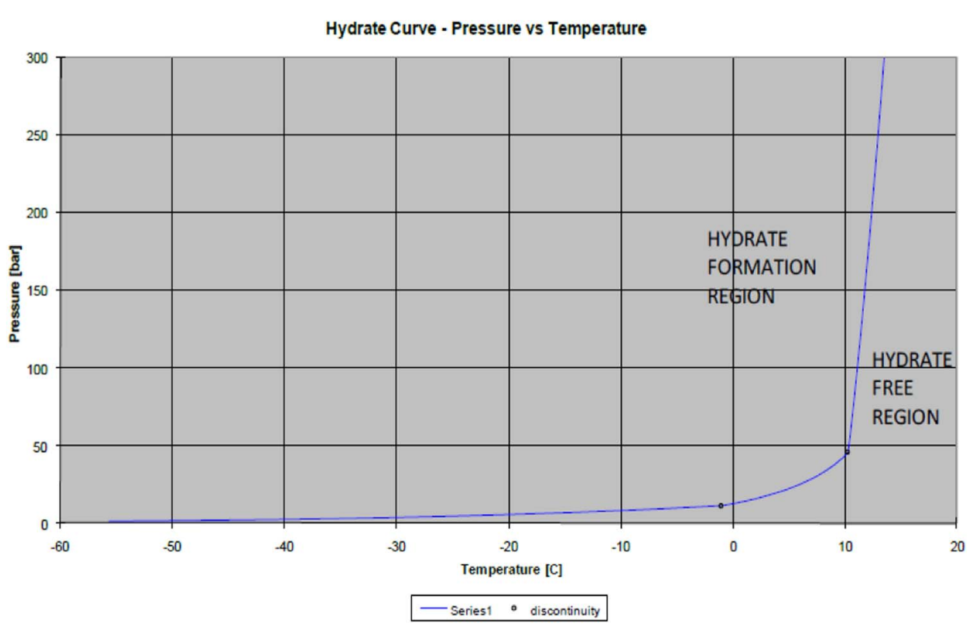

Fig. 13. CO_2 hydrate curve with free water (Reproduced from Scottish Power CCS Consortium [219]. Copyright Scottish Power CCS Consortium 2011).

Fig. 14. Photographs of the instrumented target and of a release of CO_2 through a 0.5 in. orifice [142].

operating temperature and pressure, as well as on whether the CO_2 release and dispersion is planned or accidental [78,102,190,224,234–236]. Furthermore, a change in the CO_2 phase gives rise to dry ice formation in the pipeline surroundings that has an indirect effect on the concentration and impurities around the faulty pipeline [190,237].

An industrial-scale experiment on the release and dispersal of CO_2 known as CO_2PIPETRANS was conducted by BP and Shell (Fig. 14). The data gathered from this experiment were used to validate simulations of CO_2 release and dispersion [24,30,235,236,238]. From the material integrity viewpoint, it is necessary to have control of the rate of depressurisation, as too fast depressurisation can accelerate the temperature drop rate within the pipeline that can make the steel wall brittle [96,157,239].

4.6. Health and safety

Economics do not favour transportation of a large amount of CO_2 at a low pressure over a long distance. Therefore, transport of CO_2 should be carried out at a high pressure and, as a consequence, this may pose some health and safety risks [3,17,24,41,78,117,134,137,240–242]. In the assessment of environmental risks for the CO_2 transport pipeline, ensuring the safe operation of the high-pressure pipeline has been identified as a major risk [24,105,115,196,227,243–245]. It has been indicated that an emergency planning zone (EPZ) around the pipeline, which requires detailed emergency response planning, needs to be considered at the design and planning stage [78,224,228,235,246].

4.6.1. Toxicity

CO_2 is known to be neither toxic when released in small quantities nor explosive. However, if the CO_2 transport pipeline is accidentally ruptured, it can release a considerable amount of CO_2 into the air that could pose harm to humans under particular circumstances. Considering the fact that certain regions of the earth, such as the European Union, are characterised by a high population density and that some of the CO_2 capture sites are located near cities, existing regulations should be strengthened to route high-pressure pipelines away from buildings and dwellings [24,41,110,115,190,224,227,238,244,247]. Moreover, care must be taken to significantly reduce the impurities content in the CO_2 stream that can pose injury or harm to humans, such as H_2S. In this sense, CO_2 transport pipelines must be buried deep enough to prevent digging equipment from reaching them. Furthermore, crack arrestors should be fitted in CO_2 pipelines and, for urban transit pipelines, a pressure release mechanism, such as a supervisory control and data acquisition (SCADA) system, should be fitted [24].

4.6.2. CO_2 pipeline leakage

Based on the experiences of the natural gas pipelines industry, failure rates associated with leaks for CO_2 transport pipelines are estimated to range between 0.7 and 6.1×10^{-4} yr^{-1} km^{-1} [108]. Most of the recorded failures to date were caused largely by third party interference, pipeline corrosion, material and construction defects, such as welds, and movement of ground or operator errors [102,115,167,190,224,229,237,248]. Leakage could also be a result of existing or induced defects, fractures, or along a spill position [235].

Currently, there are not enough empirical data and experience to accurately determine the likelihood of failure of CO_2 transport pipelines, compared to natural gas pipelines. This is further complicated due to the presence of impurities in the CO_2 stream [115,190]. When considering pressures for offshore and onshore pipelines, several authors maintained that the offshore CO_2 transport pipeline route can be designed for higher pressure than the onshore (up to 300 bars). This is because of reduced risks associated with the human population onshore [40,102,115,148,151,164,229,237,249].

5. Financing CO_2 pipeline projects

5.1. Estimated costs

A cost estimation of the CO_2 transport pipeline projects is important because this determines the feasibility of the project for the potential operators and investors. In general, for any long-distance movement of products to occur, there must be an overwhelming economic incentive based on the demand, similarly to the case of the hydrocarbon production and transport chain. Importantly, this can also be applied to the transport of CO_2 via pipelines. However, the value of CO_2 is given on the basis of both environmental and societal needs for it to be stored, rather than the monetary value of CO_2 itself [21,24,164,242]. Furthermore, several sources claimed that the economics of scale are required to reduce the cost of CO_2 transport via single large-capacity pipelines [21,64,250–252]. This is important as it has been estimated that the CO_2 transport pipeline constitutes about 21% of the overall cost of a full-chain CCS project as shown in Table 6 [217]. The cost of a CO_2 transport pipeline varies from one project to another and depends on the amount of CO_2 to be transported, as well as the diameter and length, and material of the pipeline. Other important factors that affect the cost of CO_2 transport are labour cost and expected system lifetime [3,15,21,67,154,242,253].

5.2. Financing options and capital availability

The CO_2 transport infrastructure requires a large capital invest-

Table 6
Summary of estimated project cost at the end of Front End Engineering Design [217].

Section	Post-FEED (£million)
Capture	1656.5 (49%)
Transport	281.2 (21%)
Storage	207.8 (16%)
Total	1145.5 (85%)
Risk & Contingency	194.8 (15%)
Total Project Capex	1340 (100%)
Estimated Range	1200 to 1519

ment. As a result, governments are expected to play a leading role in financing the full-chain CCS projects. However, the opportunities on how the captured CO_2 can be transported to the end users or to a location of its permanent storage can add value and create confidence in the process, and should be explored. Importantly, captured CO_2 can be utilised for EOR, as based on the significant experience in the USA where EOR has been applied for decades, and oil producers are willing to pay between \$9 and \$18 per tonne of CO_2 supplied [254]. CO_2 can also be applied in the extraction of methane from deep coal beds and in the cultivation of algae for biofuel production [255]. All these utilisation opportunities, when properly exploited, add value to the CO_2 pipeline transportation infrastructure development.

Importantly, if CCS is designed to provide CO_2 for EOR, the business case exists for such scenario as there is a potential revenue stream that supports a timely deployment of CCS. Furthermore, there are carbon tax incentives and added competitive advantages for companies that are perceived as environmentally friendly. In order to reduce costs, the design and operational experience from existing projects (Fig. 15) need to be gathered and utilised to implement 2nd and 3rd generation CCS technologies in the near future.

5.3. Commercial risks

Commercial risks related to the CO_2 transfer pipelines as part of CCS chains could occur in scenarios such as scaling down, abandonment, late completion and total cancellation of projects. Presently, the most important limitations of the CCS chain are related to the capital cost of the infrastructure and the operational cost. Consequently, a substantial effort is being directed to cutting these costs by developing less energy-intensive processes and configurations. One of the ways utilised to achieve this target is application of reliable and accurate techno-economic models. However, the cost estimations from different models may vary by tens or hundreds of millions pounds at the Pre-FEED and FEED phase for the CO_2 transport pipeline projects [3,77]. Differences of this scale, which can arise from different assumptions behind and accuracy of the existing economic models, can introduce an unwarranted uncertainty to the viability of the CO_2 transport pipeline project. This effect can result in a misestimation of the actual costs of the project and, in turn, abandonment of the project. Table 7 shows the introduction of Aspen Process Economic Analyser© V8.8 (APEA), an industry standard tool used to accomplish CO_2 pipeline cost estimation and economic analysis. This tool has been recognised to be far more accurate than factor-based costing methods. This model is built on the basis of regional construction cost information which is updated annually. To this effect, it is more reliable in cost estimation of CO_2 pipelines in comparison to other models [3,77].

Furthermore, Table 7 reveals similarities between the most relevant techno-economics models reported by MIT, Ecofys, McCoy and Rubin, Ogden and the mathematical simulation tool, Aspen Process Economic Analyser [77]. These can be observed in the applied methods for estimation of the pipeline diameter, as well as operating and maintenance costs. However, there are differences in some factors, such as the terrain factor, friction factor and absolute roughness. Importantly, an accurate and reliable estimation of the project costs reduces the uncertainty and thus increases the confidence that the estimated values will be close to the actual project costs. Additionally, it has been highlighted that reducing the uncertainty would reduce in reduction of the project cost in the long run [3,66].

Furthermore, it has been shown that the cost of a CO_2 transport pipeline is significantly affected by its location [21,24,164,242]. Namely, it has been estimated that pipelines located in remote and sparsely populated regions would cost between 50–80% less, compared to pipelines located in highly populated areas. Moreover, pipelines constructed offshore could be between 40–70% more expensive than their onshore equivalent. This is because when considering offshore pipeline trajectory, the depth at which the pipelines are laid directly affects the cost. As indicated above, corrosion may have a significant impact on the feasibility of CO_2 transport via pipelines. Jackman [256] has identified that the costs related to corrosion can be divided into avoidable and unavoidable. The former costs are those that can be reduced or eliminated by applying the proper and the most economical corrosion control system that is available at the time, especially by adhering to all the technical considerations. The latter costs are related to the effect of corrosion that, at the time of design, was not predictable based on the existing knowledge and available information [26,68,195,256,257]. In a review of the studies that estimated pipeline

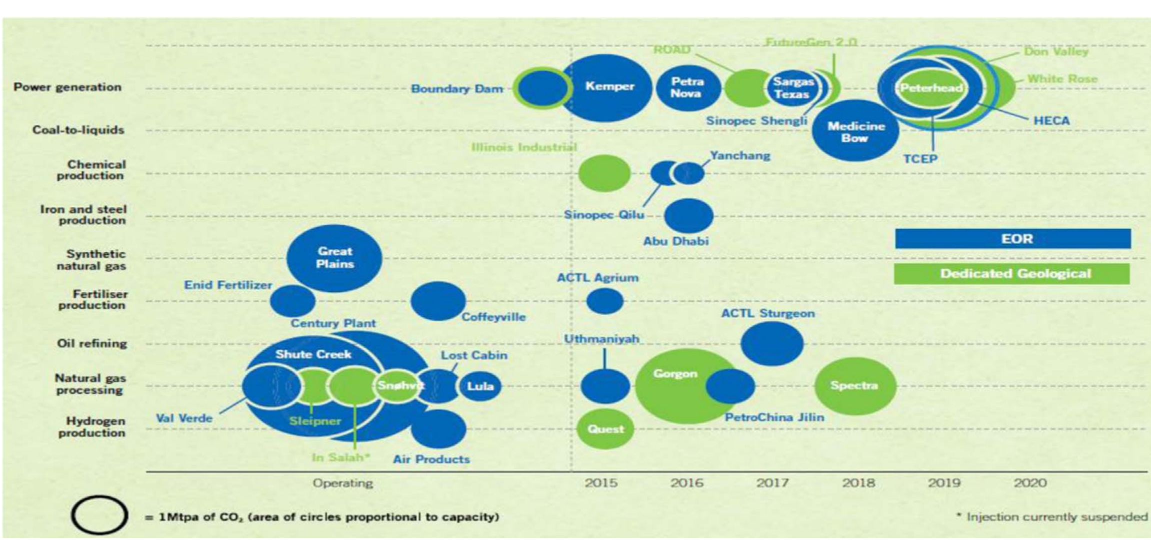

Fig. 15. Actual and expected operation dates for large-scale CCS projects in the Operate, Execute and Define stages by industry and storage type (Reproduced fro Global CCS Institute [20]. Copyright Global CCS Institute 2014).

Table 7
Comparison of techno-economic models (Adapted from Ghazi and Race [77]. Copyright American Society of Civil Engineers 2013).

Model Components and Assumptions	Techno-Economic Models							
	MIT	**Ecofys**	**McCoy & Rubin**	**Ogden**	**IEA GHG PH4/6**	**IEAGHG 2005/2**	**IEAGHG 2005/3**	**APEA©**
Hydraulic Basis for Diameter Calculations	Darcy-Weisbach	Darcy-Weisbach	Mechanical Energy Balance	Mechanical Energy Balance	Darcy-Weisbach	Mass Flowrate	Rule of Thumb	Mass Flowrate
O & M Factor	\$3100/km/a	2.3%/a of total capital cost	\$3250/km/a	4.0%/a of total capital cost	By equation	$3^1/_2$% of pipeline capital–5% of booster capital	$2^1/_2$% of total capital cost	3% of the total project cost
Booster Station Calculation	No	No	No	No	Available option	Yes	No	Yes
Plant Capacity Factor[%]	80	–	75	–	User specify	90	–	User Defined
Friction Factor or Absolute Roughness –z [mm]	~0.0033 (Moody Chart)	0.015–0.0020 (=4xf)	c =0.0457	~	0.015 (=4xf)	–	–	System specified
Terrain Factor	–	1	by Table	–	1.05–1.50 (by terrain)	1.05–1.50 (by terrain)	1.17	User Defined
Location Factor	–	–	by Table	–	0.7–1.2 (by location)	–	–	User Defined
Currency	USD	Euro	USD	USD	USD	Euro	USD	GBP
Reference Cost Year	1998	2005	2004	2001	2000	2000	2002	2014
Capital Recovery Factor	15	–	15	15	–	–	–	–
Discount Rate, i	–	10	–	–	–	10	10	–
Operational Life Time (yrs)	–	25	30					25
Cost of Electricity [/kwh]	–	–	–	–	User specified	₡0.04	–	User Defined
CO_2 Temperature [°C]	25	10	12	4.44–37.78	–	–	–	20
CO_2 Density [kg/m^3]	884	800	–	–	800	800	–	System specified
CO_2 Viscosity [Ns/m^2]	6.06×10^{-4}	–	–	–	–	–	–	5.5×10^{-4}

costs, Knoope et al. [68] identified two major types of the capital cost models that are currently in use. These include models relating capital and operating costs of the CO_2 transport pipeline to its diameter or the mass flow of the CO_2 stream. Knoope et al. [3] also reported that the Global CCS estimated the cost of transporting CO_2 onshore over 100 km at between 0.4 and 1.5 €$_{2010}$/tCO_2. The cost varies because of variation in a number of factors such as topographic conditions, geographical region, pipeline economic life, and interest rate through to the type of steel, type of coating insulation, as well as the type of compressor and intermediate pumps. Furthermore, several sources provided an insight into the cost-effective solutions for CO_2 transport, which are especially important as it affects the economics of the comparative risks and opportunities related to developing point-to-point CO_2 pipelines or backbone pipeline networks [21,64,134,146].

5.4. Reducing costs, EOR, use of existing infrastructure

A reduction of the CO_2 transport pipeline costs determines the commercial feasibility of CCS. One of the potential options to reduce these costs is utilisation of existing pipeline infrastructure, although it potentially introduces significant design constraints on the CO_2 specifications and process conditions. In addition, utilising CO_2 captured from fossil fuel power plants and industrial sources, rather than that from natural sources, for EOR will add value to the CCS chain. Over the years, the oil and gas industry have constructed an extensive pipeline network in both offshore and onshore locations, especially in the UK [164]. Similarly, Dooley et al. [29] reported that in the last 60 years, a substantial number of natural gas pipelines has been constructed in the US. These existing pipeline networks can be utilised for CO_2 transport as an interim solution, until new pipelines are constructed. However, there are some impediments that impose the requirement to alter the operation and maintenance processes of the existing oil and gas pipelines to make them suitable for CO_2 transport [164]. Importantly, it has been indicated that the design pressure of the existing oil and gas pipelines (60–80 bar) is lower than that required for transport of CO_2 (70–110 bar) [29,115,142,190]. Furthermore, the outstanding service lifetime of the existing pipeline networks is uncertain and must be determined on a case-by-case basis to evaluate the feasibility of their adaptation to CO_2 transport. This is essential because the internal corrosion and the outstanding fatigue life must be accounted for [164,169]. Moreover, most of the onshore pipelines are buried and require an appropriate revalidation, as well as an agreement with the current operator that will establish the time when these pipelines can to be re-employed for CO_2 transport. A comprehensive impact assessment is required before implementing any design changes to an existing pipeline infrastructure to utilise it in the CCS chain. It is also recommended that the experience gained in the hydrocarbon pipeline routing should be applied with respect to CO_2 pipelines. ISO 13623 should be used when determining restrictions on pipelines that traverse highly populated sites [142].

Uncertainty associated with the unexpected costs of CO_2 transport pipelines can be reduced, or even avoided, when satisfactory modelling is carried out prior to the design and building of any pipeline network, especially of those that will traverse urban areas. This will help to identify and deal with the challenges that might arise during the deployment and operation stages of the pipeline system. Furthermore, crack modelling of the CO_2 transport pipeline is essential to understand the potential risks associated with pipeline failure [82,258].

In general, CO_2 pipelines constructed in urban areas are more complex in nature because the planning, technical, safety and legal challenges must be resolved [258]. In contrast to this, when constructing CO_2 pipelines offshore, experience gained from the oil and gas industry is very useful. For instance, the CO_2 pipeline can follow the existing oil and gas pipeline trajectory. This helps to reduce cost and limit delays associated with planning procedures [164]. In the same vein, it has been reported that securing rights of way alongside known easements such as gas pipe will facilitate the establishment of new CO_2 pipelines [259]. However, it was concluded that there are no technical barriers to pipeline networks in the long run, but there exist challenges in the design, procurement, management and the development of a business model for the CO_2 transport infrastructure [227,260,261]. Nevertheless, one way in which CCS pipeline cost can be significantly reduced is by employing the economies of scale. This involves sharing a single CO_2 transport and storage facility between different operators of individual CO_2 generation plants. A reduction in the transport and storage services costs can be achieved in this case because the cost for each unit capacity related to the construction and running of an individual large-capacity pipeline asset is less than those related to many, small capacity assets of the same aggregate capacity [21,23,242,262,263].

In summary, there is little or no driving force associated with rapid commercialisation of CCS other than the societal perception of the environment and for uses like EOR. Effort should be geared toward avoidance of commercial risks associated with CCS from demonstration to implementation. Therefore, developing a techno-economic framework that will broaden understanding of the outcome of CCS pipeline projects resulting from risks/uncertainties becomes necessary.

6. Future directions

6.1. Summary of findings

In this review, gaps in knowledge and lack of certainties associated with CO_2 transport as it affects properties, design, operations and financing have been identified and discussed in brief. It has been recognised that consideration for the impurities content in the CO_2 composition impurities stream requires a holistic approach which will support all previous work carried out mostly in mono-, binary- and ternary-based assessment. Furthermore, the review recognised that in a trunk-line-based CO_2 pipeline transport system, streams with different impurities levels are expected to be compressed and transmitted transported through the pipeline. This, however, poses both corrosion and health and safety challenges, especially in densely populated regions. Further research is, therefore, required for the implementation of the composite fluid regime.

In order to evaluate the correct pipeline length with some degree of certainty before the installation of the next booster station, the consequences of pressure drop caused by elevation along the pipeline route, using detailed simulation and experimental work are required to gain full knowledge of the behaviour of CO_2 in the supercritical phase when it encounters a steep elevation. The simulations and experiments are expected to help to understand how likely it is for the CO_2 stream to loss its supercritical state and whether this kind of upset can be reversed or not. A gap was also identified in the provision of data at the early project stages to model the pipeline trajectory to ascertain in full the impact of elevation of the pipeline fluid dynamics.

It was also identified that a gap exists in the early commencement of procedures to install, manage and run corrosion mitigation measures at the conceptual stage of the pipeline project. Free water presents an expensive problem in CO_2 transport, both in terms of hydrate formation and its impact on corrosion rate on the inner wall of the pipeline. However, there is an uncertainty in the universal allowable free water content in the CO_2 stream.

This review also found that it is necessary to develop a techno-economic framework that will broaden the understanding of the outcome of CCS pipeline projects resulting from risks and uncertainties. Further, commercial deployment of CCS pipelines makes it imperative to evaluate the economics of CO_2 transport considering multiple small- and single large-capacity pipelines early in the planning stages of the project to forestall commercial risks of abandonment of the project. Another important knowledge gap was in the pipeline over-specification as a result of expected future use. This could be very expensive if it is not carried out satisfactorily. For this systematic review of key challenges of CO_2 pipeline transport, important knowledge gaps identified are linked mostly to the technical aspects of CO_2 pipeline transport, ranging from properties, design and operations to financing without delving into the regulatory and policy aspects of the CO_2 transport.

6.2. Discussion

A number of commercial risks could lead to project cancellation, abandonment and commercial partners pulling out of the project. These can be avoided via comprehensive techno-economic assessments to minimise project uncertainty. This will ensure that most of the grey areas are adequately analysed prior to commencement of the project. In the techno-economic analysis, it is important to understand that, at the moment, a major driving force for CCS projects is EOR. Therefore, efforts should be made to locate the CCS projects where there are sufficient oil fields. A balance should be struck between generating a market situation for investment in CCS projects, while not causing the price of electricity to increase excessively. There should be a political will for carbon trading which will give incentives to CCS projects and initiate a move away from harvesting naturally occurring CO_2 for EOR and replacing it with anthropogenic CO_2.

Regional cooperation is also necessary to reduce the cost of the CO_2 transport pipeline infrastructure and maintenance. Development of regional CO_2 pipeline transport with implementation of a technical and economic model helps to create a framework for initial decision making by the stakeholder, which influences project viability and inculcates confidence in the industry. This requires consideration of, among others, information on the estimation of the number and location of the large industrial CO_2 emitters in the region under consideration and, because CO_2 will rarely be stored at the site of capture, transportation to a geologically suitable site or industrial utilisation location. The technical and economic requirements for transport of captured CO_2 are determined by the distance and the location of the storage site, and need to consider the pipeline, ship, rail and truck as means of transportation. Amongst these means of transport, the pipeline has a further advantage over the others because it does not in most cases require interim storage.

The CO_2 pipeline infrastructure technical and economic framework considers, amongst other issues, the cost estimation of the CO_2 transport pipeline. The cost estimation is calculated as a function of diameter, pipeline length and mass flow of the CO_2 stream. This, in turn, determines the location for sequestration by the individual operators. However, the viability of a sequestration site and the decision by the operators in a region to transport via a direct pipeline or share a trunk line can lead to manifold differences in the implementation of CO_2 pipeline lengths and consequent cost differences.

From the perspective of different fossil fuel power plants or other CO_2 capture sources, higher variability in the CO_2 pipeline costs may have huge consequences. For example, if the cost becomes excessive for an individual plant, it may lead to difficulties in financing the whole project. Some analysts are of the view that costs can be moderated in the future if the fossil fuel power plants can site their plants close to sequestration sites. However, consideration of the cost of electricity transmission may outweigh the cost of CO_2 pipelines when construction costs are considered.

To protect the material integrity of the CO_2 transport pipeline, monitoring and control of the CO_2 stream regime must be implemented. Appropriately, the operators of the pipeline facility would specify an allowable stream composition with which the CO_2 transport pipeline users have to comply for the injection of CO_2. This will help to maintain a fluid composition standard and will ensure the proper operation of the system. Quality specification for CO_2 transported in pipelines close to public areas has been reported as an important challenge that needs to be solved In order to limit the negative impact of impurities in the CO_2 stream; thus, it is expected to comply with a specific recommendation. There are data available from the reviewed literature on the types of impurities present in the CO_2 streams. Such studies involve mono-, binary- and ternary-impurities. However, the effect of the combined impurities associated with coal- and gas-fired power plants, or any other stationary installations producing flue gas from combustion of fossil fuels, have not been adequately reflected. Further experimental or computer-aided research to ascertain the complete effect of these impurities on the pipeline hydraulics and thermodynamics is necessary. This will help in setting up a composition regime, thereby regulating the level of impurities in the transported CO_2 stream that is a mixture of a number of streams from different CO_2 capture sources.

Arguably, the best time to incorporate the operation and maintenance of the CO_2 pipeline infrastructure, which considers various issues that affect its integrity and falls under asset integrity management, is at the pipeline conceptual design phase. The CO_2 pipeline integrity management conveys the reputation of an environmentally friendly operator who is keen on the safety of its employees. It also benefits the pipeline operators by ensuring that the efficiency of operation, as well as the return on the capital investment, are maximised. An effective asset integrity management plan will consider, among other issues, the impurities content in the CO_2 stream, flow assurance, material selection and corrosion. The CO_2 transport pipeline is expected to adapt to variable flow rates of and impurities content in the CO_2 stream. The latter has implications on corrosion, seals, coatings, gaskets and internal lining materials as well as integrity-critical and other safety issues. The effect of impurities content on the thermodynamic and transport properties of the transported CO_2 must be considered when designing the pipeline capacity, compression and pumping power, and re-compression distance.

Experience from the more developed oil and gas industry will be of advantage. This can be applied when considering the content of impurities in the CO_2 stream, types of equipment, piping and fittings, together with the pressure, temperature and velocity that will determine the material selection. The heat and mass balances, description of equipment and the process flow scheme should be carried out in close collaboration between specialised corrosion and process engineers right from the beginng of the project to minimise errors. Material selection is a critical aspect of the CO_2 transport system because, if carried out properly, it will safeguard against potential failures and, at the same time, will minimise both capital and operating costs. In general, carbon steel is the most cost-effective material for CO_2 pipeline transport, though the choice of a grade of carbon steel such API 5 L X100, X70, etc., is guided by the level of impurities in the CO_2 stream and the total allowable cost of the pipeline. During material selection, consideration should be given for the strength, corrosion resistance, and availability. Amongst these three issues, availability may be considered of the highest importance.

Corrosion is important in the integrity management of the CO_2 transport pipeline. An efficient corrosion management approach is to identify the potential for the corrosion occurrence in all the lines and parts of the pipeline. This should then be followed by quantifying the corrosion rates. For general corrosion of the CO_2 transport pipeline, a corrosion prediction model may be applied. However, to estimate the local corrosion rates, consideration of the corrosion risks appears to be a more suitable approach. Once the potential corrosion for the entire system is identified, it becomes easier to select the material that will reduce the probability of corrosion occurrence and, at the same time, will minimise the economic burden. Importantly, the selected material should not have the quality of being susceptible to any of the localised corrosion phenomena identified. Evaluation of corrosion allowance with a suitable prediction model should be then carried out. The identification of the correct pipeline material should be followed by verification of the eventual recommendation such as post-weld heat treatment and hardness limitation for cracking. This verification could be carried out by using company reports, general standards and the opinion of other experienced engineers, and will consider how well or poorly the material performs under design pressure and temperature, and how long the material will stand before failure occurs. Also, compatibility with the external environment of the selected pipeline material is important. For example, consideration should be given to the impact of exposure of stainless steel in a marine environment that may suffer from chloride-induced stress cracking, or of carbon steel to the atmosphere or buried in the soil. Some of the external corrosion issues are commonly managed by application of appropriate paints and/or coatings. To make the right selection, one must consult the supplier's recommendations or company standards. It is important to remember the issue of corrosion under insulation if thermal insulation is to be applied.

Agreeing on the allowable level of free water in the CO_2 stream is still a subject of debate. However, its presence in the CO_2 stream is of the utmost importance it can initiate the formation of different types of acid given the right conditions, including carbonic acid, which may affect the pipeline integrity. Therefore, adequate collaboration amongst researchers should be promoted and the field experience should be gathered for knowledge generation. For example, the corrosion rates resulting from laboratory tests should be reflected in an appropriate selection of the pipeline material.

The trajectory of the CO_2 transport pipeline is highly dependent on the terrain characteristics. Importantly, the effect of sharp elevation changes, which may cause the CO_2 stream to go below the minimum pressure that maintains the dense phase, must be considered at the pipeline design stage. This is because two-phase flow may occur that will initiate the separation of impurities. As this phenomenon is not yet fully understood, further research needs to be conducted in this area.

Elevated expectancy of the amount of CO_2 to be transported via the pipeline at the inception of a project would result in oversizing of the pipelines and is an important aspect that needs to be considered at the pipeline design stage. If the pipeline diameter is increased by a factor of two, it will be able to accommodate the CO_2 stream flow increased by a factor of four [165]. When considering oversizing the CO_2 transport pipeline, care must be taken to reliabliy assess the amount of CO_2 to be transported via the pipeline to avoid its underutilisation. It can be expected that the economies of scale will reduce the cost associated with the development of the CO_2 transport pipeline networks and storage clusters, and these need to be cautiously aligned with the CO_2 capture investments.

An effective CO_2 pipeline infrastructure technical and economic framework should consider carefully the routing of the pipeline from the point of capture to the location of sequestration. This will involve getting approval from regulatory bodies as well as securing the right of way from landowners. As these are not always easy to obtain, consideration should be given to securing the right of way alongside existing pipeline infrastructure such as a gas pipeline.

In summary, developments in CO_2 pipeline technology help in accelerating the commercialisation of CO_2 transport pipeline projects, and addressing the gaps identified in this work is important in obtaining the FEED decision. The time it presently takes from the demonstration phase to implementation of CCS projects will be shortened. It will also enhance the commercialisation of CCS by generating a market situation for investment in CCS projects.

7. Conclusion

This review aimed to ascertain whether certain crucial technical and economic knowledge, on issues that may hinder CO_2 pipeline transport project implementation, is lacking in the literature. The challenges of CO_2 transport via pipeline such as integrity, flow assurance, capital and operating costs, and health, safety and environmental (HSE) concerns were reviewed and discussed. The most relevant techno-economics models such as MIT, Ecofys, McCoy and Rubin, and Ogden were compared to a mathematical simulation tool, Aspen Process Economic Analyser. Similarities were found in the areas of hydraulic basis for diameter calculations and operation and maintenance, while there were differences in the terrain and friction factor or absolute roughness assumptions. The review equally highlighted the need for impurities, corrosion and pipeline integrity management systems.

The review scope included assessment of major issues related to CO_2 transport, identification of knowledge gaps and the outlook for the CO_2 transport system after those gaps have been addressed. In order to bridge these gaps, which will reduce the uncertainties associated with CO_2 pipeline transport, it is useful for further research to be conducted into the effects of elevation and impurities on pressure drop along the pipeline which influences the length of the pipeline before the next compressor or pumping station. Similarly, detailed analysis of corrosion impact and mitigation measures should be carried out at the conceptual phase to reduce the avoidable cost associated with corrosion during the operation and maintenance phase.

Active collaborations between research endeavours and field operators, especially in the determination of permissible water content in transported CO_2, is necessary. While actual research on CO_2 transport challenges is concentrated in some specific regions of the world, its implementation is globally disposed of. Therefore, there is a need to overcome the issues that prevent active research collaboration and project implementation. Some of the challenges that hinder an effective dissemination of research findings can be addressed through the use of information technology to improve communication amongst all the parties involved. Furthermore, an effective collaboration in terms of implementation of CO_2 pipeline research tests can be enhanced by considering the three levels of input involved in the implementation of this research. These include the corporate aspect of implementation which considers system engineering and development of key component innovation. This can be followed by manufacturing implementation which looks at incremental product improvement, and then field engineering which considers customised solutions.

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