Renewable and Sustainable Energy Reviews, Vol. 81, Part 2, January 2018, pp. 2563-2583
DOI:10.1016/j.rser.2017.06.064

A systematic review of key challenges of CO_2 transport via pipelines

Victor E. Onyebuchi, Athanasios Kolios, Dawid P. Hanak, Chechet Biliyok, and Vasilije Manovic*

School of Water, Energy and Environment

Cranfield University,

Bedford, Bedfordshire, MK43 0AL, UK

Renewable and Sustainable Energy Reviews, In Press

*Corresponding author: *Athanasios Kolios, a.kolios@cranfield.ac.uk*

ABSTRACT

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 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 andgas 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) (Figure 1).

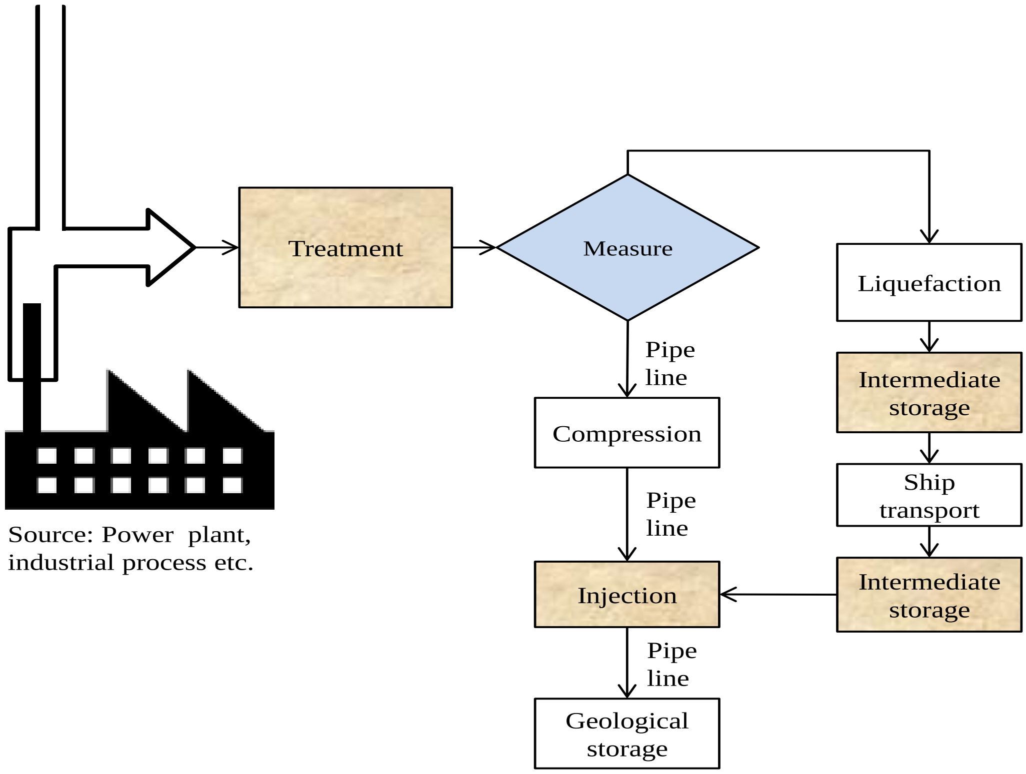

Figure 1: Liquefaction and compression transport schemes (Adapted from Spinelli et al. [32]. Copytright 2012 The International Society of Offshore and Polar Engineers)

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, includingin 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] (Figure 2).

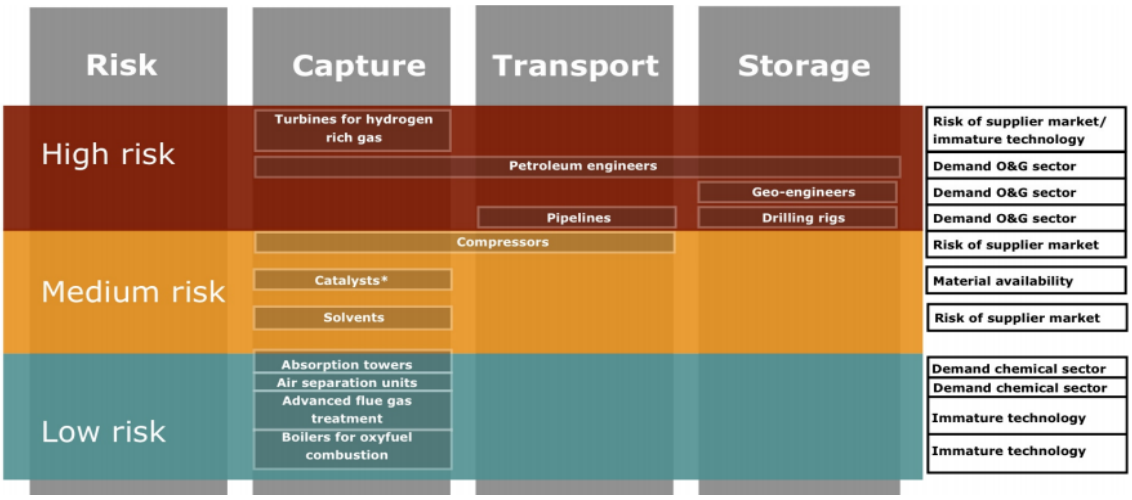

Figure 2: Potential supply chain constraints (Adapted from International Energy Agency Greenhouse Gas Programme [35]. Copyright 2012 The International Energy Agency)

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 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].

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

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 usethe 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 andmaintenance 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]

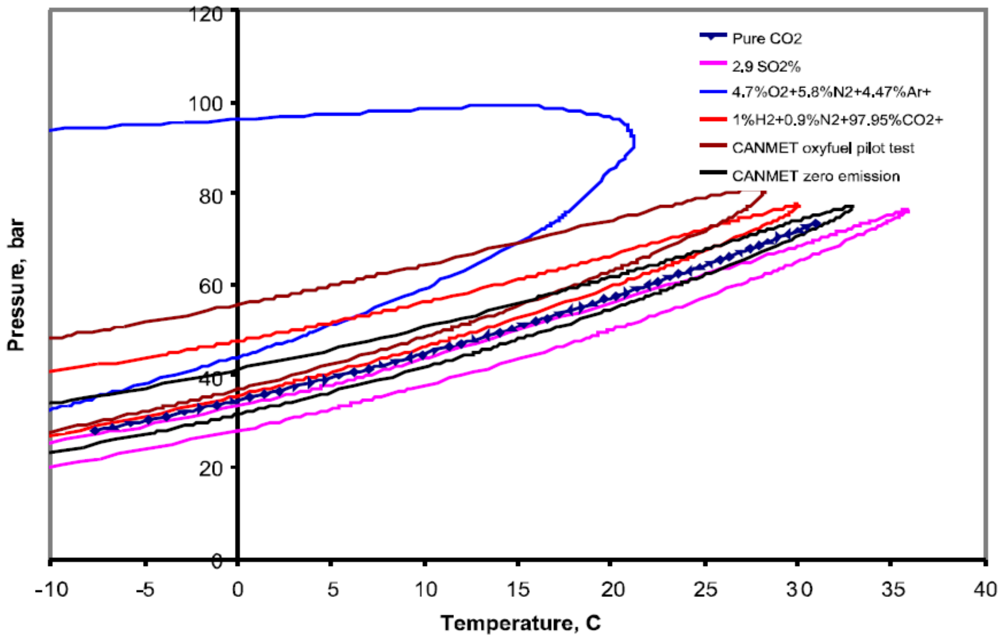

Figure 3: Phase envelopes for pure CO_2 and CO_2 mixtures (Reproduced from Wang et al. [37]. Copyright Elsevier 2011)

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 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 (Figure 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 Figure 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.

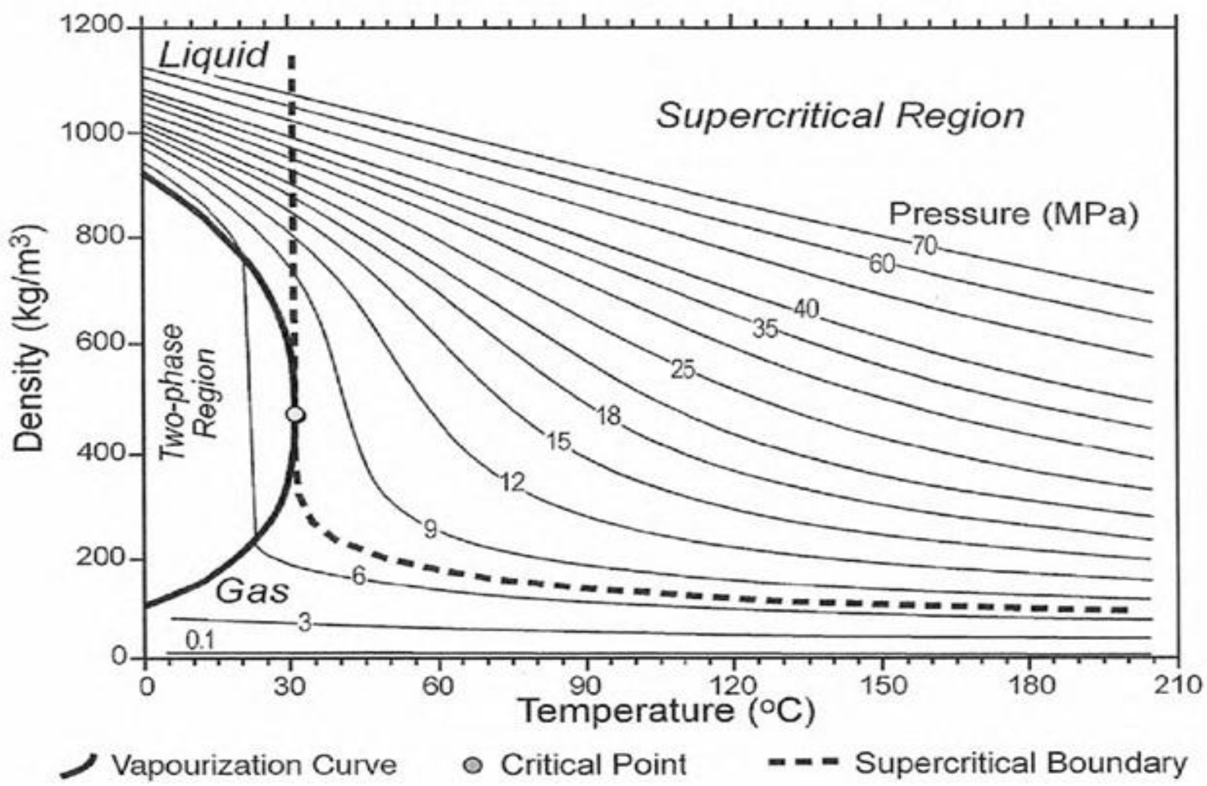

Figure 4: Variation of carbon dioxide density with temperature (Reproduced from Global CCS Institute [15]. Copyright Global CCS Institute 2013)

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]. Figure 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.

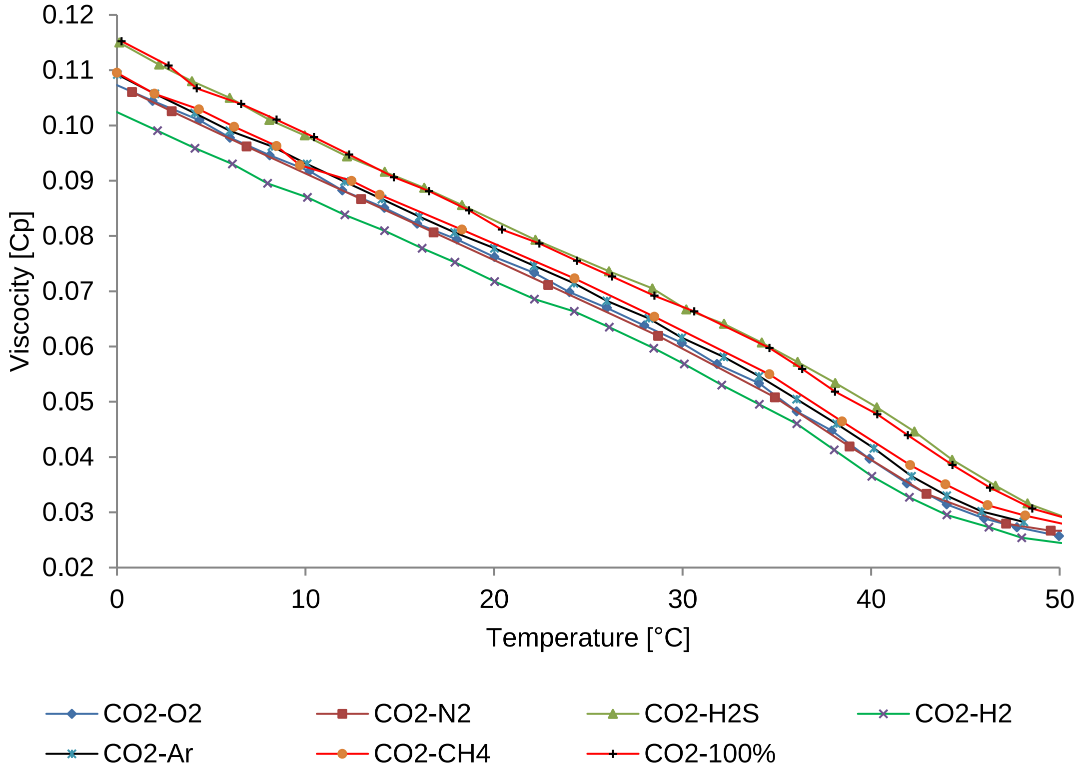

Figure 5: Effect of impurities and temperature on CO_2 stream viscosity at 100 bar (Reproduced from Lucci et al. [110]. Copyright International Society ofOffshore and Polar Engineers 2011)

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.

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

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].

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%	-

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 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 Figure 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.

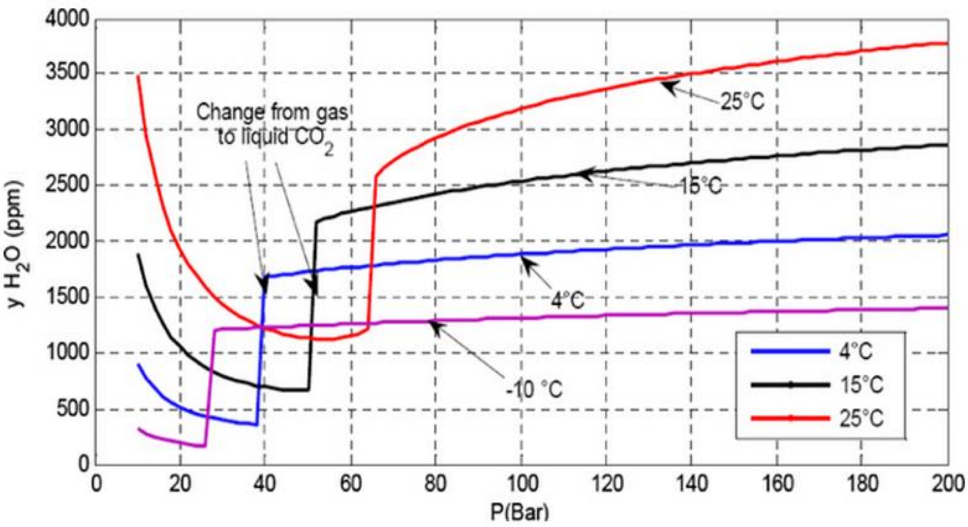

Figure 6: Solubility of water in pure CO_2 as a function of pressure and temperature (Reproducedf from de Visser et al. [126]. Copyright Elsevier 2008)

2.4 Preferred conditions for CO_2 transport

The amount of CO_2 transported via pipeline is highest in the supecritical 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 (Figure 7) [45,132] .

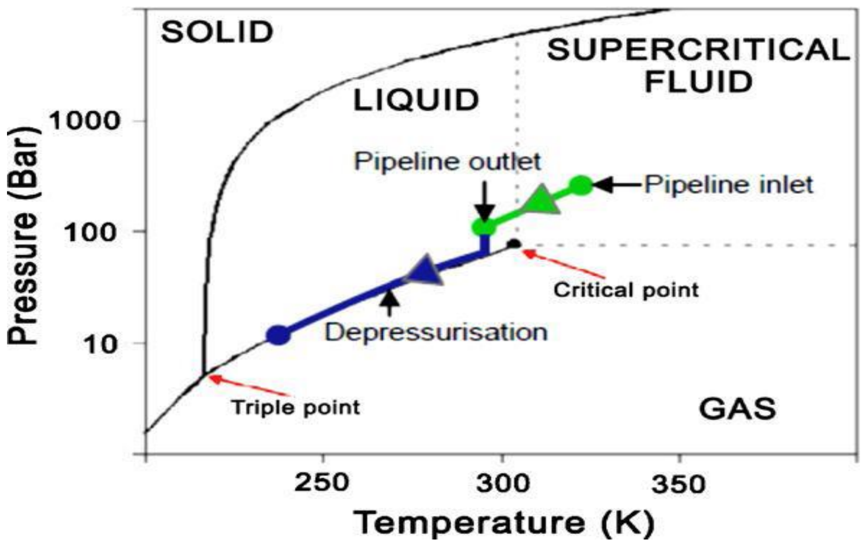

Figure 7: Operating conditions for CO_2 transport pipeline (Reproduced from Cole et al. [43]. Copyright Elsevier 2011)

However, for the captured CO_2 to be transported in the supercritical phase, it has to be compressed to a 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 siteshould 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 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 $x10^{-2}$ to 0.4 $x10^{-2}$ (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.

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.

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

X100 was used to demonstrate a typical stress-strain curve (Figure 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.

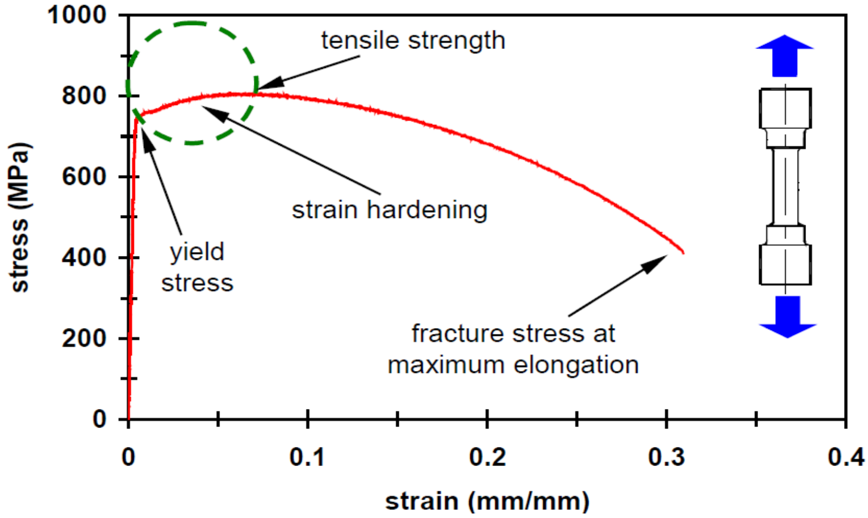

Figure 8: A typical stress-strain plot for X100 steel (Reproduced from Hashemi et al. [153]. Copyright European Structural Integrity Society 2004)

For large-scale exploitation, where CO_2 is captured from different point sources and transported over long distances for storage, as shown in Figure 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 Figure 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].

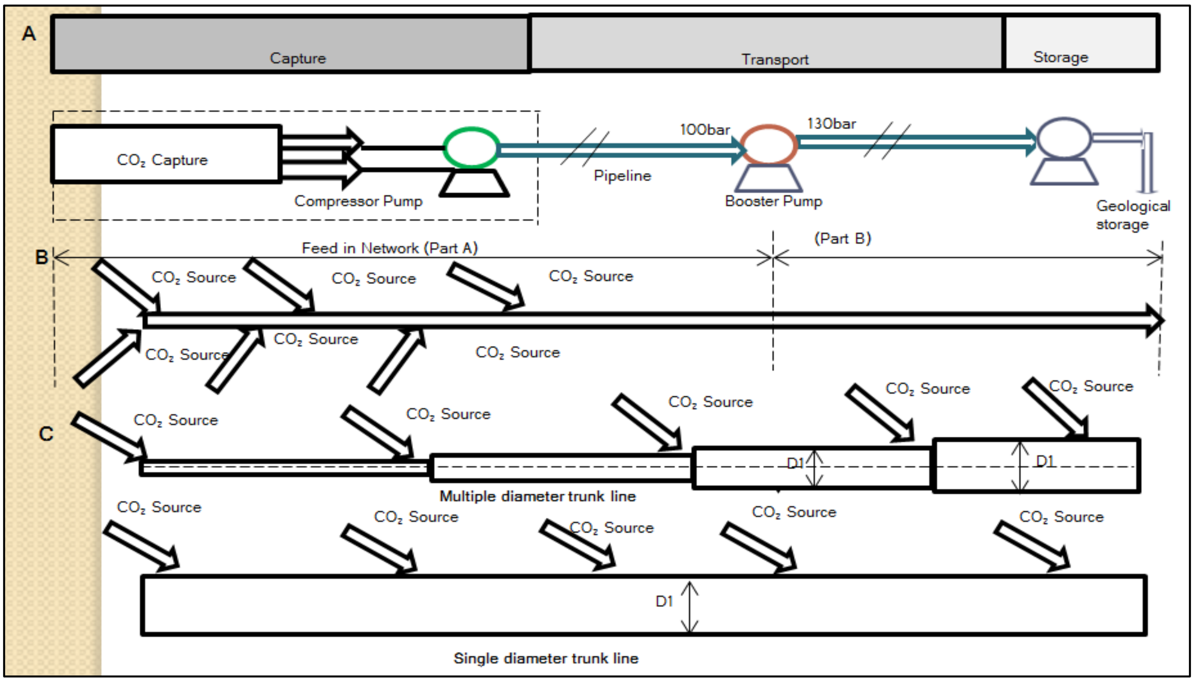

Figure 9: Schematic of CO_2 transport network configuration (A) with a single CO_2 source connected to a storage site; (B) linking multiple supplies to a trunk line (Part A) that then to a storage site (Part B); (C) with a multi-diameter trunk line connected to a storage site or a single-diameter trunk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

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 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 (Figure 10).

Figure 10. Crack repair using crack arrestors [163]

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.

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.

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]

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 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 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 (Figure 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.

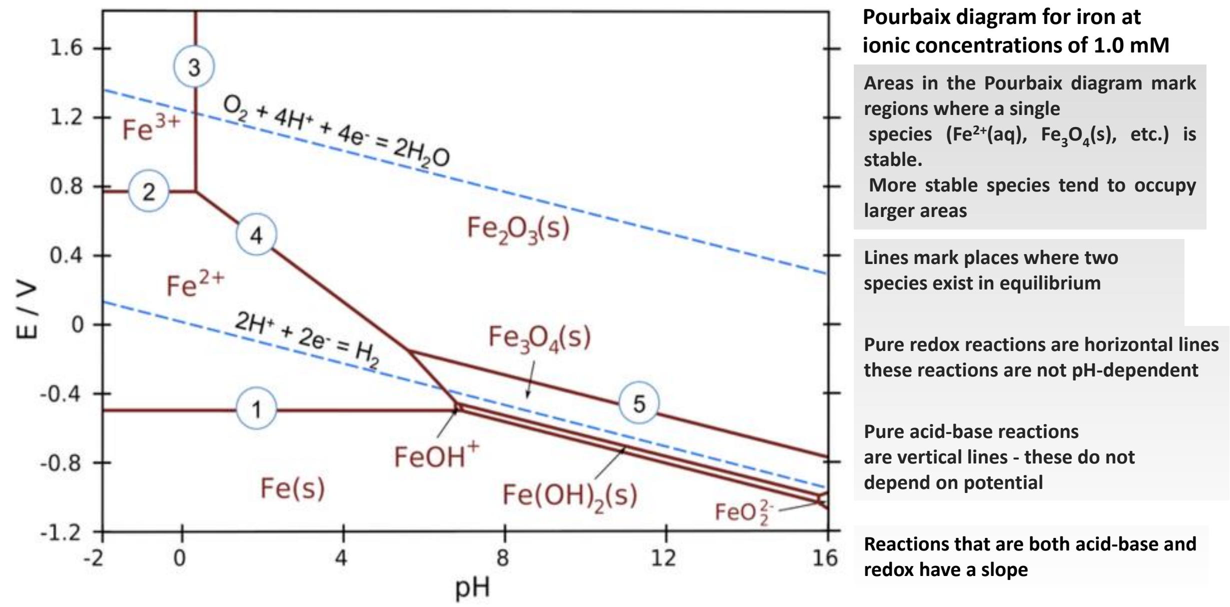

Figure 11: Pourbaix diagram for iron (Reproduced from Western Oregon University [183]. Copyright Western Oregon University 2013)

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 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 comparsion 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 (Figure 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].

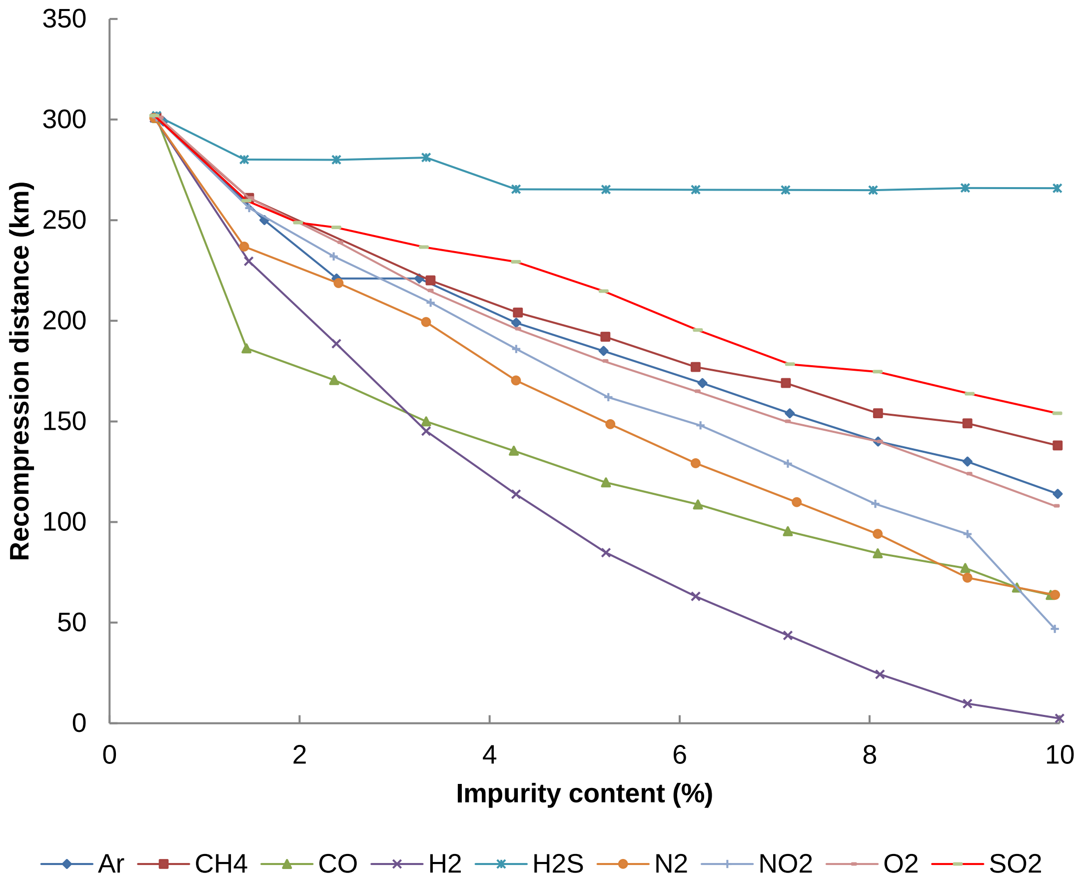

Figure 12. Relationship between recompression and impurity (Reproduced from Lucci et al. [41]. Copyright The International Society of Offshore and Polar Engineers 2011)

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 (Figure 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 curve will be moved further to the left (Figure 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 [216,176].

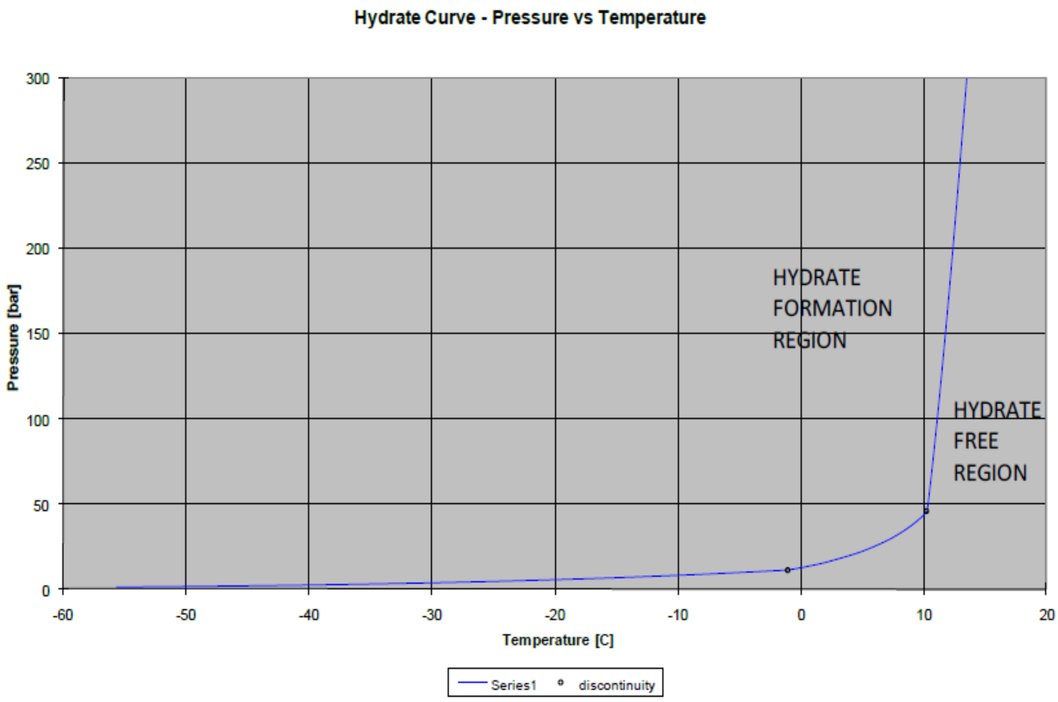

Figure 13. CO_2 hydrate curve with free water (Reproduced from Scottish Power CCS Consortium [219]. Copyright Scottish Power CCS Consortium 2011)

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, 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].

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

An industrial-scale experiment on the release and dispersal of CO_2 known as CO_2PIPETRANS was conducted by BP and Shell (Figure 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 $6.1X10^{-4}$ 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].

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

Section	Post-FEED (£million)
Capture	1,656.5 (49%)
Transport	281.2 (21%)
Storage	207.8 (16%)
Total	1,145.5 (85%)
Risk & Contingency	194.8 (15%)
Total Project Capex	1,340 (100%)
Estimated Range	1,200 to 1,519

5.2 Financing options and capital availability

The CO_2 transport infrastructure requires a large capital investment. 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. Imporantly, 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 (Figure 15) need to be gathered and utilised to implement 2nd and 3rd generation CCS technologies in the near future.

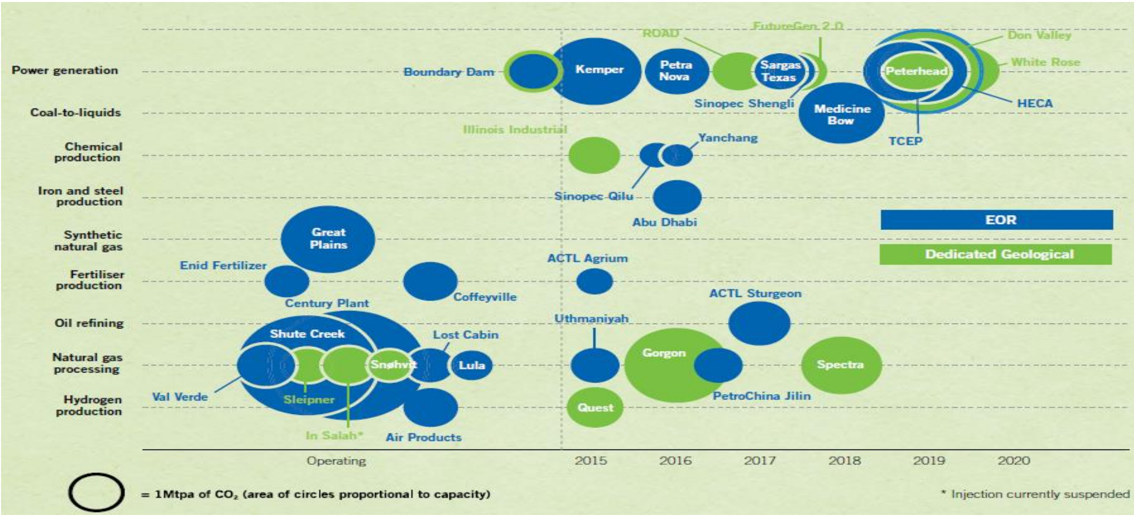

Figure 15: Actual and expected operation dates for large-scale CCS projects in the Operate, Execute and Define stages by industry and storage type (Reproduced fro Global CCS Institute [20]. Copyright Global CCS Institute 2014)

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].

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	$3,100/km/a	2.3%/a of total capital cost	$3,250/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 [ºC]	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]	$6.06x10^{-4}$	-	-	-	-	-	-	$5.5x10^{-4}$

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 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, athough 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 beginnng 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 5L 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 occurence 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 undestood, 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 reviewd 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 intergrity 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.

REFERENCES

[1] IPCC. Climate Change Threatens Irreversible and Dangerous impacts, but options exist to limit its effects 2014. https://www.ipcc.ch/pdf/ar5/prpc_syr/11022014_syr_copenhagen.pdf (accessed June 8, 2017).

[2] UN. Adoption of the Paris Agreement. United Nations Framework Convenction on Climate Change. Paris: 2015

[3] Knoope MMJ, Ramírez A, Faaij APC. A state-of-the-art review of techno-economic models predicting the costs of CO_2 pipeline transport. International Journal of Greenhouse Gas Control 2013;16:241–270. doi: 10.1016/j.ijggc.2013.01.005.

[4] Thiruvenkatachari R, Su S, Yu XX, Bae J-S. Application of carbon fibre composites to CO_2 capture from flue gas. International Journal of Greenhouse Gas Control 2013;13:191–200. doi: 10.1016/j.ijggc.2012.12.014.

[5] Kennedy, A., Hood, C., Burghgraeve,S., Quadrelli R. CO_2 Emissions from Fuel combustion Highlights. Paris: 2015.

[6] Olivier, J.G, Janssens-Maenhout G, Muntean, M. JAHWP. Trends in Global CO_2 Emissions. Hague: 2015.

[7] Ramanathan V, Feng Y. On avoiding dangerous anthropogenic interference with the climate system: formidable challenges ahead. Proceedings of the National Academy of Sciences of the United States of America 2008;105:14245–50. doi: 10.1073/pnas.0803838105.

[8] Smith JB, Schneider SH, Oppenheimer M, Yohe GW, Hare W, Mastrandrea MD, et al. Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) reasons for concern. Proceedings of the National Academy of Sciences of the United States of America 2009;106:4133–7. doi:10.1073/pnas.0812355106.

[9] Peters GP, Andrew RM, Boden T, Canadell JG, Ciais P, Le Quéré C, et al. The challenge to keep global warming below 2°C. Nature Climate Change 2013;3:4–6.

[10] IEA. Tracking Clean Energy Progress 2015. Energy Technology Perspectives 2015 Excerpt. IEA Input to the Clean Energy Ministerial. IEA Publications. Paris, France: 2015.

[11] Jiang R, Wang J, Guan Y. Robust unit commitment with wind power and pumped storage hydro. IEEE Transactions on Power Systems 2012;27:800–10. doi:10.1109/TPWRS.2011.2169817.

[12] Singh M, Khadkikar V, Chandra A, Varma RK. Grid interconnection of renewable energy sources at the distribution level with power-quality improvement features. IEEE Transactions on Power Delivery 2011;26:307–15. doi:10.1109/TPWRD.2010.2081384.

[13] Rochelle GT. Amine Scrubbing for CO_2 Capture. Science 2009;325:1652–4. doi:10.1126/science.1176731.

[14] Edgar Santoyo-Castelazo AA. Sustainability assessment of energy systems: integrating environmental, economic and social aspects. Journal of Cleaner Production 2014;80:119–138. doi: 10.1016/j.jclepro.2014.05.061.

[15] Global CCS Institute. The Global Status of CCS. https://www.globalccsinstitute.com/publications/global-status-ccs-2013; 2013

(accessed June 8, 2017).

[16] Suzuki T, Toriumi M, Sakemi T, Masui N, Yano S, Fujita H, et al. Conceptual Design of CO_2 Transportation System for CCS. GHGT-11 2013;37:2989–96. doi: 10.1016/j.egypro.2013.06.185.

[17] Neele F, Mikunda T, Seebregts A, Santen S, van der Burgt A, Stiff S, et al. A Roadmap Towards a European CO_2 Transport Infrastructure. Energy Procedia 2013;37:7774–82. doi:10.1016/j.egypro.2013.06.724.

[18] Azar C, Lindgren K, Larson E, Möllersten K. Carbon capture and storage from fossil fuels and biomass–Costs and potential role in stabilizing the atmosphere. Climatic Change 2006;74:47–79. doi: 10.1007/s10584-005-3484-7.

[19] Connell DP. Carbon Dioxide Capture Options for Large Point Sources in the Midwestern United States: An Assessment of Candidate Technologies. Final Report, CONSOL Energy Inc 2005:7.

[20] Global CCS Institute. The Global Status of CCS. http://www.globalccsinstitute.com/publications/global-status-ccs-2014; 2014 (accessed June 8, 2017).

[21] Global CCS Institute. Capacity charging mechanism for shared CO_2 transportation and storage infrastructure. https://www.globalccsinstitute.com/publications/capacity-charging-mechanism-shared-co2-transportation-and-storage-infrastructure; 2013 (accessed June 8, 2017).

[22] Al-Juaied M, Whitmore A. Realistic costs of carbon capture. Belfer Center for Science and International Affairs, Discussion Paper 2009;8.

[23] Chandel MK, Pratson LF, Williams E. Potential economies of scale in CO_2 transport through use of a trunk pipeline. Energy Conversion and Management 2010;51:2825–34. doi: 10.1016/j.enconman.2010.06.020.

[24] Coleman DL. Transport infrastructure rationale for carbon dioxide capture & storage in the European Union to 2050. Energy Procedia 2009;1:1673–81. doi: 10.1016/j.egypro.2009.01.219.

[25] Jung J-Y, Huh C, Kang S-G, Seo Y, Chang D. CO_2 transport strategy and its cost estimation for the offshore CCS in Korea. Applied Energy 2013;111:1054–60. doi: 10.1016/j.apenergy.2013.06.055.

[26] Liu H, Gallagher KS. Preparing to ramp up large-scale CCS demonstrations: An engineering-economic assessment of CO_2 pipeline transportation in China. International Journal of Greenhouse Gas Control 2011;5:798–804. doi:10.1016/j.ijggc.2010.11.005.

[27] Herzog H, Golomb D. Carbon capture and storage from fossil fuel use. Encyclopedia of Energy 2004;1:1–11.

[28] Chapoy A, Burgass R, Tohidi B, Austell JM, Eickhoff C. Effect of Common Impurities on the Phase Behavior of Carbon-Dioxide-Rich Systems: Minimizing the Risk of Hydrate Formation and Two-Phase Flow. SPE Journal 2011;16:921-930. doi: 10.2118/123778-PA.

[29] Dooley JJ, Dahowski RT, Davidson CL. Comparing Existing Pipeline Networks with the Potential Scale of Future US CO_2 Pipeline Networks. Energy Procedia 2009;1:1595–602. doi: 10.1016/j.egypro.2009.01.209.

[30] Cooper R. National Grid's COOLTRANS research programme. Journal of Pipeline Engineering 2012;11.

[31] Nykvist B. Ten times more difficult: Quantifying the carbon capture and storage challenge. Energy Policy 2013;55:683–689. doi:10.1016/j.enpol.2012.12.026.

[32] Spinelli CM, Demofonti G, Biagio M Di, Lucci A. CO_2 Full Scale Facilities Challenges For EOR/CCTS Testing On Transportation Issues, The International Society of Offshore and Polar Engineers; 2012.

[33] Lucci, A., Demofonti, G., Tudori, P. and Spinelli CM. CCTS (Carbon Capture Transportation & Storage) Transportation issues. The International Society of Offshore and Polar Engineers, 2011.

[34] Godec ML. From CO_2 -EOR to CCS: Prospects and Challenges of Combining CO_2 -EOR with Storage. Advanced Resource International 2012. https://www.iea.org/media/workshops/2012/ieaopec/Godec.pdf (accessed June 8, 2017).

[35] International Energy Agency Greenhouse Gas Programme. CO_2 Capture at gas fired power plants. http://www.ieaghg.org/docs/General_Docs/Reports/2012-08.pdf; 2012 (Accessed June 7, 2017).

[36] Viebahn P, Vallentin D, Höller S. Prospects of carbon capture and storage (CCS) in India's power sector - An integrated assessment. Applied Energy 2014;117:62–75. doi: 10.1016/j.apenergy.2013.11.054.

[37] Wang J, Ryan D, Anthony EJ, Wildgust N, Aiken T. Effects of impurities on CO_2 transport, injection and storage. Energy Procedia 2011;4:3071–8. doi: 10.1016/j.egypro.2011.02.219.

[38] Wetenhall B, Race JM, Downie MJ. The Effect of CO_2 Purity on the Development of Pipeline Networks for Carbon Capture and Storage Schemes. International Journal of Greenhouse Gas Control 2014;30:197–211. doi: 10.1016/j.ijggc.2014.09.016.

[39] Verma S, Oakes CS, Chugunov N, Ramakrishnan TS. Effect of contaminants on the thermodynamic properties of CO_2 -rich fluids and ramifications in the design of surface and injection facilities for geologic CO_2 sequestration. Energy Procedia 2011;4:2340–7. doi:10.1016/j.egypro.2011.02.125.

[40] Race JM, Seevam PN, Downie MJ. Challenges for offshore transport of anthropogenic carbon dioxide. ASME 2007 26th International Conference on Offshore Mechanics and Arctic Engineering, American Society of Mechanical Engineers; 2007,589–602.

[41] Lucci, A., Demofonti, G. and Spinelli CM. CO_2 Anthropogenic Pipeline Transportation. The International Society of Offshore and Polar Engineers, 2011.

[42] Lewicki, J.L., Birkholzer, J. & Tsang C. Natural and industrial analogues for leakage of CO_2 from storage reservoirs: identification of features, events, and processes and lessons learned. Environmental Geology 2007. doi:10.1007/s00254-006-0479-7.

[43] Cole IS, Corrigan P, Sim S, Birbilis N. Corrosion of pipelines used for CO_2 transport in CCS: Is it a real problem? International Journal of Greenhouse Gas Control 2011;5:749–56 doi:10.1016/j.ijggc.2011.05.010.

[44] Thomas DC, Kerr HR. Introduction. Carbon Dioxide Capture for Storage in Deep Geologic Formations, Elsevier. Amsterdam: 2005, 1–15. doi: 10.1016/B978-008044570-0/50085-4.

[45] Wetenhall B, Race J, Downie M. The Effect of Impurities on a Simplified CCS Network, Pipeline Simulation Interest Group; 2013.

[46] Yoon-Seok Choi, Srdjan Nesic and DY. Effect of Impurities on the Corrosion Behavior of CO_2 Transmission Pipeline Steel in Supercritical CO_2−Water Environments.

Corrosion studies conducted on both mild steel and a corrosion resistant alloy in supercritical CO_2 with H_2O, O_2, and SO_2 impurities are outlined., Athens Ohio: NACE International; 201AD, 5. doi:10.1021/es102578c.

[47] Bachu S, Gunter WD. Overview of acid-gas injection operations in Western Canada. In: E.S. Rubin, C.F. Gilboy, M. Wilson, T. Morris, J.Gale, Thambimuthu K. Greenhouse Gas Control Technologies 7, Elsevier. Oxford: 2005, 443–448. doi:10.1016/B978-008044704-9/50045-8.

[48] Carter LD. Capture and storage of CO_2 with other air pollutants. http://www.uscsc.org/Files/Admin/Educational_Papers/IEA_Co-Sequestration_Paper.pdf; 2010.

[49] Global CCS Institute. Overview of CCS large scale projects, 2017. https://www.globalccsinstitute.com/projects/large-scale-ccs-projects (accessed June 7, 2017).

[50] Global CCS Institute. ROAD project: Flow assurance and control philosophy. https://www.globalccsinstitute.com/publications/road-project-flow-assurance-and-control-philosophy; 2013 (accessed June 8, 2017).

[51] Jackson DFB. Filtering Elevation Profile Data To Improve Performance of Multiphase Pipeline Simulations. Society of Petroleum Engineers doi:102118/114884-MS 2008.

[52] Teh C, Barifcani A, Pack D, Tade MO. The importance of ground temperature to a liquid carbon dioxide pipeline. International Journal of Greenhouse Gas Control 2015;39:463–9. doi:10.1016/j.ijggc.2015.06.004.

[53] Hetland J, Barnett J, Read A, Zapatero J, Veltin J. CO_2 Transport Systems Development: Status of Three Large European CCS Demonstration Projects with EEPR Funding. Energy Procedia 2014;63:2458–66. doi: 10.1016/j.egypro.2014.11.268.

[54] McCoy S, Rubin E. An engineering-economic model of pipeline transport of CO_2 with application to carbon capture and storage. International Journal of Greenhouse Gas Control 2008;2:219–29. doi:10.1016/S1750-5836(07)00119-3.

[55] Zhang ZX, Wang GX, Massarotto P, Rudolph V. Optimization of pipeline transport for CO_2 sequestration. Energy Conversion and Management 2006;47:702–15. doi:10.1016/j.enconman.2005.06.001.

[56] Lee J-Y, Keener TC, Yang YJ. Potential Flue Gas Impurities in Carbon Dioxide Streams Separated from Coal-Fired Power Plants. Journal of the Air & Waste Management Association 2009;59:725–32. doi:10.3155/1047-3289.59.6.725.

[57] Jung, W., & Nicot J-P. Impurities in CO_2-Rich Mixtures Impact CO_2 Pipeline Design: Implications for Calculating CO_2 Transport Capacity. Society of Petroleum Engineers 2010.

[58] Eickhoff C, Neele F, Hammer M, Dibiagio M, Hofstee C, Koenen M, et al. IMPACTS: Economic trade-offs for CO_2 impurity specification. Energy Procedia 2014;63:7379–7388.

[59] Tan Y, Nookuea W, Li H, Thorin E, Yan J. Property impacts on Carbon Capture and Storage (CCS) processes: A review. Energy Conversion and Management 2016;118. doi:10.1016/j.enconman.2016.03.079.

[60] Nakaten N, Schlüter R, Azzam R, Kempka T. Development of a techno-economic model for dynamic calculation of cost of electricity, energy demand and CO_2 emissions of an integrated UCG–CCS process. Energy 2014;66:779–90.

doi:10.1016/j.energy.2014.01.014.

[61] International Energy Agency Greenhouse Gas R&D Programme. Transmission of CO_2 and Energy. Cheltenham, International Energy Agency Greenhouse Gas R&D Programme. Cheltenham: 2002.

[62] Roddy DJ. Development of a CO_2 network for industrial emissions. Applied Energy 2012;91:459–65. doi:10.1016/j.apenergy.2011.10.016.

[63] Belaissaoui B, Cabot G, Cabot M-S, Willson D, Favre E. An energetic analysis of CO_2 capture on a gas turbine combining flue gas recirculation and membrane separation. Energy 2012;38:167–75. doi:10.1016/j.energy.2011.12.018.

[64] Vandeginste V, Piessens K. Pipeline design for a least-cost router application for CO_2 transport in the CO_2 sequestration cycle. Internatinal Journal of Greenhouse Gas Control 2008;2:571–81. doi: 10.1016/j.ijggc.2008.02.001.

[65] Kirat D, Ahamada I. The impact of the European Union emission trading scheme on the electricity-generation sector. Energy Economics 2011;33:995–1003. doi:10.1016/j.eneco.2011.01.012.

[66] Lone S, Cockerill T, Macchietto S. The techno-economics of a phased approach to developing a UK carbon dioxide pipeline network. Journal of Pipeline Engineering 2010;9:223–34.

[67] Parfomak PW, Folger P. Pipelines for carbon dioxide (CO_2) control: Network needs and cost uncertaintieses. Carbon Capture and Greenhouse Gases 2013:115–28.

[68] Knoope MMJ, Ramírez A, Faaij APC. Economic Optimization of CO2 Pipeline Configurations. Energy Procedia 2013;37:3105–12. doi:10.1016/j.egypro.2013.06.196.

[69] Knoope MMJ, Guijt W, Ramírez A, Faaij APC. Improved cost models for optimizing CO_2 pipeline configuration for point-to-point pipelines and simple networks. International Journal of Greenhouse Gas Control 2014;22:25–46. doi: 10.1016/j.ijggc.2013.12.016.

[70] George K, Waard K de, Wang S, Nesic S. Modeling of CO_2 Corrosion of Mild Steel in the Presence of High Partial Pressures of CO_2 and Acetic Acid - Electrochemical Modeling and a Modification to the de Waard Corrosion Model, NACE International; 2004.

[71] George K, Waard K de, Nesic S. Electrochemical Investigation and Modeling of Carbon Dioxide Corrosion of Carbon Steel in the Presence of Acetic Acid, NACE International 2004.

[72] Mora-Mendoza J., Turgoose S. Fe_3C influence on the corrosion rate of mild steel in aqueous CO_2 systems under turbulent flow conditions. Corrosion Science 2002;44:1223–46. doi:10.1016/S0010-938X(01)00141-X.

[73] Eslami, A., Chen, W., Worthingham, R., Kania, R., & Been J. Effect Of CO_2 On Near-Neutral Ph Stress Corrosion Cracking Initiation Of Pipeline Steel. NACE International 2010.

[74] Beverskog B, Puigdomenech I. Revised pourbaix diagrams for chromium at 25–300°C. Corrosion Science 1997;39:43–57. doi:http://dx.doi.org/10.1016/S0010-938X(97)89244-X.

[75] Ashassi-Sorkhabi H, Ghasemi Z, Seifzadeh D. The inhibition effect of some amino acids towards the corrosion of aluminum in 1M HCl+1M H_2SO_4 solution. Applied Surface Science 2005;249:408–18. doi:10.1016/j.apsusc.2004.12.016.

[76] Patchigolla K, Oakey JE, Anthony EJ. Understanding dense phase CO_2 corrosion problems. Energy Procedia 2014;63:2493–9. doi:10.1016/j.egypro.2014.11.272.

[77] Ghazi, N., Race J. Techno-economic modelling and analysis of CO_2 pipelines. The Journal of Pipeline Engineering 2013;12:83–92.

[78] Koornneef J, Spruijt M, Molag M, Ramírez A, Turkenburg W, Faaij A. Quantitative risk assessment of CO_2 transport by pipelines—A review of uncertainties and their impacts. Journal of Hazardous Materials 2010;177:12–27.

[79] Oosterkamp A, Ramsen J. State-of-the-Art Overview of CO_2 Pipeline Transport with relevance to offshore pipelines. Polytec Report Number: POL-O-2007-138-A 2008.

[80] Barrie J, Brown K, Hatcher PR, Schellhase HU. Carbon dioxide pipelines: A preliminary review of design and risks. Greenhouse Gas Control Technologies 2004;7:315–20.

[81] Barker R, Hua Y, Neville A. Internal corrosion of carbon steel pipelines for dense-phase CO_2 transport in carbon capture and storage (CCS) – a review. International Materials Reviews 2017;62:1–31.

[82] Aursand P, Hammer M, Munkejord ST, Wilhelmsen Ø. Pipeline transport of CO_2 mixtures: Models for transient simulation. International Journal of Greenhouse Gas Control 2013;15:174–85.

[83] Spinelli, C.M., Demofonti, G., Lucci, A., Di Biagio, M. and Ahmad, M., 2014 A. CO_2 Pipeline Transportation New Needs. In The Twenty-fourth International Ocean and Polar Engineering Conference. International Society of Offshore and Polar Engineers., Busan: International Offshore and Polar Engineering Conference 2014.

[84] Demofonti G, Biagio M Di, Fonzo A, Lucci A, Spinelli CM. Definition of Requirements for Safe and Reliable CO_2 Transportation Network Through an Integrated Laboratory, Computer Modelling and Full Scale Methodology, International Society of Offshore and Polar Engineers 2013.

[85] Drescher M, Wilhelmsen Ã, Aursand P, Aursand E, de Koeijer G, Held R. Heat Transfer Characteristics of a Pipeline for CO_2 Transport with Water as Surrounding Substance. GHGT-11 2013;37:3047–56.

[86] Seevam PN, Race JM, Downie MJ, Hopkins P. Transporting the next generation of CO_2 for carbon, capture and storage: the impact of impurities on supercritical CO_2 pipelines. 2008 7th International Pipeline Conference, American Society of Mechanical Engineers; 2008, p. 39–51.

[87] Bratfos HA, Leinum BH, Torbergsen LE, Saugerud OT. Challenges to the pipeline transportation of dense CO_2. Global Pipeline Monthly, Hovik, Norway: 2007.

[88] Mahgerefteh H, Atti O. Modeling low-temperature induced failure of pressurized pipelines. AIChE Journal 2006;52:1248–56. doi:10.1002/aic.10719.

[89] Xu N, Dong J, Wang Y, Shi J. High pressure vapor liquid equilibria at 293 K for systems containing nitrogen, methane and carbon dioxide. Fluid Phase Equilibria 1992;81:175–86. doi:10.1016/0378-3812(92)85150-7.

[90] Svandal A, Kuznetsova T, Kvamme B. Thermodynamic properties and phase transitions in the $H_2O/CO_2/CH_4$ system. Fluid Phase Equilibria 2006;246:177–84. doi:10.1016/j.fluid.2006.06.003.

[91] Seitz JC, Blencoe JG, Bodnar RJ. Volumetric properties for $\{x1CO_2+x2CH_4+(1-x1-x2)N_2\}$ at the pressures (19.94, 39.94, 59.93, and 99.93) MPa and temperatures (323.15, 373.15, 473.15, and 573.15) K. The Journal of Chemical Thermodynamics

1996;28:539–50. doi:10.1006/jcht.1996.0050.

[92] Bezanehtak K, Combes GB, Dehghani F, Foster NR, Tomasko DL. Vapor-liquid equilibrium for binary systems of carbon dioxide methanol, hydrogen methanol, and hydrogen carbon dioxide at high pressures. Journal of Chemical & Engineering Data 2002;47:161–8.

[93] Lovseth SW, Skaugen G, Jacob Stang HG, Jakobsen JP, Wilhelmsen Ø, Span R, et al. CO_2 Mix Project: Experimental Determination of Thermo Physical Properties of CO_2-Rich Mixtures. Energy Procedia 2013;37:2888–96. doi:10.1016/j.egypro.2013.06.174.

[94] Bahadori A, Vuthaluru H. A Simple Method for Prediction of Transport Properties of Carbon Dioxide. Asia Pacific Health, Safety, Security and Environment Conference, Jakarta, Indonesia: Society of Petroleum Engineers 2009.

[95] Botnen HA, Omar AM, Aavatsmark I, Alendal G, Johannessen T. PVTx Properties of a Two-phase CO_2 Jet from Ruptured Pipeline. Energy Procedia 2013;37:3031–8.

[96] Clausen S, Munkejord ST. Depressurization of CO_2 – a Numerical Benchmark Study. Energy Procedia 2012;23:266–73. doi:10.1016/j.egypro.2012.06.021.

[97] Dauber IF, Gernert D-IJ, Span IR, Schley IP. On the use of highly accurate thermodynamic property models in process simulation. International Gas Research Conference Proceedings 2011;3011–3018.

[98] Fornari RE, Alessi P, Kikic I. High pressure fluid phase equilibria: experimental methods and systems investigated (1978–1987). Fluid Phase Equilibria 1990;57:1–33. doi:http://dx.doi.org/10.1016/0378-3812(90)80010-9.

[99] Jacob Stang HG, Løvseth SW, Størset SØ, Malvik B, Rekstad H. Accurate Measurements of CO_2 Rich Mixture Phase Equilibria Relevant for CCS Transport and Conditioning. GHGT-11 2013;37:2897–903. doi: 10.1016/j.egypro.2013.06.175.

[100] Li H, Yan J. Evaluating cubic equations of state for calculation of vapor–liquid equilibrium of CO_2 and CO_2-mixtures for CO_2 capture and storage processes. Applied Energy;86:826–36. doi: 10.1016/j.apenergy.2008.05.018.

[101] Shock EL, Helgeson HC, Sverjensky DA. Calculation of the thermodynamic and transport properties of aqueous species at high pressures and temperatures: Standard partial molal properties of inorganic neutral species. Geochimica et Cosmochimica Acta 1989;53:2157–83. doi: 10.1016/0016-7037(89)90341-4.

[102] Witkowski, S A, Rusin, A, Majkut, M RS. Comprehensive analysis of pipeline transportation systems for CO_2 sequestration. Thermodynamics and safety problems. Thermodynamics and Safety Problems Energy Conversion and Management 2013;76:665–73.

[103] Lucci A, Demofonti G, Spinelli CM. CO_2 Anthropogenic Pipeline Transportation, The International Society of Offshore and Polar Engineers 2011.

[104] Aspelund A, Mølnvik MJ, De Koeijer G. Ship Transport of CO_2: Technical Solutions and Analysis of Costs, Energy Utilization, Exergy Efficiency and CO_2 Emissions. Carbon Capture and Storage. Chemical Engineering Research and Design 2006;84:847–55. doi: 10.1205/cherd.5147.

[105] Chaczykowski M, Osiadacz AJ. Dynamic simulation of pipelines containing dense phase/supercritical CO_2-rich mixtures for carbon capture and storage. International Journal of Greenhouse Gas Control 2012;9:446–56. doi:10.1016/j.ijggc.2012.05.007.

[106] Li H, Yan J. Impacts of equations of state (EOS) and impurities on the volume

calculation of CO_2 mixtures in the applications of CO_2 capture and storage (CCS) processes. Applied Energy 2009;86:2760–70. doi 10.1016/j.apenergy.2009.04.013.

[107] Mazzoccoli M, Bosio B, Arato E. Pressure-density-temperature measurements of binary mixtures rich in CO_2 for pipeline transportation in the CCS process. Journal of Chemical and Engineering Data 2012;57:2774–83.

[108] Jensen MD, Pei P, Snyder AC, Heebink L V, Botnen LS, Gorecki CD, et al. Methodology for Phased Development of a Hypothetical Pipeline Network for CO_2 Transport during Carbon Capture, Utilization, and Storage. Energy & Fuels 2013;27:4175–82.

[109] Li H, Wilhelmsen Ø, Lv Y, Wang W, Yan J. Viscosities, thermal conductivities and diffusion coefficients of CO_2 mixtures: Review of experimental data and theoretical models. International Journal of Greenhouse Gas Control 2011;5:1119–39. doi: 10.1016/j.ijggc.2011.07.009.

[110] Lucci A, Demofonti G, Tudori P, Spinelli CM. CCTS (Carbon Capture Transportation & Storage) Transportation Issues. International Society of Offshore and Polar Engineers 2011.

[111] Xiang, Y., Wang, Z., Yang, X., Li, Z. and Ni W. The upper limit of moisture content for supercritical CO_2 pipeline transpor. The Journal of Supercritical Fluids 2012;67:14–21.

[112] Lim JY, McKrell TJ, Eastwick G, Ballinger RG. Corrosion of Materials in Supercritical Carbon Dioxide Environments, NACE International; 2008.

[113] Farelas F, Choi YS, Nesic S. Effects of CO_2 Phase Change SO_2 Content And Flow On the Corrosion of CO_2 Transmission Pipeline Steel. Corrosion 2012.

[114] Bonis M. Managing the Corrosion Impact of Dense Phase CO_2 Injection for an EOR Purpose. Abu Dhabi International Petroleum Conference and Exhibition, Abu Dhabi, UAE: Society of Petroleum Engineers 2012.

[115] Koornneef J, Ramírez A, Turkenburg W, Faaij A. The environmental impact and risk assessment of CO_2 capture, transport and storage – An evaluation of the knowledge base. Progress in Energy and Combustion Science 2012;38:62–86. doi: 10.1016/j.pecs.2011.05.002.

[116] Kongshaug KO, Seiersten M. Baseline Experiments for the Modeling of Corrosion at High CO_2 Pressure, NACE International 2004.

[117] International Energy Agency Greenhouse Gas Programme. Development of a global CO_2 pipeline infrastructure. h http://ieaghg.org/docs/General_Docs/Reports/2010-13.pdf; 2010 (accessed June 8, 2017).

[118] Granite EJ, O'Brien T. Review of novel methods for carbon dioxide separation from flue and fuel gases. Fuel Processing Technology 2005;86:1423–34. doi: 10.1016/j.fuproc.2005.01.001.

[119] Alhajaj A, Shah N. Design and Analysis of CO_2 Capture, Transport, and Storage Networks. Carbon Management Technology Conference, Orlando, Florida, USA: Carbon Management Technology Conference 2012.

[120] European CCS Demonstration Project Network. A public report outlining the progress, lessons learnt and details of the European CCS Demonstration Project Network 2012.

[121] Thomas DC, Benson SM. Carbon Dioxide Capture for Storage in Deep Geologic Formations-Results from the CO_2 Capture Project: Vol 1-Capture and Separation of Carbon Dioxide from Combustion, Vol 2-Geologic Storage of Carbon Dioxide with Monitoring and Verification. Elsevier 2005.

[122] Yang, S., Akhiyarov, D., Erickson, D. and Winning. Challenges Associated With Flow Assurance Modeling of CO_2-Rich Pipelines. NACE International 2012.

[123] Choi, Y., Nesic, S. and Young D. Effect of Impurities on the Corrosion Behavior of CO_2 Transmission Pipeline Steel in Supercritical CO_2− Water Environments. Environmental Science & Technology 2010;44:9233–8.

[124] Dugstad, A., Morland, B. and Clausen S. Corrosion of transport pipelines for CO_2 Effect of water ingress. Energy Procedia 2011;4:3063–3070.

[125] Ruhl AS, Kranzmann A. Corrosion behavior of various steels in a continuous flow of carbon dioxide containing impurities. International Journal of Greenhouse Gas Control 2012;9:85–90. 10.1016/j.ijggc.2012.03.005.

[126] de Visser E, Hendriks C, Barrio M, Mølnvik MJ, de Koeijer G, Liljemark S, et al. Dynamis CO_2 quality recommendations. International Journal of Greenhouse Gas Control 2008;2:478–84. doi: 10.1016/j.ijggc.2008.04.006.

[127] Global CCS Institute. Technical guidance on hazard analysis for onshore carbon capture installations and onshore pipelines. https://www.globalccsinstitute.com/publications/technical-guidance-hazard-analysis-onshore-carbon-capture-installations-and-onshore-pip; 2010 (accessed June 8, 2017).

[128] Aspelund A, Jordal K. Gas conditioning—the interface between CO_2 capture and transport. International Journal of Greenhouse Gas Control 2007;1:343–54.

[129] Brown S, Beck J, Mahgerefteh H, Fraga ES. Global sensitivity analysis of the impact of impurities on CO_2 pipeline failure. Reliability Engineering & System Safety 2013;115:43–54. doi:10.1016/j.ress.2013.02.006.

[130] Kumar S, Zarzour O, King G. Design of CO_2 dehydration and compression facilities. Society of Petroleum Engineers - 14th Abu Dhabi International Petroleum Exhibition and Conference 2010, ADIPEC 2010, vol. 1, 2010, p. 773–81.

[131] Mohitpour M, Botros KK, Van Hardeveld T. Pipeline Pumping and Compression Systems: A Practical Approach. ASME Press; 2008.

[132] Jung W, Nicot JP. Impurities in CO_2 - Rich Mixtures Impact CO_2 Pipeline Design: Implications for Calculating CO_2 Transport Capacity. SPE International Conference on CO_2 Capture, Storage, and Utilization, New Orleans, Louisiana, USA: Society of Petroleum Engineers 2010.

[133] American Electric Power. CO_2 Compression Report. American Electric Power Mountaineer CCS II Project: Phase 1. http://www.globalccsinstitute.com/publications/CO_2-compression-report; 2011 (accessed June 8, 2017).

[134] McCoy ST, Rubin ES. An engineering-economic model of pipeline transport of CO_2 with application to carbon capture and storage. International Journal of Greenhouse Gas Control 2008;2:219–29.

[135] McCoy ST. The economics of carbon dioxide transport by pipeline and storage in saline aquifers and oil reservoirs. PhD Thesis 2008.

[136] Fimbres Weihs GA, Wiley DE. Steady-state design of CO_2 pipeline networks for minimal cost per tonne of CO_2 avoided. International Journal of Greenhouse Gas Control 2012;8:150–68. doi:10.1016/j.ijggc.2012.02.008.

[137] Serpa J, Morbee J, Tzimas E. Technical and economic characteristics of a CO_2 transmission pipeline infrastructure. European Commission, Joint Research Centre Report 2011.

[138] Spycher N, Pruess K, Ennis-King J. CO_2-H_2O mixtures in the geological sequestration of CO_2. I. Assessment and calculation of mutual solubilities from 12 to 100°C and up to 600 bar. Geochimica et Cosmochimica Acta 2003;67:3015–31. doi: 10.1016/S0016-7037(03)00273-4.

[139] Ikeh L, Race JM, Aminu AG. Comparing the Effects of Pipe Diameter on Flow Capacity of a CO_2 Pipeline. Nigeria Annual International Conference and Exhibition, Abuja, Nigeria: Society of Petroleum Engineers 2011.

[140] Brunsvold A, Jakobsen JP, Husebye J, Kalinin A. Case studies on CO_2 transport infrastructure: Optimization of pipeline network, effect of ownership, and political incentives. Energy Procedia 2011;4:3024–31. doi: 10.1016/j.egypro.2011.02.213.

[141] Wang Z, Cardenas GI, Fimbres Weihs GA, Wiley DE. Optimal Pipeline Design with Increasing CO_2 Flow Rates. Energy Procedia 2013;37:3089–96. doi:/10.1016/j.egypro.2013.06.194.

[142] Johnsen K, Helle K, RÃ¸neid S, Holt H. DNV recommended practice: Design and operation of CO_2 pipelines. Energy Procedia 2011;4:3032–9.

[143] Chandel MK, Pratson LF, Williams E. Potential economies of scale in CO_2 transport through use of a trunk pipeline. Energy Conversion and Management 2010;51:2825–34.

[144] Oosterkamp A, Clausen S, Postvoll W. Simulation of steady-state pipeline transmission of CO_2 ? a comparative study, Pipeline Simulation Interest Group 2013.

[145] Cole S, Itani S. The Alberta Carbon Trunk Line and the Benefits of CO_2. Energy Procedia 2013;37:6133–9. doi:http://dx.doi.org/10.1016/j.egypro.2013.06.542.

[146] Chrysostomidis I, Zakkour P, Bohm M, Beynon E, de Filippo R, Lee A. Assessing issues of financing a CO_2 transportation pipeline infrastructure. Energy Procedia 2009;1:1625–32. doi:10.1016/j.egypro.2009.01.213.

[147] Morbee J, Serpa J, Tzimas E. Optimised deployment of a European CO_2 transport network. International Journal of Greenhouse Gas Control 2012;7:48–61. doi: 10.1016/j.ijggc.2011.11.011.

[148] Nimtz M, Klatt M, Wiese B, Kühn M, Joachim Krautz H. Modelling of the CO_2 process- and transport chain in CCS systems-Examination of transport and storage processes. Chemie Der Erde - Geochemistry 2010;70:185–92.

[149] Seevam PN, Race JM, Downie MJ. 13 - Infrastructure and pipeline technology for carbon dioxide (CO_2) transport. In: Maroto-Valer MM, editor. Developments and Innovation in Carbon Dioxide (CO_2) Capture and Storage Technology, vol. 1, Woodhead Publishing2010:408–34. doi: 10.1533/9781845699574.4.408.

[150] Jensen MD, Pei P, Snyder AC, Heebink L V, Gorecki CD, Steadman EN, et al. A Phased Approach to Building a Hypothetical Pipeline Network for CO_2 Transport During CCUS. Energy Procedia 2013;37:3097–104. doi:10.1016/j.egypro.2013.06.195.

[151] Patchigolla K, Oakey JE. Design Overview of High Pressure Dense Phase CO_2 Pipeline Transport in Flow Mode. Energy Procedia 2013;37:3123–30. doi:10.1016/j.egypro.2013.06.198.

[152] Hashem A. Oil and Gas Pipeline Design maintenance and Repair 2014. https://goo.gl/oIzj1g (accessed June 8, 2017).

[153] Hashemi S.H., Howard I.C. YJR and ARM. Micro-mechanical Damage Modelling of Notched Bar Testing on Modern Pipeline Steel. Proceedings of The 15th European

Conference of Fracture, Stockholm: 2004.

[154] Coussy P, Roussanaly S, Bureau–Cauchois G, Wildenborg T. Economic CO_2 network optimization model COCATE European Project (2010-2013). Energy Procedia 2013;37:2923–31. doi:10.1016/j.egypro.2013.06.178.

[155] Billingham MA, Lee C-H, Smith L, Haines M, James SR, Goh BKW, et al. Corrosion and materials selection issues in carbon capture plants. Energy Procedia 2011;4:2020–7.

[156] Steel pipes for pipelines for combustible fluids —Technical delivery conditions Part 1. European Standard BS EN 10208–1:2009.

[157] EPSRC. Materials for Next Generation CO_2 Transport Systems (MATTRAN) 2013. http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/G061955/1.

[158] Huizinga S, de Mul L, Orzessek K, Koers R. Materials Selection and Corrosion Control for a CO_2 Transport and Injection System. Corrosion 2013, NACE International 2013.

[159] Kermani B, Daguerre F. Materials optimization for co_2 transportation in co_2 capture and storage, NACE International 2010.

[160] Papavinasam S, Zanganesh K, Li J, Emadi D, Doiron A, Salvador C, et al. Materials Issues In CO_2 Capture, Transport, And Storage Infrastructure, NACE International 2012.

[161] Seiersten M. Materials Selection for Separation, Transportation and Disposal of CO_2, NACE International 2001.

[162] Thodla R, Francois A, Sridhar N. Materials performance in supercritical co2 environments, NACE International; 2009.

[163] Behance. Pipeline Composite Repair Project 2013. http://www.behance.net/gallery/Pipeline-Composite-Repair-Project/4907953 (accessed June 8, 2017).

[164] DECC. Potential cost reductions in CCS in the power sector Discussion Paper Department of Energy and Climate Change. https://www.gov.uk/government/publications/potential-cost-reductions-in-ccs-in-the-power-sector; 2012.

[165] de Koeijer G, Henrik Borch J, Drescher M, Li H, Wilhelmsen Ø, Jakobsen J. CO_2 transport–Depressurization, heat transfer and impurities. Energy Procedia 2011;4:3008–15.

[166] Ahmad I, Gazwi RH, Elosheby IIM. Pipeline Integrity Management Through Corrosion Mitigation and Inspection Strategy in Corrosive Environment: An Experience of Arabian Gulf Oil Company in Libya. Corrosion 2011.

[167] Azevedo CRF. Failure analysis of a crude oil pipeline. Engineering Failure Analysis 2007;14:978–94. doi:10.1016/j.engfailanal.2006.12.001.

[168] Allison C, Robinson MJ. Assessment of Vented Flexible Liners For Corrosion Protection of Pipelines, NACE International 2011.

[169] Monti C, Cherubini P. Pipeline Integrity Management As A Part Of Facilities Integrity Management. Offshore Mediterranean Conference and Exhibition, Offshore Mediterranean Conference 2009.

[170] Ayello, F., Sridhar, N., Evans, K. and Thodla R. Effect of liquid impurities on corrosion of carbon steel in supercritical CO_2. Proceedings of the 8th International Pipeline Conference (IPC2010), 2010.

[171] Mohamed MF, Nor AM, Suhor MF, Singer M, Choi YS, Nešić S. Water Chemistry For Corrosion Prediction In High Pressure CO_2 Environments, NACE International 2011.

[172] Anselmo N, May JE, Mariano NA, Nascente PAP, Kuri SE. Corrosion behavior of supermartensitic stainless steel in aerated and CO2-saturated synthetic seawater. Materials Science and Engineering: A 2006;428:73–9. doi:10.1016/j.msea.2006.04.107.

[173] Collier J, Papavinasam S, Li J, Shi C, Liu P, Gravel J-P. Effect of Impurities on the Corrosion Performance of Steels in Supercritical Carbon Dioxide: Optimization of Experimental Procedure, NACE International 2013.

[174] Guo S, Xu L, Zhang L, Chang W, Lu M. Corrosion of alloy steels containing 2% chromium in CO_2 environments. Corrosion Science 2012;63:246–58. doi: 10.1016/j.corsci.2012.06.006.

[175] Paschke B, Kather A. Corrosion of Pipeline and Compressor Materials Due to Impurities in Separated CO_2 from Fossil-Fuelled Power Plants. Energy Procedia 2012;23:207–15. doi: 10.1016/j.egypro.2012.06.030.

[176] Xiang, Y., Wang, Z., Xu, C., Zhou, C., Li, Z. and Ni W. Impact of SO_2 concentration on the corrosion rate of X70 steel and iron in water-saturated supercritical CO_2 mixed with SO_2. The Journal of Supercritical Fluids 2011;58:286–94.

[177] McGrail BP, Schaef HT, Glezakou V-A, Dang LX, Owen AT. Water reactivity in the liquid and supercritical CO_2 phase: Has half the story been neglected? Energy Procedia 2009;1:3415–9. doi:10.1016/j.egypro.2009.02.131.

[178] Russick EM, Poulter GA, Adkins CLJ, Sorensen NR. Corrosive effects of supercritical carbon dioxide and cosolvents on metals. The Journal of Supercritical Fluids 1996;9:43–50.

[179] Sim S, Birbilis N, Cole IS, Corrigan P. Internal Corrosion of CO_2 Pipelines for Carbon Capture and Storage, NACE International 2013.

[180] Sumida K, Rogow DL, Mason JA, McDonald TM, Bloch ED, Herm ZR, et al. Carbon dioxide capture in metal–organic frameworks. Chemical Reviews 2011;112:724–81.

[181] Ruhl AS, Kranzmann A. Investigation of corrosive effects of sulphur dioxide, oxygen and water vapour on pipeline steels. International Journal of Greenhouse Gas Control 2013;13:9–16. doi: 10.1016/j.ijggc.2012.12.007.

[182] Nordsveen M, Nyborg SNR, Stangeland A. A Mechanistic Model for Carbon Dioxide Corrosion of Mild Steel in the Presence of Protective Iron Carbonate Films Part 1: Theory and Verification. Corrosion 2003;59.

[183] Western Oregon University. Simplified Pourbaix diagram for 1 M iron solutions. 2013. https://www.wou.edu/las/physci/ch412/pourbaix.htm (accessed June 8, 2017).

[184] Antill JE, Warburton JB. Behaviour of carbon during the corrosion of stainless steel by carbon dioxide. Corrosion Science 1967;7:645–9. doi:10.1016/0010-938X(67)80039-8.

[185] Hu X, Neville A. CO_2 erosion–corrosion of pipeline steel (API X65) in oil and gas conditions—A systematic approach. Water;267:2027–32. doi:http://dx.doi.org/10.1016/j.wear.2009.07.023.

[186] Grise SL, Saldanha BJ. Effects of Oxygen, Temperature and Salinity On Carbon Steel Corrosion in Aqueous Solutions; Model Predictions versus Laboratory Results, NACE International 2008.

[187] Dugstad, A. and Halseid M. Internal Corrosion In Dense Phase CO_2 Transport

Pipelines - State of the Art And the Need For Further R&D. NACE International 2012.

[188] Marcoulaki EC, Tsoutsias A V, Papazoglou IA. Optimal routing, design and maintenance of main pipelines considering internal corrosion. 11th International Probabilistic Safety Assessment and Management Conference and the Annual European Safety and Reliability Conference 2012, PSAM11 ESREL 2012;1: 481–90.

[189] Santhyani D. Advance study of top of line corrosion risk: Methodology and evaluation of mitigation for new pipeline. Society of Petroleum Engineers - SPE Asia Pacific Oil and Gas Conference and Exhibition, APOGCE 2013: Maximising the Mature, Elevating the Young 2013;1:106–18.

[190] Eldevik, F., Graver, B., Torbergsen, L. E. and Saugerud OT. Development of a Guideline for Safe, Reliable and Cost Efficient Transmission of CO_2 in Pipelines. Energy Procedia 2009;1:1579–85.

[191] Veltin J, Belfroid S. Dynamics of CO_2 Transport and Injection Strategies in a Depleted Gas Field. Carbon Management Technology Conference, Orlando, Florida, USA: Carbon Management Technology Conference; 2012.

[192] Sandana D, Dale M, Charles EA, Race J. Transport of Gaseous and Dense Carbon Dioxide in Pipelines: Is There an Internal Stress Corrosion Cracking Risk?, NACE International 2013.

[193] Brenna A, Lazzari L, Ormellese M. AC interference corrosion of carbon steel in cathodic protection condition: A two-steps mechanism. EUROCORR 2013 - European Corrosion Congress, 2013.

[194] Caleyo F, González JL, Hallen JM. A study on the reliability assessment methodology for pipelines with active corrosion defects. International Journal of Pressure Vessels and Piping 2002;79:77–86. doi:http://dx.doi.org/10.1016/S0308-0161(01)00124-7.

[195] Valor A, Caleyo F, Hallen JM, Velázquez JC. Reliability assessment of buried pipelines based on different corrosion rate models. Corrosion Science 2013;66:78–87. doi: 10.1016/j.corsci.2012.09.005.

[196] Cosham A, Hopkins P, Macdonald KA. Best practice for the assessment of defects in pipelines – Corrosion. Engineering Failure Analysis 2007;14:1245–65. doi: 10.1016/j.engfailanal.2006.11.035.

[197] Kapusta SD, Connell RA, Pots BFM. Corrosion Management of Wet Gas Pipelines, NACE International 1999.

[198] Olsen S, Halvorsen AM, Lunde PG, Nyborg R. CO_2 Corrosion Prediction Model-Basic Principles. Corrosion 2005.

[199] Saleem MA, Hulaibi AA. External pipeline coating performance evaluation, NACE International 2008.

[200] Morks MF, Fahim NF, Cole IS. Environmental phosphate coating for corrosion prevention in CO_2 pipelines. Materials Letters 2013;94:95–9.

[201] Neville A, Wang C. Erosion–corrosion of engineering steels—Can it be managed by use of chemicals? ICAP 2008 2009;267:2018–26. doi: 10.1016/j.wear.2009.06.041.

[202] de Koeijer G, Henrik Borch J, Drescher M, Li H, Wilhelmsen Ø, Jakobsen J. CO_2 transport–Depressurization, heat transfer and impurities. Energy Procedia 2011;4:3008–15. doi:10.1016/j.egypro.2011.02.211.

[203] Alabdulkarem A, Hwang Y, Radermacher R. Energy consumption reduction in CO_2 capturing and sequestration of an LNG plant through process integration and waste

heat utilization. International Journal of Greenhouse Gas Control 2012;10:215–28. doi:10.1016/j.ijggc.2012.06.006.

[204] International Energy Agency Greenhouse Gas Programme. Pipeline transmission of CO_2 and energy. Report PH 2002;4.

[205] Haghshenas Fard M. CFD modeling of heat transfer of CO_2 at supercritical pressures flowing vertically in porous tubes. International Communications in Heat and Mass Transfer 2010;37:98–102. doi:10.1016/j.icheatmasstransfer.2009.08.004.

[206] Span R, Gernert J, Jäger A. Accurate Thermodynamic-Property Models for CO_2-Rich Mixtures. Energy Procedia 2013;37:2914–22. doi:10.1016/j.egypro.2013.06.177.

[207] He S, Jiang P-X, Xu Y-J, Shi R-F, Kim WS, Jackson JD. A computational study of convection heat transfer to CO_2 at supercritical pressures in a vertical mini tube. ASME 2004 2nd International Conference on Microchannels and Minichannels, American Society of Mechanical Engineers 2004:297–304.

[208] Kruizenga A, Anderson M, Fatima R, Corradini M, Towne A, Ranjan D. Heat transfer of supercritical carbon dioxide in printed circuit heat exchanger geometries. Journal of Thermal Science and Engineering Applications 2011;3:31002.

[209] Munkejord ST, Bernstone C, Clausen S, de Koeijer G, Mølnvik MJ. Combining Thermodynamic and Fluid Flow Modelling for CO_2 Flow Assurance. GHGT-11 2013;37:2904–13. doi: 10.1016/j.egypro.2013.06.176.

[210] Göttlicher G. The Energetics of Carbon Dioxide Capture in Power Plants. 2004.

[211] Botero, C, Finkenrath, M., Belloni, C., Bertolo, S., D'Ercole, M., Gori, E., Tacconelli R. Thermoeconomic evaluation of CO_2 compression strategies for post-combustion CO_2 capture application. Proceedings of ASME Turbo Expo 2009: Power for Land, Sea and Air, Orlando, Florida, USA: American Society of Mechanical Engineers 2009.

[212] Gong J, Shi B, Zhao J. Natural gas hydrate shell model in gas-slurry pipeline flow. Journal of Natural Gas Chemistry 2010;19:261–6. doi:10.1016/S1003-9953(09)60062-1.

[213] Munkejord ST, Bernstone C, Clausen S, de Koeijer G, Mølnvik MJ. Combining Thermodynamic and Fluid Flow Modelling for CO_2 Flow Assurance. Energy Procedia 2013;37:2904–13. doi:10.1016/j.egypro.2013.06.176.

[214] Tenaska. Tenaska Trailblazer front end engineering design (FEED) study. https://www.globalccsinstitute.com/publications/tenaska-trailblazer-front-end-engineering-design-feed-study 2012 (accessed June 8, 2017).

[215] Munkejord ST, Jakobsen JP, Austegard A, Mølnvik MJ. Thermo- and fluid-dynamical modelling of two-phase multi-component carbon dioxide mixtures. International Journal of Greenhouse Gas Control 2010;4:589–96. doi:10.1016/j.ijggc.2010.02.003.

[216] Böser W, Belfroid S. Flow Assurance Study. Energy Procedia 2013;37:3018–30. doi:10.1016/j.egypro.2013.06.188.

[217] Garnham PJ, Tucker OD. The Longannet to Goldeneye Project: Challenges in Developing an End-to- End CCS Scheme. Carbon Management Technology Conference, Orlando, Florida, USA: Carbon Management Technology Conference 2012.

[218] Kvamme B, Kuznetsova T, Kivelæ P-H, Bauman J. Can hydrate form in carbon dioxide from dissolved water? Physical Chemistry Chemical Physics 2013;15:2063–74.

[219] UK Carbon Capture and Storage Demonstration Competition. Fluid Flow Assurance and Technical Design. UKCCS-KT. ScottishPower CCS Consortium 2011.

[220] Manan SBA, Iskandar BS, Ridzuan PD. Reliability-Based Maintenance System for Offshore Pipelines in Malaysia 2013.

[221] Veritas DN. Design and operation of CO_2 pipelines. http://www.globalccsinstitute.com/publications/design-and-operation-CO_2 -pipelines; 2010 (accessed June 8, 2017).

[222] Bravin F, Touil A, Musi A, Saysset S, Zarea M. Safety and pipe integrity: from natural gas to CO_2 transport by pipes. International Gas Union Research Conference 2011;4.

[223] Berstad T, Dørum C, Jakobsen JP, Kragset S, Li H, Lund H, et al. CO_2 pipeline integrity: A new evaluation methodology. Energy Procedia 2011;4:3000–7.

[224] Duncan IJ, Wang H. Estimating the likelihood of pipeline failure in CO_2 transmission pipelines: New insights on risks of carbon capture and storage. International Journal of Greenhouse Gas Control 2014;21:49–60. doi: 10.1016/j.ijggc.2013.11.005.

[225] Li Q, Jü H, Tang X, Li Y. CO_2/H_2S corrosion rate prediction modeling based on artificial neural network. Corrosion and Protection 2013;34:10–2.

[226] Sim S, Cavanaugh MK, Corrigan P, Cole IS, Birbilis N. Aqueous corrosion testing and neural network modeling to simulate corrosion of supercritical CO_2 pipelines in the carbon capture and storage cycle. Corrosion 2013;69:477–86.

[227] Energy Institute. Hazard analysis for offshore carbon capture platforms and offshore pipelines. https://www.globalccsinstitute.com/publications/hazard-analysis-offshore-carbon-capture-platforms-and-offshore-pipelines 2013.

[228] Gartland PO, Salomonsen JE. A Pipeline Integrity Management Strategy Based on Multiphase Fluid Flow & Corrosion Modelling. Corrosion 1999.

[229] Alonaizi F, Pevzner R, Bona A, Alshamry M, Caspari E, Gurevich B. Application of diffracted wave analysis to time-lapse seismic data for CO_2 leakage detection. Geophysical Prospecting 2014;62:197–209.

[230] Kishawy HA, Gabbar HA. Review of pipeline integrity management practices. International Journal of Pressure Vessels and Piping 2010;87:373–80. doi:10.1016/j.ijpvp.2010.04.003.

[231] Song W, Fadaei H, Sinton D. Determination of dew point conditions for CO_2 with impurities using microfluidics. Environmental Science and Technology 2014;48:3567–74.

[232] Song FM. A comprehensive model for predicting CO_2 corrosion rate in oil and gas production and transportation systems. Electrochimica Acta 2010;55:689–700. doi: 10.1016/j.electacta.2009.07.087.

[233] Lund H, Flåtten T, Tollak Munkejord S. Depressurization of carbon dioxide in pipelines–models and methods. Energy Procedia 2011;4:2984–91.

[234] Yu M, Xing X, Zhang H, Zhao J, Eadie R, Chen W, et al. Corrosion fatigue crack growth behavior of pipeline steel under underload-type variable amplitude loading schemes. Acta Materialia 2015;96:159–69. doi:10.1016/j.actamat.2015.05.049.

[235] Gorenz P, Herzog N, Egbers C. Investigation of CO_2 release pressures in pipeline cracks. EGU General Assembly Conference Abstracts, 2013;15:5816.

[236] Mazzoldi A, Picard D, Sriram PG, Oldenburg CM. Simulation-based estimates of safety distances for pipeline transportation of carbon dioxide. Greenhouse Gases:

Science and Technology 2013;3:66–83.

[237] Mazzoldi A, Hill T, Colls JJ. CFD and Gaussian atmospheric dispersion models: A comparison for leak from carbon dioxide transportation and storage facilities. Atmospheric Environment 2008;42:8046–54.

[238] DNV. Design and operation of CO_2 pipelines 2010. https://www.globalccsinstitute.com/publications/design-and-operation-co2-pipelinest (accessed June 8, 2017)

[239] Clausen S, Oosterkamp A, Strøm KL. Depressurization of a 50 km Long 24 inches CO_2 Pipeline. Energy Procedia 2012;23:256–65.

[240] Mohitpour M, Golshan H, Murray A. Pipeline design & construction: a practical approach, The American Society of Mechanical 2nd Engineers; Three Park Av., New York, NY 2003.

[241] King GG, Kumar S. How to select wall thickness, steel toughness, and operating pressure for long CO_2 pipelines. Journal of Pipeline Engineering 2010;9.

[242] Norişor M, Badea A, Dincă C. Economical And Technical Analysis Of CO_2 Transport Ways. UPB Sci Bull 2012;74.

[243] Alta T. Project Pioneer: Transporting CO_2: A non-confidential report . http://www.globalccsinstitute.com/publications; 2012.

[244] Fogg J, Hadley H. Hydraulic Considerations for Pipelines Crossing Stream Channels. US Bureau of Land Management Papers 2007:14.

[245] Gale J, Davison J. Transmission of CO_2—safety and economic considerations. Energy 2004;29:1319–28. doi: 10.1016/j.energy.2004.03.090.

[246] Finley RJ, Frailey SM, Leetaru HE, Senel O, Couëslan ML, Scott M. Early Operational Experience at a One-million Tonne CCS Demonstration Project, Decatur, Illinois, USA. Energy Procedia 2013;37:6149–55. doi:10.1016/j.egypro.2013.06.544.

[247] Huh C, Kang S-G, Cho M-I, Baek J-H. Effect of water and nitrogen impurities on CO_2 pipeline transport for geological storage. Energy Procedia 2011;4:2214–21. doi:10.1016/j.egypro.2011.02.109.

[248] Eldevik F, Graver B, Torbergsen LE, Saugerud OT. Development of a Guideline for Safe, Reliable and Cost Efficient Transmission of CO_2 in Pipelines. Energy Procedia 2009;1:1579-1585, doi:10.1016/j.egypro.2009.01.207.

[249] International Energy Agency Greenhouse Gas Programme. Corrosion and materials selection in CCS systems. https://www.globalccsinstitute.com/publications/corrosion-and-materials-selection-ccs-systems 2010 (accessed June 8, 2017).

[250] Schoots K, Rivera-Tinoco R, Verbong G, van der Zwaan B. Historical variation in the capital costs of natural gas, carbon dioxide and hydrogen pipelines and implications for future infrastructure. International Journal of Greenhouse Gas Control 2011;5:1614–23. doi:10.1016/j.ijggc.2011.09.008.

[251] van der Zwaan BCC, Schoots K, Rivera-Tinoco R, Verbong GPJ. The cost of pipelining climate change mitigation: An overview of the economics of CH_4, CO_2 and H_2 transportation. Applied Energy 2011;88:3821–31. doi: 10.1016/j.apenergy.2011.05.019.

[252] Han C, Zahid U, An J, Kim K, Kim C. CO_2 transport: design considerations and project outlook. Current Opinion in Chemical Engineering 2015;10:42–8. doi:10.1016/j.coche.2015.08.001.

[253] Pires JCM, Martins FG, Alvim-Ferraz MCM, Simões M. Recent developments on carbon capture and storage: An overview. Chemical Engineering Research and Design 2011;89:1446–60.

[254] Ferguson RC, Nichols C, Leeuwen T Van, Kuuskraa VA. Storing CO_2 with enhanced oil recovery. Energy Procedia 2009;1:1989–96. doi:10.1016/j.egypro.2009.01.259.

[255] Hamelinck CN, Faaij APC, Turkenburg WC, Van Bergen F, Pagnier HJM, Barzandji OHM, et al. CO_2 enhanced coalbed methane production in the Netherlands. Energy 2002;27:647–74.

[256] Jackman PS. Guidelines for compilation of corrosion cost data and for the calculation of life cycle cost of corrosion. Prepared by working party on corrosion in oil and gas EFC 2001; 13.

[257] Knoope MMJ, Ramirez A, Faaij APC. Investing in CO_2 transport infrastructure under uncertainty: A comparison between ships and pipelines. International Journal of Greenhouse Gas Control 2015;41. doi:10.1016/j.ijggc.2015.07.013.

[258] Nordhaus RR, Pitlick E. Carbon dioxide pipeline regulation. Energy 2009;30:85.

[259] Parfomak PW and Folger P. Pipelines for carbon dioxide (CO_2) control: Network needs and cost uncertainties. Congressional Research Service 2008. https://digital.library.unt.edu/ark:/67531/metadc96797/ (accessed June 8, 2017).

[260] Gough C, Mander S, Haszeldine S. A roadmap for carbon capture and storage in the UK. International Journal of Greenhouse Gas Control 2010;4:1–12. doi: 10.1016/j.ijggc.2009.10.014.

[261] Energy Institute. Good plant design and operation for onshore carbon capture installations and onshore pipelines. https://www.globalccsinstitute.com/publications/good-plant-design-and-operation-onshore-carbon-capture-installations-and-onshore-pipeli, Global CCS Institute 2010.

[262] Cooper R, Barnett J. Pipelines for transporting CO_2 in the UK. Energy Procedia 2014;63:2412–31. doi:10.1016/j.egypro.2014.11.264.

[263] OECD. Transcontinental infrastructure needs to 2030 / 2050. Port of Rotterdam Authority Annual Report 2010.