Project no.:
226317

Project acronym:
CO2Europipe

Project title:
Towards a transport infrastructure for large-scale CCS in Europe

Collaborative Project

Start date of project: 2009-04-01
Duration: 2½ years

D3.1.1
WP3.1 Report
Transport network design and CO_2 management

Revision: 2

Organisation name of lead contractor for this deliverable:
NV Nederlandse Gasunie

Project co-funded by the European Commission within the Seventh Framework Programme		
Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential , only for members of the consortium (including the Commission Services)	

Deliverable number:	D3.1.1
Deliverable name:	Transport network design and CO_2 management
Work package:	3.1
Lead contractor:	N.V. Nederlandse Gasunie

Status of deliverable		
Action	**By**	**Date**
Submitted (Author(s))	Luuk Buit (Gasunie)	Nov. 29, 2011
Verified (WP-leader)	Luuk Buit (Gasunie)	Nov. 29, 2011
Approved (SP-leader)	Ad Seebregts (ECN)	Nov. 29, 2011

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EXECUTIVE SUMMARY

CO_2 transport network development

Technical issues

According to earlier CO2Europipe work, several options are open for pipeline routes in the development of a CO_2 transport network in Europe. The basic idea in all transport cases should be to start with small volumes and corresponding pipeline diameters. Over dimensioning of a pipeline will probably be infeasible from a commercial point of view. Expansion of the capacity of a pipeline route will probably be realised with a pipeline parallel to the existing one. No technical difficulties are foreseen in expanding the transport capacity in this way.

Modification of a pipeline is not more difficult for a CO_2 pipeline than for natural gas pipelines, although the pressure of a CO_2 pipeline will probably be much higher than that of a natural gas pipeline. Thus, making a tie in to a pipeline under higher pressure would possibly require more robust pressure resistant equipment. A tie in to double a pipeline could be done without interrupting the CO_2 flow, enabling capacity increase with minimal negative consequences. An even easier way to take care of doubling a pipeline route over a certain distance would be by applying a few capped tees (for instance at each quarter of the length) as a pre-investment.

Capacity expansion is also possible by utilising the pressure range of the pipeline through additional compression capacity or installation of an intermediate pumping station.

A combination of playing with pressure, pipeline looping and number of pumping stations probably will result in the most freedom to cope with developments and optimise the investment plan.

Pipeline construction capacities

According to CO2Europipe CCS development projections, the total length of the transmission network would amount to 23,400 km in 2050 for the Reference scenario and about 33,000 km for the Offshore-only and EOR scenarios (Neele 2010). Similar predictions have been made elsewhere. Assuming a gradual network development from 2030 until 2050; about 500 km of large capacity CO_2 transmission pipelines should be built every year. In addition, smaller collection and distribution pipelines at CO_2 capture and storage clusters have to be constructed. This pace of network development would be slower than the development of oil and gas pipelines in Europe. Based on this analysis, no CO_2 pipeline construction bottleneck is expected to occur.

However, a large part of the existing pipelines (mostly oil and gas) is to be replaced before 2035. Furthermore, the natural gas transmission infrastructure in Europe will expand. This could put serious strain on the availability of onshore pipeline construction capacity, but is not beyond the current construction capacity to achieve.

Offshore construction, on the other hand, is a different market altogether. Other than the onshore pipeline construction business, offshore construction is little influenced by other markets. The main constraint in offshore construction is planning the pipe laying vessels. Therefore, offshore construction will be less difficult to realise than onshore construction.

Components of a CO_2 transmission system

Pipeline transport

A CO_2 transmission system consists of entry points, pipelines, possibly pumping stations, valves, pressure reducers and exit points, requiring in-depth insight in operational parameters such as flow and pressure at crucial points in the network. Operating such a system is not very different from operating a natural gas transmission network. The phase diagram of the transported fluid, being CO_2 with certain impurities, is different, requiring strict pressure regimes for transport, either in the gas phase or in the dense phase.

The participation of the CO_2 emitters in the Emission Trading Scheme (ETS) will require that the volumes of CO_2 taken in at capture installations and delivered at storage sites are recorded, which means the volumes will be monitored in real time.

Transport of CO_2 in point-to-point connections can be operated by separate operators, but when interconnections transform these one-on-one connections into a network, central operation and control is advisable.

It is also advisable that, on a European level, standards are developed for the operating pressure regimes and allowed impurities (this coheres strongly with choice for metal specifications, standard pipeline diameters and wall thickness), as well as welding procedures and checks, maintenance, safety zoning, quality and quantity measurement.

Compression
In dense phase CO_2 transport, a compressor is required to increase the pressure of the CO_2 to a value that ensures the CO_2 will stay in the dense phase along the pipeline, until the CO_2 is either injected or is re-pressurized. The exact discharge pressure varies hereby case wise and depends on pipeline length, operating conditions, booster pump stations and storage conditions.

In this report, three compression paths are compared, considering stand-alone compression from the capture plant, and, for the most suitable path, two compression solutions are evaluated. It is concluded that the preferred and most efficient solution for CO_2 compression is the integrally geared compressor, especially regarding its relatively low power consumption.

Shipping
CO_2 can be transported by pipeline, but shipping it with dedicated CO_2 vessels is also possible. In certain situations, shipping has a number of advantages over transport by pipeline. Transport by ship creates flexibility to changing CO_2 volumes over time. Another benefit is that a ship can easily reach either smaller fields or fields located out of the vicinity of a CO_2 trunk line, which would be expensive to connect to by pipeline. Furthermore, shipping based CO_2 transport can be complementary to pipeline projects because of their relatively fast deployment and their flexibility. Thus, a shipping-based CO_2 transport solution could be considered as a viable option to open up the market for the short term and as a more flexible long term solution.

Injection
The requirements for CO_2 injection depend on the storage compartment (for example gas reservoir versus virgin aquifer) and the way the CO_2 is transported (pipeline versus vessel). In addition, there are differences between off- and onshore applications.

The condition of the well is crucial for successful injection of CO_2. Depending on reservoir conditions, the CO_2 may need to be heated before injection, in which case heaters have to be installed at the wellhead. It may also be necessary that the CO_2 is heated temporarily before start-up of injection. Heating at the injection well would, of course, have a very negative impact

on the overall CCS chain energy efficiency. When the injection facility is supplied with CO_2 by shipping, a heat exchanger is needed to heat the CO_2 from around -50 °C to the required injection temperature. Buffer storage capacity may also be necessary if continuous injection is be required.

In general, there are no unforeseen difficulties related to CO_2 injection if the storage reservoir has been carefully selected.

Dynamic operation of a CO_2 transmission system

In designing a CO_2 transport network, dynamical operation must be taken into account. The network is designed to support certain operational limits, such as flows, temperatures and pressures. Varying-load operation of a power plant and maintenance of the network are some of the causes for fluctuation of the CO_2 flow. The effect of maintenance planning on the operation of the CO_2 network is discussed. Following this discussion, events affecting production assurance are described.

Any technical system requires some kind of preventive maintenance to reduce the risk of unplanned maintenance from failures and to extend the lifetime of the system. Within any company, maintenance plans are set up to match required maintenance activities and time slots (maintenance windows) that become available as part of the natural operating pattern of the systems within the company.

In a *network* consisting of several commercial players, as will be the likely case in a CCS chain, such coordination is also necessary between the players to ensure that the entire chain is available for carbon capture, transport and storage when required. The challenge is to establish effective routines between the players in the chain to minimise overall downtime. Of course, the ability to handle varying CO_2 flows will be an important transport system requirement.

Production assurance will be an important part of the development and operation of future CO_2 transport networks. Production assurance evaluations are a requirement in different project phases either by qualitative evaluations or quantitative calculations. Several important areas of activities for a CO_2 transport network will be supported by Production Assurance evaluations/calculations, such as:

- Infrastructure development
- Capacity management/utilization
- Daily operations & operation planning
- Modification Projects

In a CO_2 transport network, contributions to regularity and availability will be different from component to component of the system. The impact from each component (or set of components) on a system will mainly depend on the level of redundancy, the function of the component in the system, the failure frequency and the downtime (given a failure). E.g. multiple compressors can be installed to reduce the impact of downtime of one compressor.

Redundancy can also occur in the transport chain itself, when multiple transport routes are available. This is a clear advantage of having a network with multiple transport routes and storage reservoirs, as opposed to a set of one-on-one transport chains.

PROJECT SUMMARY

The CO2Europipe project aims at paving the road towards large-scale, Europe-wide infrastructure for the transport and injection of CO_2 captured from industrial sources and low-emission power plants. The project, in which key stakeholders in the field of carbon capture, transport and storage (CCTS) participate, will prepare for the optimum transition from initially small-scale, local initiatives starting around 2010 towards the large-scale CO_2 transport and storage that must be prepared to commence from 2015 to 2020, if near- to medium-term CCS is to be effectively realized. This transition, as well as the development of large-scale CO_2 infrastructure, will be studied by developing business cases using a number of realistic scenarios. Business cases include the Rotterdam region, the Rhine-Ruhr region, an offshore pipeline from the Norwegian coast and the development of CCS in the Czech Republic and Poland.

The project has the following objectives:

1. describe the infrastructure required for large-scale transport of CO_2, including the injection facilities at the storage sites, which is the topic of this report.
2. describe the options for re-use of existing infrastructure for the transport of natural gas, that is expected to be slowly phased out in the next few decades;
3. provide advice on how to remove any organizational, financial, legal, environmental and societal hurdles to the realization of large-scale CO_2 infrastructure;
4. develop a business case for a series of realistic scenarios, to study both initial CCS projects and their coalescence into larger-scale CCS infrastructure;
5. demonstrate, through the development of the business cases listed above, the need for international cooperation on CCS;
6. summarise all findings in terms of actions to be taken by EU and national governments to facilitate and optimize the development of large-scale, European CCS infrastructure.

Project partners

Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek- TNO	Netherlands
Stichting Energieonderzoek Centrum Nederland	Netherlands
Etudes et Productions Schlumberger	France
Vattenfall Research & Development AB	Sweden
Linde Gas Benelux BV	Netherlands
Siemens AG	Germany
RWE DEA AG	Germany
E.ON Benelux NV	Netherlands, Belgium, Luxemburg
PGE Polska Gruppa Energetyczna SA	Poland
CEZ AS	Czech Republic
Shell Downstream Services International BV	Netherlands, United Kingdom
CO_2-Net BV	Netherlands
CO_2-Global AS	Norway
Nacap Benelux BV	Netherlands
Gassco AS	Norway
Anthony Veder CO_2 Shipping BV	Netherlands
E.ON New Build & Technology Ltd	United Kingdom
Stedin BV	Netherlands
N.V. Nederlandse Gasunie	Netherlands

The CO2Europipe project is partially funded by the European Union, under the 7th Framework program, contract n° 226317.

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1 INTRODUCTION

This report describes the design of a large-scale European CO_2 transport network. The central issue is what technical challenges can be identified in the design, construction and operation of a large-scale CO_2 transmission network. All main technical aspects of CO_2 transportation are taken into account. The impact of impurities on the network and standards for CO_2 is outside the scope of this report, as they form the main subject of the CO2Europipe report D3.1.2, 'Standards for CO_2'.

Chapter 2 outlines some basic design issues related to CO_2 transport and tackles the question of how to develop a pipeline transport network. An important question regarding network development is whether the pipeline construction industry will be able to construct the required pipelines onshore and offshore at the necessary pace. In addition, components of a pipeline transport system are discussed in more detail, especially compression. External safety is not tackled in this report, although it is an important design issue. The reason for this omission is that safety receives ample attention in the CO2Europipe report 'Societal and environmental aspects' (Seebregts, 2011).

Shipping, the subject of the third chapter, could overcome some barriers for the evolution of a CO_2 transport network. Our analysis shows that shipping is a good alternative to pipeline transport in case of long distances (hundreds of kilometers), variable supply or injection of CO_2 and small storage reservoirs.

The final phase in CO_2 transport is the injection into the storage reservoir. Chapter 4 gives insight in the boundary conditions for CO_2 transport imposed by the injection process.

Transport of CO_2 for CCS has to be able to deal with varying supply and demand of CO_2. A system has to be designed to accommodate variations in flow. This topic is dealt with in the fifth chapter of this report.

In the concluding chapter, the main findings are reproduced, resulting in a number of recommendations.

2 TRANSPORT BY PIPELINE

2.1 Pipeline design, construction and operation

2.1.1 Introduction

The transport of CO_2 in dense phase in carbon steel pipelines has been practised for several decades. As a result, considerable experience has been gathered, which is reflected in that CO_2 is being mentioned specifically in pipeline standards throughout the world.

Operational experience in Europe with dense phase CO_2 transport over a long distance has been acquired in the Snøhvit project in Norway. As part of a larger project where LNG is produced, CO_2 is removed from the natural gas, compressed, transported back at high pressure and injected into a formation below the hydrocarbon reservoirs.

Since 2005 an existing oil pipeline (85 km length, 26 inch diameter) in the Netherlands has been retrofitted for usage as a gaseous CO_2 transport pipeline at moderate pressures (11-25 bar) supplying CO_2 to greenhouses. Today, this OCAP pipeline, which is part of a 250km CO_2 pipeline transport, has already been in operation for 6 years. A major part of this pipeline network is located in dense populated areas and, as such, the design has been subject to extensive HAZOP and Quality Risk Assessment studies.

In an engineering study sponsored by the Rotterdam Climate Initiative and the Clinton Climate Foundation, this onshore pipeline network has been further studied to be used for on-shore transport of large volumes (4000-5000 kTon per annum) of gaseous CO_2 to off-shore oil and gas fields in the North Sea.

In a comprehensive study executed by the World Resources Institute (WRI 2008) with the contribution of major players in the Oil and Gas industry, having extensive experience with operating pipeline networks for a wide range of gases and liquids, the design and operating experience of large pipelines has been described. In this paragraph, a brief overview of this design and operating experience on existing CO_2 transport pipeline networks is reported.

Besides the WRI report two other comprehensive guideline documents (DNV, 2010; Energy Institute, 2010), developed independently, are providing guidance in all relevant aspects (codes & standards, material selection, and safety etc.) for a proper design and operation of large CO_2 pipeline networks. Other work by DNV, GCCSI, IEA, Energy Institute and the experience of the industrial gas suppliers represented by EIGA is also aimed at ensuring that demonstration programmes benefit from all available knowledge from a number of industries.

Based on a comparison of international pipeline standards with regard to the key technical issues, no significant technical gaps in the internationally common applied standards have been found. Notwithstanding the above, no design issues relating to sub-

sea pipeline transportation of CO_2 were identified that were not already covered in existing codes for pipeline transportation of gases and liquids. In summary, the existing standards cover all identified issues. Using industry standard Quantitative Risk Assessment and goal setting procedures might even result in some improvements of these standards. The adoption of such practices should contribute to increase confidence that industry best practises are being employed to reduce the risk of leakages in the event of pipeline ruptures. Considering that large CO_2 pipeline infrastructures inevitably will be developed in densely populated areas, a reliable basis for risk management is important.

Current design practices and regulations have been put to the test in carbon dioxide pipelines. It may be argued that CCS as a whole should be taking more of a risk-based approach given the predicted volumes and particularly Europe's increased urban density compared to the US areas with CO_2 for EOR.

Nevertheless all studies have indicated that when taking into account the below mentioned critical design issues, including the already existing operational experience, dense and gaseous phase CO_2 transport can be done in a safe manner.

The critical issues to consider include;

- System dynamics - the dynamic interaction between system components
- Flow assurance modelling - modelling of hydrate potential, hydraulics, pressure transients
- Validation of dispersion modelling methods - clarification of source terms, accurate modelling, empirical modelling, definition of separation distances between pipelines and habitation
- Physical properties - validation of multi-component modelling techniques, empirical data generation
- Mechanical design - fracture control prediction and techniques, material selection.

2.1.2 General pipeline design considerations

In the literature (e.g. Mohitpour et al., 2007) the design parameters for the design of pipelines are extensively described and these could also be applied for the design of CO_2 pipelines.
Design specifications for CO_2 pipelines should be fit-for-purpose and consistent with the projected concentrations of co-constituents, especially water, hydrogen sulfide (H_2S), oxygen, hydrocarbons, and mercury. More on the topic of impurities in CO_2 is discussed in the CO_2Europipe report 'Standards for CO_2' (D3.1.2).

In this section, some parts of the WRI Report findings have been quoted, as they are describing all design aspects in a condensed manner reflecting common practice in design and engineering of gaseous and liquid pipelines.

“Pipeline safety and integrity guidelines” (WRI 2008)

- Operators should follow the existing Occupational Safety and Health Administration (OSHA) and EIGA (European Industrial Gas Association) standards for safe handling of CO_2.
- Plants operating small in-plant pipelines should consider adopting Office of Pipeline Safety (OPS) regulations as a minimum for best practice.
- Pipelines located in vulnerable areas (populated, ecologically sensitive, or seismically active areas) require extra due diligence[1] by operators to ensure safe pipeline operations. Options for increasing due diligence include decreased spacing of mainline valves, greater depths of burial, and increased frequency of pipeline integrity assessments and monitoring for leaks.

"Siting of CO_2 pipelines guidelines" (WRI 2008)

- Considering the extent of CO_2 pipeline needs for large scale CCS, a more efficient means of regulating the siting of cross border CO_2 pipelines should be considered at national level, based on consultation with states, industry, and other stakeholders.
- As a broader CO_2 pipeline infrastructure develops, regulators should consider allowing CO_2 pipeline developers to take advantage of current national condemnation statutes and regulations that will facilitate right-of-way acquisition negotiations.

The most relevant design parameters, as described in the standard British Standard BS PD 8010-1 (British Standards Institution, 2004), are shown in the following block flow diagram.

[1] Condition assessment

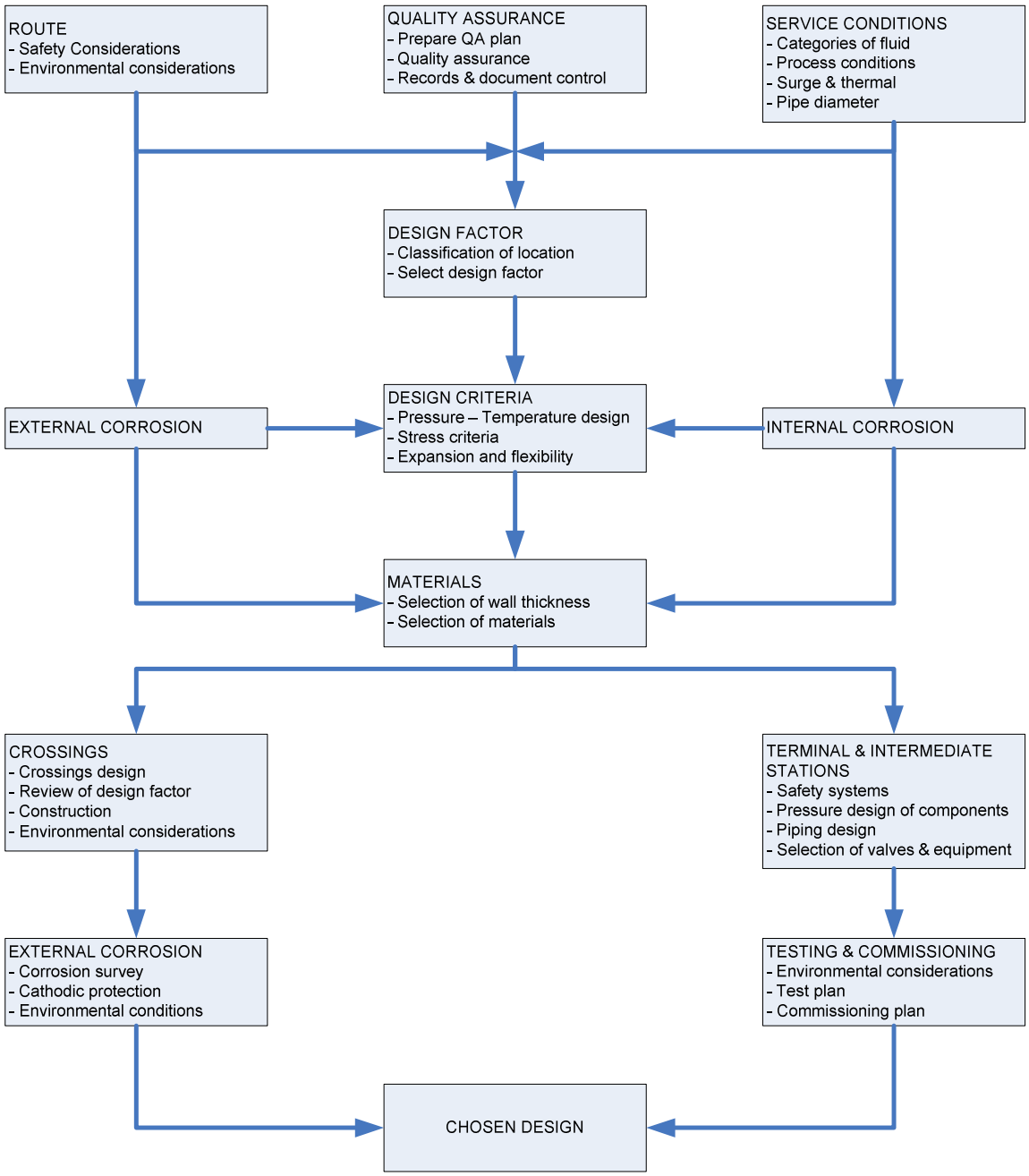


Figure 3-1 Pipeline design flow diagram (Energy Institute, 2010)

2.1.3 "Pipeline design" (WRI 2008)

Designing a CO_2 pipeline the following criteria should be taken into account being: pressure, temperature, and properties of the liquid; the elevation or slope of the terrain; dynamic effects, such as earthquakes, waves, currents, live and dead loads, and thermal expansion and contraction; and the relative movement of connected components. The

compressibility and density of CO_2 undergo significant nonlinear variation in normal pipeline operating conditions (within normal pipeline pressure and temperature ranges). Therefore, the design of CO_2 pipelines requires point-by-point estimation of fluid properties using computational models (MRCSP 2005).

The main components of a pipeline include valves, compressors, booster pumps, pig launchers and receivers, batching stations and instrumentation, metering stations, and Supervisory Control And Data Acquisition (SCADA) systems. Valves are typically used for control functions around compressor and metering stations and at the injection sites. One important consideration in pipeline design is the distance between block valves. Block valves are used to isolate sections of pipe in the event of a leak or for maintenance. Block valve spacings of between 16 and 32 kilometers have been used, depending on the location of the pipe, and are installed more frequently near critical locations, such as road and river crossings and urban areas. Installing more block valves per unit of length increases both the cost of the pipeline and the risk of leakage from the valves themselves. The further apart the valves are installed, the greater the volume contained between the valves, which increases the distance from the pipeline required for the gas to dissipate to a safe level in the event of a pipeline rupture (Gale and Davidson, 2004).

2.1.4 "Pipeline construction" (WRI 2008)

For pipeline construction, selection of pipe diameter, wall thickness, material strength, and toughness depends on the transmissible fluid's temperature, pressure, composition, and flow rate. For example, fluid flow rates are lower in larger-diameter pipes. Lower fluid flow rates result in fewer pressure drops, allowing a pipeline engineer consider reducing the pressure requirements for CO_2 entering the pipeline, or reducing the number of compressors along the pipeline. However, the installation costs of pipelines rise with increases in diameter. The design must consider the economic trade off of increasing pipeline diameter against the cost of CO_2 compression.

The majority of existing onshore CO_2 pipelines are buried over most of their length, to a depth of 1 to 2 meters, except at metering or pumping stations, and most offshore lines are also usually buried below the shallow water seabed. In deeper water, only pipelines with a diameter of less than 0.4 meters are trenched and sometimes buried to protect them against damage. The exact depth varies based on project-specific needs, and variances can be granted where appropriate.

Experience from decades of pipeline operations suggests that the optimum design and engineering of a CO_2 pipeline will be site specific and will depend on different factors, including volumes of CO_2 to be transmitted, gas composition, local population density, topography, and meteorological conditions.

2.1.5 "Compression" (WRI 2008)

Depending on the length and terrain of pipeline, recompression or decompression of CO_2 may be required to maintain supercritical phase CO_2. The CO_2 pipeline industry currently uses centrifugal, single-stage, radial-split pumps for recompression, rather

than compressors (Mohitpour et al., 2007). These booster pumping stations are installed as required to maintain sufficient pressure at high elevation points, in order to ensure a single-phase CO_2 flow (Nestleroth, 2007).

2.1.6 "Fracture control and propagation" (WRI 2008)

Avoiding initiation and propagation of longitudinal-running fractures is also essential. Fracture arresters are typically installed every 500 meters, and lower-strength steel and thicker-wall pipe are employed (IPCC 2005; Mohitpour et al. 2007). The pipelines for CO_2 transportation are usually constructed of carbon steel, taking into account CO_2 specific issues as, carbon equivalent, hardness value and fracture strength, valve, fittings, actuators and trim types, bends.

The optimum strength and wall thickness are determined based on the aforementioned factors, as well as fabrication and handling considerations. To reduce the chances of corrosion, CO_2 pipelines typically have an external coating of fusion-bonded epoxy or polyurethane with full cathodic protection (MRCSP 2005).

2.1.7 "Pipeline operating temperature & pressure" (WRI 2008)

The most efficient way to transport CO_2 is in the dense phase. The critical point of CO_2 is 73 bars and 31°C. CO_2 is generally transported at temperature and pressure ranges between 13°C and 43°C and 85 and 150 bars, respectively (Mohitpour et al. 2007; KinderMorgan 2006). The lower pressure limit is set by the phase behaviour of CO_2, and should be sufficient to maintain supercritical condition. The upper temperature limit is determined by the compressor-station discharge temperature and the temperature limits of the external pipeline coating material. The lower temperature limit is set by winter ground temperature (Farris 1983).

2.1.8 Safety reviews

Designing a CO_2 pipeline network, the entire CO_2 transport facility in place [compressors, valves, and upstream processes] should be reviewed. The entire transport network design should be reviewed with a HAZOP (Hazard & Operability) study with careful reviews of what can go wrong during operation of the entire CO_2 facility. An experienced HAZOP study team, typically consisting of technical people who have significant experience in design, operation, control, and safety of particular processes, jointly reviews the design and attempts to find areas where safety and operability issues may have been compromised or inadequately addressed. As an example, in a typical HAZOP study, the "system" or "subsystems" are assumed to be operating within design parameters of pressure, temperature, flow, and liquid composition. Excursions from these conditions are intentionally considered to see

a) the effect of changes to design parameters, and
b) if these changes cause safety or operability risks

If it is found that, for example, the design flow can increase due to over speeding of the compressors, and if these are driven by gas or steam turbines, the system components

need to be reviewed to ensure that adequate protection is in place to prevent or mitigate these excursions. Also, inadvertent operation of a relief valve in a CO_2 pipeline would cause freeze up of the valve due to formation of dry ice with the sudden expansion of the dense phase liquid. Pipeline design engineers should take into account each of the parameters, to ensure that flow, pressure, and temperature excursions can be safely handled whilst maintaining the CO_2 in dense phase.

2.1.9 "Pipeline safety" (WRI 2008)

Current pipeline design safety standards already take into consideration valve spacing as a function of pipeline diameter and surrounding land use. Instrumentation along the pipeline is typically used to measure the flow rate, pressure, and temperature of the CO_2 and provides sufficient information for the pipeline's normal operation. The instrumentation is located at compressor and metering stations and sometimes at the block valves. SCADA systems are used for remote monitoring and operation of the compressor stations and the pipeline. These systems are designed to provide operators at a central control center with sufficient data on the status of the pipeline to enable them to control the flows through the compressors and the pipeline as necessary (MRCSP 2005). Metering is used for computational pipeline monitoring (CPM) leak-detection systems for single-phase lines (without gas in the liquid). Currently CO_2 pipelines are not required to have CPM, mainly because it is technically difficult. Other leak-detection methods, such as pressure point analysis and aerial and visual surveys, may be used to ensure safe CO_2 transport.

The risks posed by increasing the network of CO_2 pipelines should be manageable based on the extensive CO_2 pipeline operating experience of industry. The DOT data suggest that the impacts from CO_2 pipeline incidents are typically less than those from natural gas and hazardous liquid pipelines. As measured by the lack of fatalities and injuries, and significantly lower property damage, impacts from CO_2 pipeline incidents are typically less than those from natural gas and hazardous liquid pipelines.

Up till now the main cause for incidents with CO_2 pipeline is material failure (i.e., relief valve failure, valve/gasket/weld or packing failure), followed by corrosion and outside force (Gale and Davidson 2007; Kadnar 2007). While CO_2 is more benign than many other liquids transported through pipelines, it is important to note that the CO_2 pipeline incident statistics are also probably related to the fact that there are many fewer miles of CO_2 pipelines than pipelines transporting other liquids, and they at present tend to be located in less populated areas.

2.1.10 Other CO2Europipe work on pipeline safety

One crucial factor in CO_2 pipeline safety is the behaviour of CO_2 due to a pipeline leakage or rupture. The thermodynamics and dispersion characteristics of CO_2 and the external safety of CO_2 pipelines are the subject of the CO2Europipe report 'Framework for Risk Assessment' (Seebregts, 2011).

2.2 Components of a CO_2 transmission system

2.2.1 Pipeline transport

For the operation of a gas transport system, consisting of entry points, pipelines, pumping stations, valves, pressure reducers and exit points, insight in the operational parameters such as flow and pressure at crucial points in the network is essential (Mohitpour, 2007). Operators need to have insight in the pressure at several nodes in the network, at least where the pressure is the lowest (at the end of a pipeline) and, for contractual reasons, at delivery and interconnection points (entry and exit points). This is similar for natural gas and CO_2.

As discussed in the previous section, an important distinction between the two is that pressure in CO_2 transmission systems must be kept above the phase boundary, while natural gas is transported in the gas phase only. So the actual operations will not differ largely from operation of a high pressure gas transmission network: keeping the pressure above the limit values at crucial nodes (end of the pipeline) by means of adjusting the inlet pressure if possible or by reducing the outflow of the system by means of valves (remotely controlled or automatic with a local pressure set point). As long as the pressure is kept within a certain area of the phase diagram the CO_2 is maintained in the dense phase.

As impurities determine the minimum pressure requirements as well, the composition of the fluid must be known. This will be the case as the capture installations have defined characteristics, however the composition should still be monitored. The effects of impurities in CO_2 are discussed in more detail in the CO2Europipe report D3.1.2.

The participation of the CO_2 emitters in the Emission Trading Scheme (ETS) will require that the volumes of CO_2 taken in at capture installations and delivered at storage sites are recorded, which means the volumes will be monitored in real time. Apart from the operational data acquisition (SCADA), the transport operator must use a bookkeeping system of the CO_2 volumes. The functionality is comparable to that of liberalised natural gas transmission systems.

The transport is foreseen to be of a dynamic nature: injected flows vary in time. Causes for flow variation could be that a coal burning power plant reduces production during off-peak hours or that power producers optimise fuel use between gas, coal and nuclear. Another possible cause is maintenance of some part of the storage installation. As indicated, the effects of these flow variations can be kept under control through steering the pressure with pumps and valves. The procedures used for controlling natural gas transmission are deemed suitable for operating CO_2 transport.

For the monitoring and control, a centralised control room is advisable once the CO_2 pipelines are interconnected shaping a network; otherwise multiple individual pipeline operators will be responsible for parts of an integrated system, which could prove difficult. Whether the control should be organised at national level (within the borders of a country) or in a coordinated way for the entire European network depends on the

phasing of the build-up of the transport network. When starting with short-distance pipelines, connecting sources with storage sites (point-to-point), only local control is necessary, matching the injection into the reservoir with the supply from the source. When a mature network is realised, control should be centralised and the function of the local party (a client of the network operator) is nomination of expected injection flows and possibly of flows to be injected in storages with which the injecting party has a storage contract.

This leaves the organisation of the CO_2 storage with the as of yet unanswered question: Will storage reservoirs be owned and/or operated by separate (commercial) parties, apart from the transport grid, or will transport and storage be owned, operated and controlled by a single entity. The same question arises related to offshore CO_2 pipeline transport (EBN/Gasunie, 2010).

It is advisable that, on a European level, standards are developed for the operating pressure regimes and allowed impurities (this coheres strongly with choice for metal specifications, standard pipeline diameters and wall thickness), as well as welding procedures and checks, maintenance, safety zoning, quality and quantity measurement.

2.2.2 Compression

2.2.2.1 Introduction

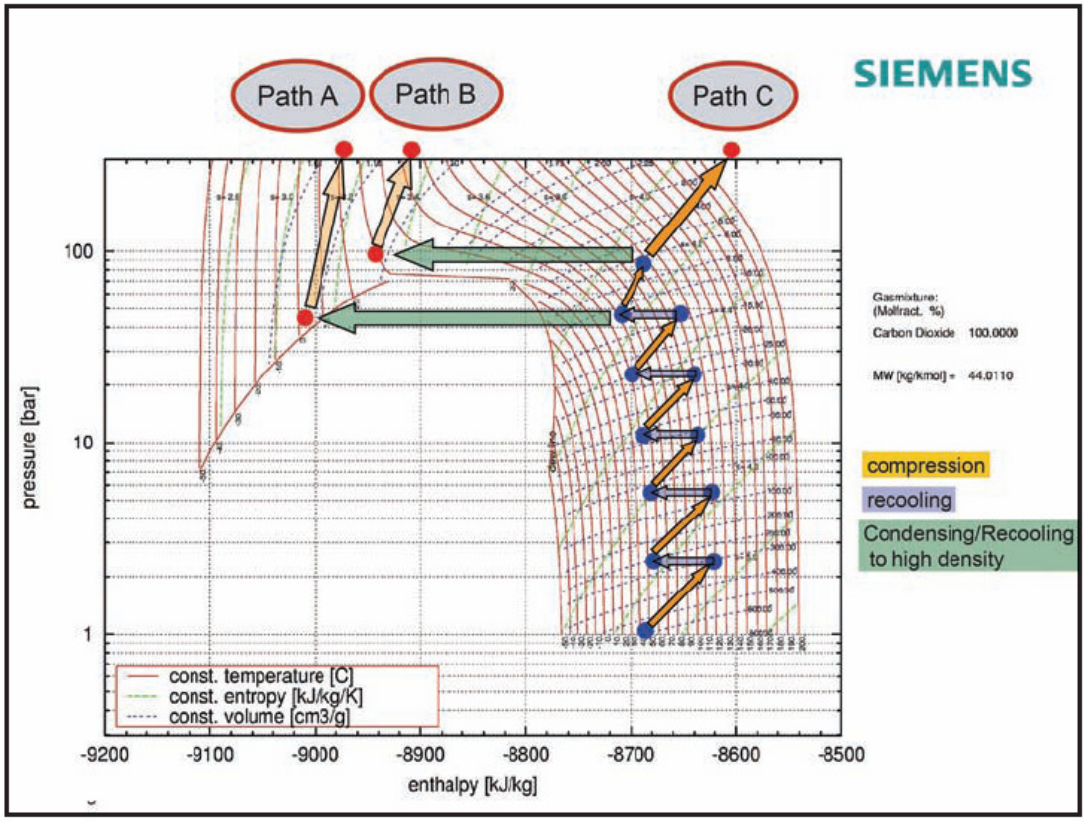
The material in this section is based on the work presented in an article in the Carbon Capture Journal. (Winter, 2009)

Compressor stations are necessary to overcome the pressure difference at the outlet of the carbon capture unit and the inlet to the pipeline system. The required pipeline operating pressure will in most cases be above the critical pressure of CO_2. The exact discharge pressure varies on a case by case basis and depends on pipeline length, operating conditions, booster pump stations and storage conditions.

2.2.2.2 Three scenarios

Three main compression paths for a reference target pressure of 200 bars are thinkable and shown in the pressure enthalpy diagram in the figure below with:

A. Compression in gas phase with condensing/subcooling and pumping
B. Compression in gas phase with recooling and compression in the high density area
C. Compression in gas phase with compression in low density area.



Three main compression paths with a reference target pressure of 200 bar

Path A

This scenario is characterized by the lowest compression power for CO_2, which can be seen by the high gradient of the depicted compression arrow. However, unless installation is near the Arctic or Antarctic circle, providing economically reasonable recooling, a dedicated refrigeration cycle will be needed. The additional compression power for this refrigeration loop will annihilate the power benefits.

Path B

In this case, the CO_2 is cooled by heat transfer to the surroundings while remaining at constant pressure. The required compression power is higher than for scenario A, however still better than for scenario C. From the overall power perspective, this compression path looks the most promising. The challenge is, however, to properly address CO_2 behavior, which still shows considerable compressible behavior and high temperature sensitivity along that path.

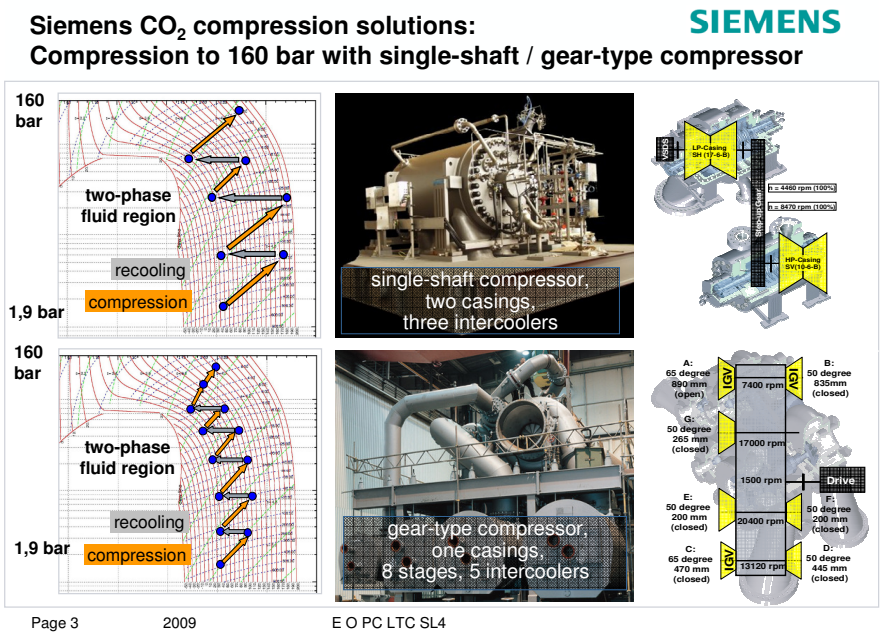
Path C

Here, a compression path in the gas phase with consecutive compression in the light density area is under investigation. Along the complete path, the fluid behavior can be modeled via conventional gas dynamics. Within Siemens concept studies the power consumption is however about 7% higher than with scenario B. Still, the overall concept

evaluation including also performance predictability, performance safety and reliability made Siemens focus on scenario C in the first place.

2.2.2.3 Design concepts for CO_2

Within this Scenario C the turbomachinery with the highest value added needs to be identified. Two concepts were investigated for scenario C, which addressed an identical compression duty: 300t/h of wet CO_2 with a specified pressure ratio of 1.9 bar to 160 bar.



1. Concept A – Single-shaft compressor train: A two-casing single-shaft compressor train, totaling four process stages, is driven by a variable-speed drive system directly coupled to the low pressure casing. The low pressure casing is a single-shaft turbocompressor with horizontally split casing, type STC-SH (17-6-B) and the high pressure casing is a single shaft compressor with vertically split casing, type STC-SV (10-6-B). To obtain optimized impeller shapes and high efficiencies in the high pressure casing, a speed-increasing gear box (ratio 1.9) was applied. Provision was made for speed control as the means of control. Both single-shaft shaft casings were selected in back to back arrangement providing in total three intercooling steps. This train setup is the classical concept for petrochemical installations in fertilizer units with a focus on robustness and highest availability.

2. Concept B – Integrally geared compressor: A seven-stage integrally geared compressor, type STC-GV (80-7), is driven via fixed-speed drive on the central bull gear. Due to the speed flexibility of each impeller pair, an optimum flow coefficient for highest efficiency can be achieved for the individual impeller. As the flow will exit after

each compression step the idea of an isothermal compression can be followed with in total five intercoolers. Due to the strong real gas behavior in the vicinity of the critical point for CO_2, the last two compressor stages are uncooled. The integrally geared compressor concept has its origin in the air separation market with the focus on highest efficiency solutions and high availability.

2.2.2.4 Results

Siemens CO_2 compression solutions: preferred machine concept

SIEMENS

SIEMENS Evaluation	Concept A	Concept B
API 617 7th edition coverage	✓	✓
Coupling power (Rated/Normal)	35,290 / 31,698	30,400 / 27,761 86,1% / 87,6%
OPEX difference @ 2,5 € / W (@ Rated)	4,890 kW = 12,225,000- €	
Operational expenses	↑	↓
Capital expenses	↗	↘
Life cycle expenses	↑	↓
Installation space & weight	↗	↘
Delivery time	→	→
Civil Engineering & expenses	↗	↘
Noise emission	↓	↑
Robustness (e.g. permissable Nozzle loads)	↗	↘
Control flexibility of (intermediate pressure)	↘	↗
Availablity	→	→

Siemens preferred solution: Integrally Geared Compressor at high efficiency

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Both machinery concepts are covered by the API 617 7th edition, which addresses machinery selection for petrochemical gas services with their requirements of superior technology at a high quality level.

Power consumption is key

Power consumption is the key differentiator between the two concepts. A benefit of 4,890 kW (13.9%) of installed coupling power can be achieved. Even under part load condition this power advantage remains valid and is further supported by larger performance map turndown ratio of Concept B with Inlet guide vane control in comparison to the speed control of Concept A.

Part load

Both compressor concepts operate at any flow rate between 0% and 100% by integrated control and safety means. This can be achieved by guide vane, speed or throttle control and in addition by bypass control if the regular turndown range is exceeded.

The decision for the train set up - one train at 100% flow, 2 trains at 50% flow or 3 trains at 33% - is a part of project optimization and the question on how much bypass flow and efficiency decrease can be tolerated. It depends further on several factors such as available compressor portfolio, overall plant availability and reliability considerations.

A major advantage of the integrally geared compressor (Concept B) is its flexibility for intermediate control of pressure/temperature or flow. This enables distinct conditions to be controlled throughout the compression chain within one single compressor. This can be of benefit when controlling pressures for feed or extraction flow or pressures on process gas treatments like dehydration. A single-shaft compressor (Concept A) is usually speed controlled and has only one degree of freedom. The availability of both compressor concepts are in the 99% range, with both being applied in critical compression services.

Different gas compositions

Different CO_2 compositions will require head and flow adjustment on the compressor which will be provided by the control means foreseen. Considerations of different gas compositions ("impurities") of CO2, Nitrogen, Oxygen, hydrogen sulfide and so forth are modelled by internal gas routines and incorporated into compressor design as state of the art for turbomachinery business. Strong molecular weight, pressure and temperature variations however must be known upfront as they must be incorporated into the compressor design.

Impeller efficiency

The main reason for this benefit of the integrally geared compressor versus the single shaft compressor is the higher impeller efficiency with axial flow intake in combination with high head coefficients and the flexibility to adjust the speed for optimum flow coefficients. Polytropic impeller efficiencies are up to 89% per stage. The polytropic efficiency is an efficiency value in which the non-ideal behaviour of a process is accounted for. In addition, an isothermal compression concept with intercooling after each impeller for the first five stages is used. Downstream of the sixth impeller stage the recooling is omitted due to the low Z-value of CO_2. The above enables Siemens to realize high pressure ratios in the first stages, slightly decreasing in the last stages due to increased mechanical loadings. With the above Siemens is able to reduce the total number of stages for compression ratios up to 200 bar to 7 or 8. In contrast to the above, the single-shaft machine suffers from running at only two different speeds with the only possibility to adjust the diameter and the number of impellers installed on the single shaft. Having a polytropic efficiency for the first process stage (made up of 3 impellers) above 82%, a strong decrease to only 70% for the last process stage is encountered. This is mainly due to the strong volume decrease throughout the compression chain, resulting in 2D vane configuration on the last stages and poor impeller performance. In addition, the overall number of impellers is twelve compared to seven on the integrally geared compressors, which is also due to the reduced head coefficients for single- shaft impellers.

Energy savings due to compact design
Even with a relatively low energy cost of 2.5 €/W value added amounting to €12.225 million can be realized by opting for the integrally geared compressor solution. In addition to the OPEX benefits, the investment cost for an integrally geared compressor is lower than for a single-shaft compressor train. This is the result of a compact design with fewer impellers and smaller impeller diameters. Overall, there is a life-cycle cost advantage for the integrally geared compressor. Due to the compact design, the installation weight is considerably lower and the space required as well. This cuts cost on the expenses for ground, concrete work and civil engineering. Furthermore, complete packaged units can be realized with coolers installed in steel frames and completely assembled piping including necessary anti-surge loops. This enables single lift units with reduced site installation time and reduces the piping interfaces to a minimum. As far as machine robustness is concerned, permissible nozzle loads on single shaft compressors with several times NEMA are higher than on integrally geared compressors. On integrally geared compressors the allowable forces and moments require a closer look and will be calculated case wise for each single compressor.

2.2.2.5 Summary
Siemens established that the preferred and most efficient solution for CO_2 compression is the integrally geared compressor. Especially the relatively low energy use of this type of compressor is beneficial for use in the CO_2 transport chain.

2.2.3 Pipeline onshore/offshore

Usually in gas transport the maximum allowed pressure for pipelines offshore exceeds the pressure for onshore lines. The risks differ (less environmental damage from an incident) and the distances to be covered without compression are larger (economic optimisation). Compression at sea should be avoided but, if necessary, compression could take place offshore, requiring a riser platform and remote compression facilities. A complicating factor is the absence of power to compress CO_2. For compression offshore, electrical power will have to be provided with an additional power cable.

In addition, compressing at the beach to the highest allowable pressure (for natural gas steel pipelines 175 bars is practised; for CO_2 200 bars should be considered) minimises the power required at the injection platform. Of course the dimensioning of facilities is a matter of economic optimising. Also, costs estimates should reveal if, apart from a high entry pressure, an oversized offshore pipeline diameter outweighs extra pumping capacity at the injection platform. and besides, such a pipeline could act as a buffer compensating for fluctuations in storage injection and onshore supply.
Procedures for control of the offshore pipeline should not be more complex than procedures for onshore transport. Maintaining the operating pressure within an operational range using the pumping facilities at the pipeline entry and the injection capacities will do.

2.2.4 Intermediate compression/pumping

Dynamic process conditions are not foreseen to cause problems in operating intermediate compression or pumping stations. If the CO_2 flow decreases, the intermediate station can just continue operation, except when the pressure downstream comes close to the phase boundary. In that case, CO_2 injection in the reservoir should be halted.

To optimise the CO_2 transport chain, it might be necessary to have intermediate pumping stations, especially for long-distance transport pipelines. A disadvantage of intermediate pumping is that (electrical) power is required far from the CO_2 capture location. However, a CO_2 pipeline crossing a long distance in Europe will pass major industrial areas in most cases. As for offshore pipelines, the North Sea is acquiring a considerable network of offshore power cables, mainly for wind farms, but also to feed oil and gas production platforms.[2]

[2] Personal communication with Mike Haines from Cofree technology.

3 TRANSPORT BY SHIP

3.1 Liquefaction/terminalling

3.1.1 Introduction

In the 19th century the technology for liquefaction of gases has been developed. And since then the liquefaction technology has been further developed and improved with the aim to produce liquids in the most efficient manner (lowest energy consumption and investment costs). Today industrial gas companies are producing a variety of liquid gases (helium, hydrogen, nitrogen, oxygen, carbon dioxide, natural gas, argon etc.) in order to be able to transport large volumes efficiently.

Besides transport by road, railway, liquid gases are also transported by ship. The most well known liquid gas transported by ship today is LNG (liquefied natural gas.),
Less known is that liquid CO2 is already transported by ship for more than 15 years.

As such liquefaction is already a widely used and proven process having its advantages because of the fact that the molecules in the liquid phase take up much less space than they do in their gaseous phase.
For example liquefaction of a gas occurs when its molecules are compressed. The molecules of most of the gases are relatively far apart from each other, while the molecules of a liquid are relatively close together. Gas molecules can be compressed together by in two ways: by increasing the pressure of the gas or by cooling the gas.

To liquefy gases two very important process design features should be taken into account being: the critical temperature and the critical pressure Critical temperature is the temperature of the liquid-vapour critical point, that is, the temperature above which a gas cannot be liquefied by an increase of pressure. The minimum pressure required to liquefy the gas at the critical temperature is called the critical pressure.

For example, the critical temperature for carbon dioxide is 31°C. That means that no amount of pressure applied to a sample of carbon dioxide gas at or above 31°C will cause the gas to liquefy. At or below that temperature, however, the gas can be liquefied provided sufficient pressure is applied. The corresponding critical pressure for carbon dioxide at 31°C is 72.9 bars. In other words, the application of a pressure of 72.9 bars on a sample of carbon dioxide gas at 31°C will cause the gas to liquefy. See Figure 3-1.

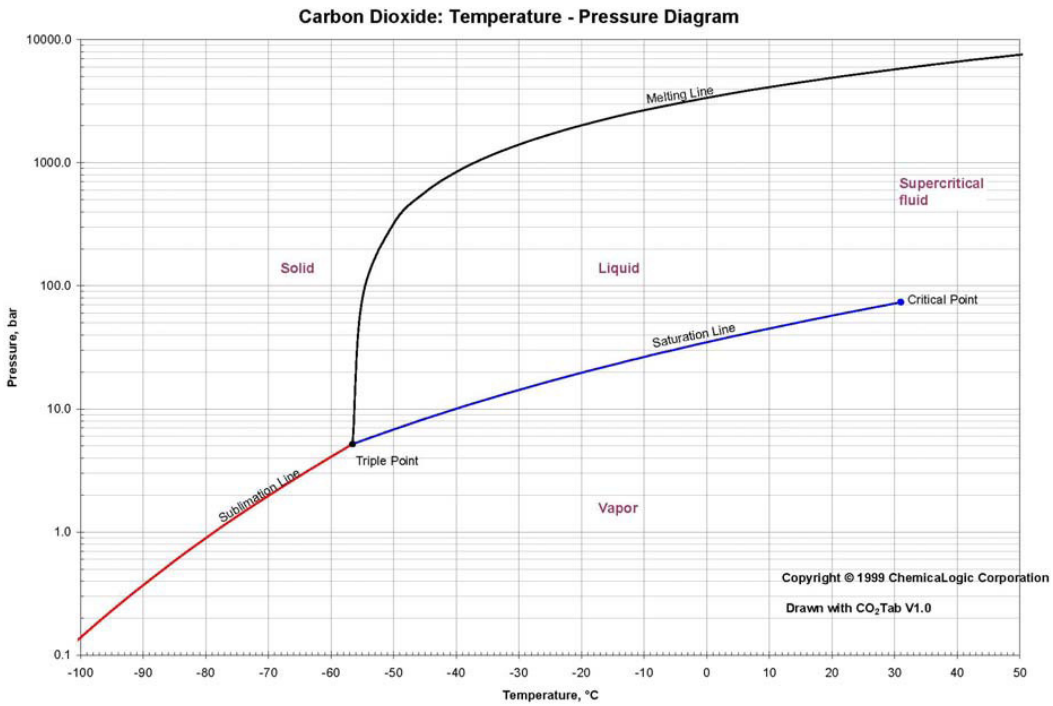


Figure 3-1 CO_2 phase diagram

The difference in critical temperatures between gases means that some gases are easier to liquefy than are others. The critical temperature of carbon dioxide is such that it can be liquefied relatively easily at or near room temperature. By comparison, the critical temperature of nitrogen gas is −147°C and that of helium is −268°C. Liquefying gases such as nitrogen and helium are more energy consuming and requiring higher investments than does the liquefaction of CO2.

3.1.2 Methods of liquefaction

In general, gases can be liquefied using the following methods:

(1). Compression; the first method; the application of pressure alone is sufficient to bring a gas into the liquid phase. For example, ammonia has a critical temperature of 133°C. This temperature is well above room temperature. Thus, it is relatively simple to convert ammonia gas into the liquid state by using sufficient pressure. At its critical temperature, it has a pressure of 112.5 bars.

(2). Alternatively, the liquefaction of a defined gas requires two steps. First, the gas is cooled where after the cooled gas is forced to do work against some external system. Here the principle is that the gas is losing its energy, causing the temperature of the gas to decrease further. As a result, the gas turns into a liquid

(3) Using the Joule-Thomson effect. Gases also can be made to liquefy by applying a principle discovered by English physicists James Prescott Joule (1818–1889) and William Thomson (later known as Lord Kelvin; 1824–1907) in 1852. The Joule-Thomson effect depends on the relationship of volume, pressure, and temperature in a gas. Change any one of these three variables, and at least one of the other two (or both) will also change. Joule and Thomson found, for example, that allowing a gas to expand very rapidly causes its temperature to drop dramatically. Reducing the pressure on a gas accomplishes the same effect.

3.1.3 CO_2 liquefaction

At any temperature between its triple point (-56.4°C) and its critical point (32°C) carbon dioxide can be liquefied, as shown in Figure 2-1, by compressing it to the corresponding liquefaction pressure, and removing the heat of condensation. Two liquefaction processes are commonly applied [5]:

- 1) Carbon dioxide is liquefied near the critical temperature; water is used for cooling. This process requires compression of the carbon dioxide gas up to a pressure of about 76 bars. After the final compression stage the gas is cooled to about 32°C whereafter water and entrained lubricating oil are removed. The purified CO_2 gas is then liquefied in a water-cooled condenser.

- 2) the liquefaction process takes place at temperatures from -12°C to 23°C, with liquefaction pressures ranging between 16–24 bar. The compressed gas is pre-cooled to 4°C to 27°C, water and entrained oil are separated, and the gas is then dried in an activated alumina, bauxite, or silica gel drier, and flows to a refrigerant-cooled condenser. Liquid CO2 is then distilled in a stripper column to remove non-combustible impurities.

The largest CO_2 liquefaction plants today in operation are producing 0.15-0.38 Mtons of LCO_2 on a yearly basis. The CO_2 is compressed to transport pressure, which normally is 14-20 bar, cleaned for unwanted components, dried and liquefied as depicted in Figure 3-2. Note that, compared with the requirements for a feasible shipping based CCS infrastructure, the output of such a plant corresponds approximately to15 to 25% of the currently foreseen capacity of CCS based liquefaction, storage and transport terminals.

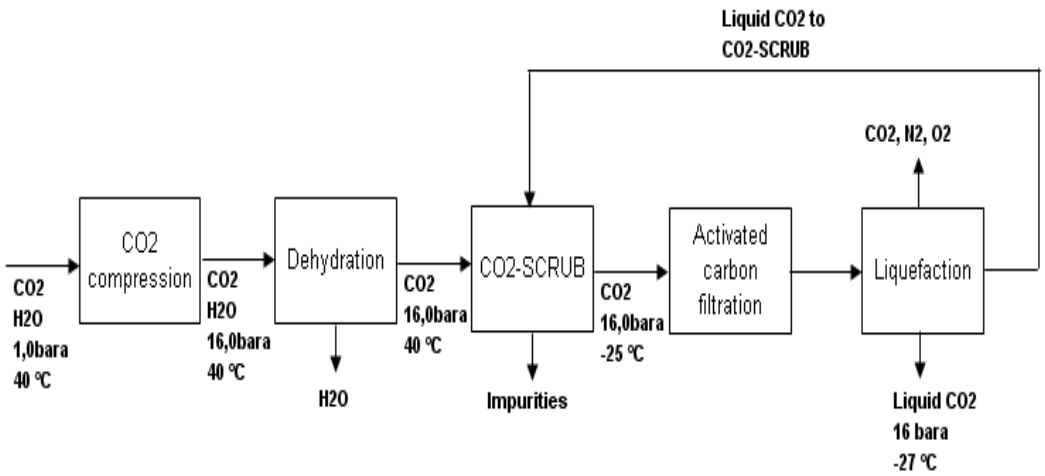


Figure 3-2 Typical block flow diagram of a CO_2 liquefaction plant

3.1.4 Intermediate Storage

For the storage of large volumes of a pressurized liquefied gas, a spherical tank type or bullet can be used. Under the current capabilities of tank storage suppliers, the maximum capacity of one tank which withstands an inner pressure of 7 bars may reach approximately 8,000-10,000 tons. The structural material is high tensile steel proofing against low temperature as commonly applied for LPG tanks. To reduce external heat adsorption thermal insulating material on the wall is applied.

A tank with this capacity would be filled with the CO_2 production of a 1000 MW coal fired power station in about 40 hours. A more general conclusion would be that the CO_2 production of a large CO_2 point source can be stored for days. If there would be a flow interruption if, say, the injection of CO_2 into the storage reservoir is temporarily not possible, the CO_2 would have to be vented after a few days, depending on the number of buffer tanks available.

3.1.5 Loading/unloading facilities

Loading/Unloading facilities from the storage tank on land to the ship would be of the jetty type (loading arm), and pumps would preferably be located on board of the ship. In some occasions, depending on the distance between storage and loading facilities, pumps on land are required. Unloading depends on the receiving facilities in the CO_2 injection facilities. However, pumps in the cargo tanks of the ship are recommended to be used. Figure 3-3 shows the layout of a typical CO_2 liquefaction and storage terminal.

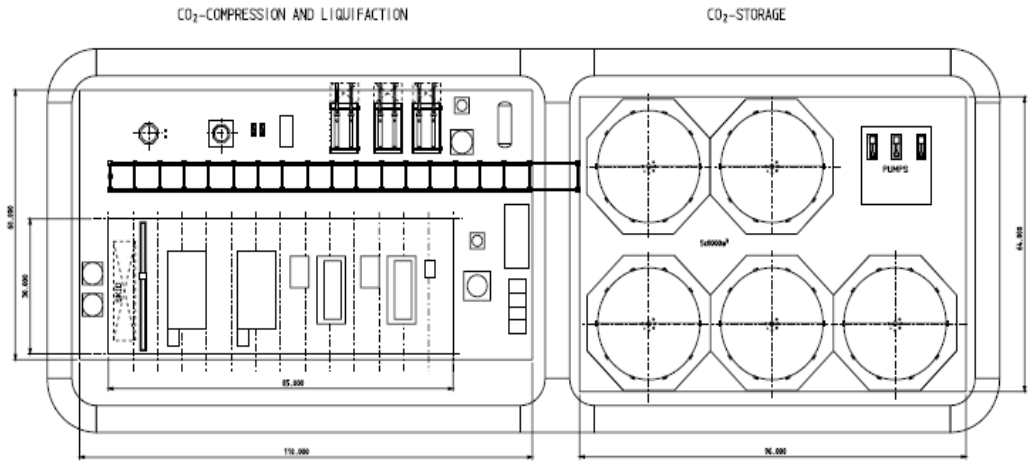


Figure 3-3 Typical layout of a CO_2 liquefaction and storage terminal

3.1.6 Conclusions

Taking into account the current installed liquefaction and storage production capacities for industrial gases like N_2 and O_2, including the build LNG and LPG liquefaction plants, the conclusion is, that there are no technological limitations for developing large scale (> 1.5 Mton/year) CO_2 liquefaction & storage terminals.

CCS is requiring transport of large volumes of CO_2, which only can be transported by pipeline or ship. Large volumes of CO_2 already are transported by pipeline, but there is less experience of transport by ship.

Presently CO_2 is transported in ships or trucks in semi-pressurized vessels at a pressure of 14-20 bars. For economic large-scale transport of CO_2 by ship, the CO_2 should be transported semi-pressurized at pressure near the triple point e.g. at 6.5 bar and –52 °C. Utilizing this pressure, the technology and experience from building and operation of conventional LPG tankers can be utilised, and large pressurized cargo tanks can be produced in an economical way.

3.2 Shipping

3.2.1 Introduction

This section is part of the CO2Europipe work package 3.3 report (Mikunda, 2011).
There is currently uncertainty regarding the volume growth of captured CO_2 and the availability of suitable sinks for storage. From this uncertainty, a shipping based CO_2 transport solution could be considered as a viable option to open up the market, for the short term and as a more flexible long term solution. For this concept, ships will be loaded at CO_2 bulk terminals or at the industrial facilities and from there sail to the location of underground storage areas, such as (i) depleted oil and gas fields (ii)

producing oil fields for enhanced oil recovery purposes, and in the longer term (iii) saline aquifers.

3.2.2 The role of CO_2 shipping

There are a number of foreseen advantages that can be associated with shipping CO_2, namely:

Volume flexibility: Transport by ship creates flexibility to changing CO_2 volumes over time. If more volume is offered for transport, an additional vessel can be introduced (as well as additional intermediate storage tanks). If volumes are reduced, ships and storage (designed for multi-purpose services), can be taken out of the CO_2 service and introduced to an alternative trade or to another (new) CO_2 trade.

Alternative use of assets: Ships represent a certain residual value (in time), especially combined carriers that can be employed in alternative trades (i.e. LPG)[3]. Residual value reduces the upfront investment risks.

Source and sink flexibility: Offshore pipelines are significant assets, to build and to operate and therefore particularly suitable for long term high volume transport of CO_2. For smaller fields, or fields located out of the vicinity of a CO_2 trunk line, laying a pipeline may prove too expensive. A ship, however, can reach these fields, and in certain cases this could be performed at a lower cost.

Complementary to pipelines: Due to its divisibility (related to volume flexibility), shipping-based CO_2 transport is complementary to pipeline projects, because of their fast(-er) deployment and flexibility. Income generation can commence prior and during the construction time of the pipeline infrastructure. Additionally, owners and operators of potential CO_2 storage fields cannot guarantee a 100% injection uptime and therefore alternative outlets must be considered, which can be facilitated with the use of CO_2 transport by ship.

3.2.3 Ship configurations

Dedicated and combined ships

Different logistic scenarios require different shipping configurations (in size and CO_2 conditioning process equipment). In this respect dedicated CO_2 ships can be used, or alternatively combined-CO_2/LPG ships can provide an attractive solution. From a technical point of view combining transport of CO_2 and LPG in one vessel is considered a feasible option, as the temperature-pressure-relation of both gases is relatively similar (liquid phase). Although a ship capable of transporting CO_2 as well as LPG requires a higher investment and has somewhat higher operational costs compared to a dedicated carrier, a combined CO_2/LPG carrier offers investment risk mitigation.

[3] Onboard CO_2 storage conditions are around -50°C to -55°C and 6 to 7 bars, Liquid Petroleum Gases (LPG) is transported at -48°C and atmospheric pressure hence the redeployability of the ship in this alternative trade.

Offshore and onshore discharge

Ships are generally designed to load their cargo in one port and discharge it in the next (onshore discharge). As an alternative, ships can be modified or purposely built to discharge at offshore locations like platforms or on a standalone basis via single point moorings directly into the well(s). Despite having additional investment and operational costs, the advantage of a ship is that it can discharge at different locations and the requirement for CO_2 infrastructure (i.e. pipelines) is reduced. One possibility is that he conditioning of the CO_2 (in order to meet the offshore storage field requirements) is performed on board of the ship. Another one is that the conditioning of CO_2 is performed on the platforms by making use of the available non-commercial gas (e.g. gas field pressure too low for economically exporting the gas to shore). A case-by-case cost review will be necessary in order to determine the best lay out.

Ship sizes

It is of course possible to design a ship dependant on the project needs, however one must bear in mind the usability of the vessel if it will be re-used for the transportation of other gases after CO_2 service life time. When considering the LPG market, the following ship sizes are likely to answer to market demands and are therefore selected for the (cost) comparison:

1. 10,000 m^3
2. 30,000 m^3

Typically these vessels will have the following dimensions:

	10,000 cbm	30,000 cbm
Loa [m]	120	205
B [m]	20	32
D [m]	12	16.8
T [m]	7.5	11
Deadweight [t]	13,000	36,000
Speed [kts]	14	15

Table 3-1 Typical vessel dimensions and specifications

4 INJECTION

The requirements for CO_2 injection depend on the storage compartment (for example gas reservoir versus virgin aquifer) and the way the CO_2 is transported (pipeline versus vessel). In addition, there are differences between off- and onshore applications (mostly due to the available space and cost differences).

4.1 Well head pressure: compression or pump capacity

For all injection facilities a sufficient well head pressure is required, to inject the CO_2 at the required mass rate. That wellhead pressure depends on the depth or the well; the hydrostatic pressure increases with depth, allowing for a lower wellhead pressure, but the friction increases with depth too and this has an opposite effect. The configuration of the injection well will determine the required wellhead pressure. This pressure is also typically higher for saline aquifers than for depleted gas reservoirs – because the reservoir pressure is higher. Depending on the phase of the CO_2 a compressor is needed (supercritical or gaseous phase), or a pump (liquid CO_2).

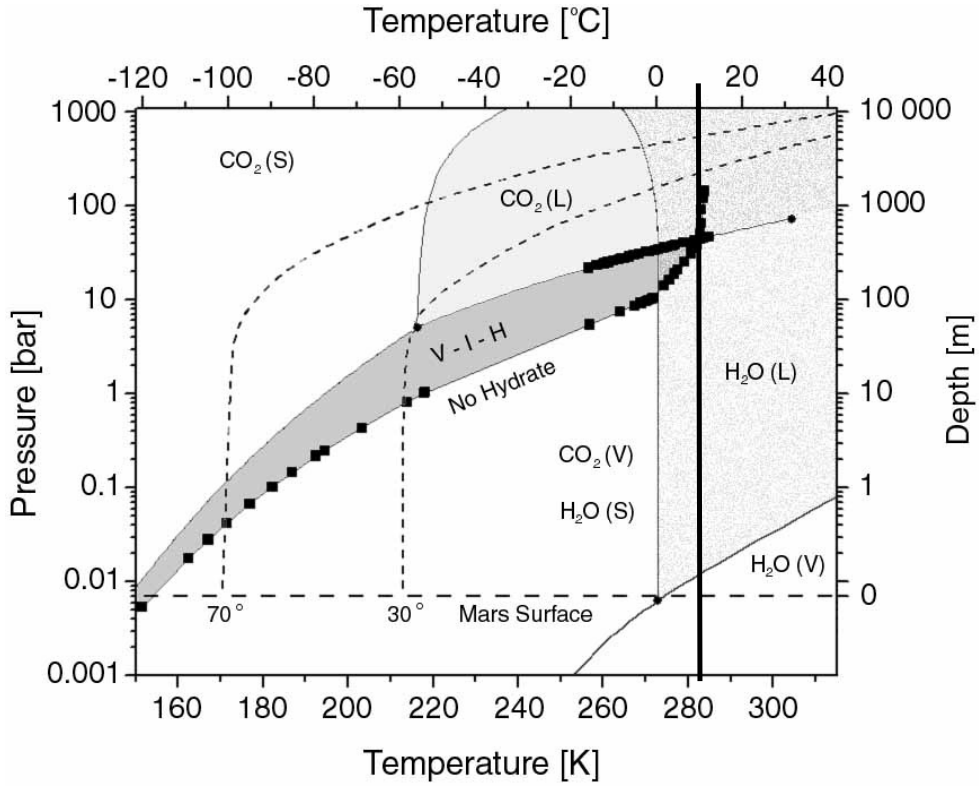
4.2 Injection well

For the injection well, apart from well isolation requirements, all parts that come into contact with CO_2 should be (CO_2) corrosion resistant, depending on the moisture content of the CO_2. The ability to withstand the aggressive moisture CO_2 stream is especially relevant for liners, packers and lubricants. In a depleted gas reservoir, a former production well is usually used, if adequate. In a virgin saline aquifer, it is required to drill for a new injector.

4.3 Well head temperature: heaters

Besides pressure, temperature effects are paramount during the injection of CO_2. Unlike conventional oil and gas applications, the critical point of CO_2 can be within the normal range of conditions under which the injection takes place. This means that is essential to consider all processes (expansion, compression), which affect pressure and temperature, and the associated phase transformations for all parts of the overall CCS chain, including the injection installations and wells. Especially in offshore application, the injected CO_2 is generally much colder than the usually warm reservoirs. The resulting temperatures and pressure gradients in the near-well area need to be considered.

One of these potential complications is the formation of hydrates. Figuur 4-1 shows the pressure and temperature conditions under which hydrate formation can be expected. Based on such a diagram, it can be concluded that a minimum bottom hole temperature of around 12 °C is required in order to minimize the complications of the solidification of the CO_2 (Satsepina, O.Y. and Pooladi-Darvish, M., 2010). If necessary, heaters should be added at the wellhead to ensure that the bottomhole temperature is always above that temperature. This is an issue especially for depleted gas reservoirs, which can be at a low pressure. Injecting low-temperature CO_2 can result in CO_2 entering the reservoir at conditions where hydrate formation is relevant. However, the impact of hydrate formation remains to be observed in full-scale injection tests.



Figuur 4-1 Phase diagram (after Sloan, 1998) showing the conditions under which hydrates form (L, S, V, H and I stand for liquid, solid, vapour, hydrate and water-ice, respectively). At temperatures above 285 K (12.3 °C), no hydrates occur.

4.4 Connection to transport pipeline

The transport between the capture facility and the storage compartment takes place trough pipelines. The pipeline needs to be connected to the injection installation. For offshore platforms, this occurs through a riser. On the platform or on the onshore injection side, there needs to be CO_2 distribution manifold, a compressor or pump, and piping systems (existing systems should be upgraded when required). All wellheads need to be equipped with CO_2-resistant materials. In most cases a heater is also needed, for either constant heating (to avoid phase transformations or cold temperatures at the bottom hole) or temporary use (at start injection or after a shutdown, when the CO_2 has been cooled by release of heat or decompression processes). Constant heating of the CO_2 would increase operational costs very significantly.

4.5 Intermittency and shutdowns

To deal with sudden stops in the overall system, it may be required to have a valve which can shut off the pipeline (for example, just before the injection site) in case of a shutdown. The pipeline then remains pressurized, which facilitates a subsequent restart.

The CO_2 in the pipeline cools down by release of heat into the environment. Because of this, temporary heating may be required when the injection is restarted. For emergency situations, vent and blow down facilities should be in place. Their design and location have to ensure the potential safety consequences of depressurization are within HSE criteria. (DNV, 2010)

4.6 Connection to a transport ship

In the case of offshore storage, transport by tankers is an option. To increase the amount of CO_2 which can be stored in the tanker under relatively low pressures, the CO_2 is cooled to around -50 °C. The tanker discharges its cargo at a single point mooring system (e.g. a turret), which is connected to the platform. After this discharge flow, it is required to increase the temperature before injection (to avoid problems as described above). This can be done with a heat exchanger, which rises the temperature close to that of sea water. Vessel transport may also require a temporary storage facility to avoid extreme injection rates and guarantee continuous injection.

Given its flexibility of ship transport and its possible valuable role in the first development phase of CCS, early (demonstration) projects should prove the feasibility of ship transport of CO_2 to offshore storage locations.

5 DYNAMIC OPERATION OF A CO_2 TRANSMISSION SYSTEM

5.1 Introduction

In designing a CO_2 transport network, dynamical operation must be taken into account. The network is designed to support certain operational limits, such as flows, temperatures and pressures. In other chapters it was already mentioned how important it is for efficient transport that the pressure is kept within operational limits. To prevent two-phase flow, the average operating pressure should be determined based on the fluctuations in the injection flows along the pipeline. The pipeline design team and the control room should have a dynamic computer model available to forecast flows through and pressures at critical nodes in the system, taking into account the composition of the various injected flows. Questions to be solved with the model are for instance, if a large source might drop out suddenly, how fast does the pressure decrease and what time is left to steer valves or start up a compressor.

Because of the expected rise of wind power, fossil-fuel power plants will be forced to have a varying load. This would cause varying CO_2 flows, requiring a transport system flexible enough to deal with this.

Maintenance of the network is one of the causes for fluctuation of CO_2 transport. This paragraph discusses the effect of maintenance planning on the operation of the CO_2 network. Following this discussion, events affecting production assurance are described.

Unplanned interruption of CO_2 flow is also possible. Anywhere along the CCS chain, incidents can cause reduced CO_2 flow or complete interruption. The power plant, the capture installation, the compressor, the pipeline and the injection facility all have a certain risk of failure. These failure modes and their impact on transport operation will be discussed as well.

5.2 Maintenance planning

Any technical system requires some kind of preventive maintenance to reduce the risk of unplanned maintenance from failures and to extend the lifetime of the system. Within any company, maintenance plans are set up to match required maintenance activities and time slots (maintenance windows) that become available as part of the natural operating pattern of the systems within the company.

In a *network* consisting of several commercial players, as will be the likely case in a CCS chain, such coordination is also necessary between the players to ensure that the entire chain is available for carbon capture, transport and storage when required. Obviously, there will be a problem if maintenance periods for the transport and storage parts of the CCS chain are planned in periods where the capture plant is planned to operate. Similarly, any maintenance periods for the capture plant represent an opportunity also for the transport and storage systems to perform planned maintenance.

Then, the challenge is to establish effective routines between the players in the chain to minimise overall downtime.

Similar systems exist today, e.g. in the Norwegian upstream gas transport network operated by Gassco. On an annual basis, the gas producers report to Gassco their need for maintenance periods for the coming year, and Gassco have the responsibility to establish a overall maintenance schedule for all of the gas producers on the entire Norwegian Continental Shelf connected to the integrated gas transport network. A similar system could be established for a future CCS network, having many similarities to today's gas transport network, i.e.;

- many "sources" connected to the same transport network. In a gas transport network the sources are the gas producers. In a CCS network, the sources will be the capture plants.
- many "exit points" from the same transport network. In a gas transport network, the exit point may be the customers or a trade hub. In a CCS network, the exit points will be the storage location.

In the following, an example of a procedure for overall maintenance planning between the players in a CCS network consisting of several sources and exit points is given.
To obtain the optimization with respect to availability of the CCS network as described in this Section, a *coordinator* is required to gather information from the players in the network, and to advise and recommend the timing of maintenance activities for each part of the network, based on such information. If only commercial players are represented in the CCS chain, some neutral body may have to take this role. In the Norwegian gas network, Gassco is not a commercial player, but an independent and neutral Operator. If an Operator of the transport or storage part of the CCS network represents the same independency and neutrality, such Operator may have this role.
Normally, preventive maintenance activities should, if possible, be performed in periods where the overall load on the CCS system is generally lower. There are two reasons for this;

- maintenance windows, i.e. periods where normal operations are reduced or completely stopped, occur more frequently
- the consequences of maintenance activities taking longer time than originally planned, are normally less severe

The first step in the maintenance coordination process would be to request information from the players in the CCS network to submit information on an annual basis related to;

- Name of location / installation / facility involved
- Major scope of work
- Number of days for maintenance and modification work
- Period (start/ending date and hours)
- Available capacity from the unit during the notified period, including the period when the capacity is reduced prior to a shut down and the period when the capacity is increased after the shut down
- Daily maximum capacity from the facilities throughout the maintenance and modification period

- Any expected changes in CO_2 quality in the notified period
- Type of work, impact on the Transportation System, scope and criticality, and possible alternative periods when the work can be performed

Guidance for the players within the CCS network when submitting this information is that activities should be planned to the periods already identified as periods with overall lower load on the CCS network (if any).

Based on input and prior to the preparation of a final co-ordinated plan for maintenance and modification work, the *coordinator* will issue an overall preliminary plan to players for comments, following an iterative process with updates, based on the dialogue with all players in the CCS network.

To ensure a plan which is as updated and optimal as possible, any changes of notified periods/activities or new activities to final coordinated plan for maintenance and modification work that may affect the availability of the CCS network must to the extent possible be avoided. If such changes cannot be avoided, reports to the *coordinator* should be made as soon as possible, for updates of the overall plan to be performed.

Based on the final overall maintenance plan, the *coordinator* should issue a report to all players in the CCS network, specifying maintenance activities and resulting availability of the different parts of the network.

5.3 Planned and unplanned downtime of transport components

5.3.1 Definition

The term Production Assurance is defined in ISO 20815 as the "activities implemented to achieve and maintain a performance that is at its optimum in terms of the overall economy and at the same time is consistent with applicable framework conditions".

5.3.2 Production assurance in a CO_2 transport network

Production assurance will be an important part of the development and operation of future CO_2 transport networks. Production assurance evaluations are a requirement in different project phases either by qualitative evaluations or quantitative calculations. Several important areas of activities for a CO_2 transport network will be supported by Production Assurance evaluations/calculations. This can be:

- Infrastructure development
  - Decision support for alternative infrastructure development projects
  - Optimize approved concepts to secure pay back of investments
- Capacity management/utilization
  - Verify production assurance consequences of alternative capacity utilization factors of the network (operational flexibility)
- Daily operations & operation planning
  - Establishing KPI (Key Performance Indicators)

- Fulfilment of Production Assurance requirements (target values) for new facilities or upgrades.
- Modification Projects
  - Evaluate the Production Assurance impact of alternative modifications projects.

5.3.3 Production assurance in operation and design

Operational parameters may be used for reporting the Production Assurance level in the operational phase. These parameters could be used in relation to a KPI target (Key Performance Indicator) or a guarantee value. A practice for reporting/calculating production assurance in a CO_2 transport network should be established to ease the communication between the respective stakeholders in the network. The nominal value of the operational availability is usually significantly higher than the design availability. Reporting of the Production Assurance has several purposes:

- Measure of performance (KPI).
- Monitor the technical condition of the facilities.
- Identify events which involved parts can implement measures to reduce or eliminate.
- Ensure that the right actions are taken.

KPI targets related to operational parameters should normally be established for each installation based on:

- The complexity of the installation.
- Sparing philosophy.
- Production Assurance definition.
- Plant specific information.
- Historical information.

The term design availability is used to calculate/document the production assurance level in different project phases, prior to installation. If production assurance is one of the main business drivers in a project, a quantitative analysis should be performed during the different project phases.

The design availability calculations form an important basis for investments connected to new project as well as modifications/maintenance projects. The results from design calculations could support investments in modifications/new facilities to secure the integrity of the respective facilities and/or form the basis for cost/benefit analyses to support investments in new facilities. The design evaluation is also beneficial for identification of bad actors (equipment with large negative influence) in proposed design. The design availability can for some facilities be connected to a predefined target/ambition value in the respective stages of a project.

Factors that can affect the design availability calculations:

- Redundancy and sparing philosophy in main or utility systems.

- The complexity of the design. Pipeline systems normally have a "simple" design (mainly pipeline and valves) compared to a process plant including more advanced equipment.
- Uncertainty in the failure data (plant specific vs. generic)

5.3.4 Production assurance definitions

To establish parameters and KPIs related to product assurance, the following three different definitions in the operational reporting and design calculations can be used.

- Deliverability
  - Measure the overall performance of the CO_2 transport system.
  - Includes compensation measures like turn-up and line pack (i.e. increasing the inventory of the pipeline by increasing the inlet pressure).
  - Uses real production or nomination (transport need as requested by the party having such need) as a reference level.
- Production availability
  - Used on pipelines, platforms and processing plants.
  - Includes internal and external events.
  - Uses real production or nomination as a reference level.
- Available yearly capacity
  - Normally mostly used for processing plants, e.g. capture plants.
  - Includes internal, external events and planned maintenance.
  - Uses real production or nomination as a reference level.

In a CO_2 transport network, contributions to security of operation and availability will be different from component to component of the system. The impact from each component (or set of components) on a system will mainly depend on the level of redundancy, the function of the component in the system, the failure frequency and the downtime (given a failure).

Compressors (or pumps) for increasing the pressure in the transport network can be assumed to be important with respect to product assurance. They perform a critical function, and high costs make evaluations related to installing redundant equipment challenging. Depending on the flow pattern in the system vulnerability related to failure may be reduced by installing 2x50% (i.e. two compressors having 50% of the required capacity each) or 3x33% as an alternative to 1x100%. Then, failure in the compressor function (i.e. the set of compressors) can be expected to occur more frequently, but the consequences of failure are reduced. In a situation where some of the sources for CO_2 have the possibility of turning down production, this may be an alternative to investigate.

For a pipeline system downstream of compressors/pumps, availability is normally significantly higher than for the rotating equipment, typically as high as 99,9%. Low complexity and few moving parts implies that failure rates normally are impacted mainly from external events, such as excavators (onshore) or anchors (offshore). In this part of the network, equipment with the most contribution to downtime are valves, however, still with an availability significantly better that compressors and pumps.

Typical comparable valves in a gas network have a mean time to failure between 20 and 500 years.

Emphasis should, however, be put on characteristics related to transport systems in this context that are special for CO_2, and where more data and experience is needed to optimize design. Such characteristics are e.g. related to corrosion mechanisms (e.g. if water comes into the CO_2 stream) and occurrence of longitudinal fractures.

Redundancy can also occur in the transport chain itself, when multiple transport routes are available. This is a clear advantage of having a network with multiple transport routes and storage reservoirs, as opposed to a set of one-on-one transport chains, because in case of point-to-point transport, the whole chain is down when a single component is down. When there is a network, failure of a component could be dealt with by rerouting the CO_2, depending on the nature of the network and the location of the failure.

6 CONCLUSIONS

6.1 Main findings

Current technology and a history of CO_2 transport suggest that CO_2 transport through a dedicated pipeline network and with CO_2 vessels is technically feasible. However, designing, engineering and operating a CO_2 network requires knowledge of CO_2 flows, pressures and compositions. This report discusses some of the required issues. Dynamic modeling and information on CO_2 metering are not tackled in this report. Nevertheless, the available information suggests that there are no insurmountable hurdles to implementing large-scale CO_2 transport network development.

Specialized firms are able to construct CO_2 compressors for up to 200 bars with state of the art technology and proven high availability. These compressors are not available off the shelf.

It is important that pipeline transport takes place in the dense phase because of the required transport capacities. Operational experience should reveal over time what the minimum margins in pressure and temperature are for optimal transport in terms of compression energy and throughput (costs of compression versus the risk of operating outside the dense phase).

Construction of 1,500 km of CO_2 pipelines per year (as projected for the period 2020-2030) on top of existing pipeline markets requires a significant construction effort, but this is certainly not impossible to achieve and not out of reach technically.

There is an important distinction between offshore and onshore CO_2 network development. Offshore construction will require proper planning of equipment/vessels, but no major problems are foreseen in this area. Onshore construction, on the other hand, will be affected by the fact that there will be large projects in the natural gas distribution networks as well, constraining the size of the available skilled work force. CO_2 transport infrastructure development cannot be regarded as independent from natural gas infrastructure developments. Onshore CO_2 pipeline infrastructure will therefore be harder to construct than offshore infrastructure.

Shipping CO_2 with vessels to offshore storage locations might be appropriate in the early stages of a CCS project and for storage in small depleted gas/oil fields. Having the injection compressors on board the vessel releases the offshore platform from the need of a compressor and logistics for fuel supply or an electric connection to the coast. Later in time, when volumes have reached such a level that an offshore pipeline is feasible, or when the small fields are filled up fully, the ships can be operated in a new CCS start up or applied for e.g. LPG transport, which makes the choice for shipping of CO_2 in certain cases an option to be taken into account from a risk mitigation point of view.

6.2 Recommendations

Pipeline construction cost tends to increase and is expected to increase further in the coming decades. It is recommended to construct pipelines as soon as it is clear that CCS is a viable option for major CO_2 emitters in Europe, in order to minimise the cost.

It is advisable that at a European level, minimum standards are developed for CO_2 transportation infrastructure (pipeline networks and shipping). These would include, in particular, minimum standards for operating pressure regimes and allowed impurities, since these affect the design specifications for pipeline or containment vessel materials, and also may be needed for welding procedures and checks, maintenance, safety zoning, quality and quantity measurement. The development of large-scale CO_2 transport could benefit from dynamic CO_2 transport models.

The technology to inject CO_2 in subsurface reservoirs is available today. Some issues remain, mostly on an operational level. These issues include the possible requirement of heaters when injecting into low-pressure depleted gas fields. Early CCS projects should be encouraged and supported in addressing these issues.

The feasibility of ship transport is to be demonstrated in early CCS projects. Ship transport can potentially play a vital role in the early phase of the development of the CO_2 transport infrastructure. It is currently thought that the technology for transport and offshore unloading are available, but the feasibility of the complete ship transport system remains to be proven. This should be done as early as possible.

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