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CO$_2$ Pipeline Infrastructure

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CO_2 PIPELINE INFRASTRUCTURE

Key Messages

- New CO_2 pipeline projects require large investments in infrastructure. Re-use of existing infrastructure can lead to substantial savings in investment costs.
- In the US, EOR has been the primary driver for CO_2 pipeline infrastructure development. Most EU projects focus on CO_2 storage within emissions reduction schemes.
- Except for the US, most countries have little or no experience with CO_2 pipelines or CO_2-EOR operations.
- Start-up, routine inspection, shutdown and venting of CO_2 pipelines can differ considerably from natural gas pipelines.
- Pipelines can usually handle the flexible operational needs of both supplier and user. Examples for pipeline networks exist in the US. These hubs have no specific set of rules, as each system has its own standards for CO_2 purity and operating conditions.
- Although CO_2 pipelines are rarely the focal point of public concern, effective communication strategies are a key element for successful implementation of the whole project.
- Currently it is not possible to draw robust conclusions, whether or not the incident rate with CO_2 pipelines would be different from other gas pipelines.
- Little information is publicly available on the costs of CO_2 pipelines.
- The contractor created a reference manual, database and interactive web tool detailing information on 29 CO_2 pipeline projects worldwide.

Background to the Study

Currently there are more than 6,500 km of CO_2 pipelines worldwide; most of them are linked to EOR operations in the United States but there are also a number of pipelines associated with or under development for CO_2 storage. Valuable experience is available from these projects for all phases of pipeline projects: from early design through to operation and decommissioning.

The aim of this study is to collate information from the public domain on existing CO_2 pipelines into a comprehensive reference document. Other objectives are to discuss the similarities and differences between CO_2 and other, especially natural gas, pipelines and to provide an overview. The overall lessons learned from this study should support project developers, decision makers, regulators, and governmental bodies who do not deal with engineering calculations and cost estimates on a regular basis.

The IEAGHG commissioned this study on behalf of the Global CCS Institute. Ecofys was the main contractor with SNC-Lavalin, who has extensive experience in the oil and gas industry, e.g. in US-based EOR operations, acting as a subcontractor.

Scope of Work

The deliverables for this study consist of a reference manual, database, interactive web tool and webinar. The reference manual highlights key design, construction, operational and regulatory learnings. A database, containing more than 100 data elements, complements the reference manual. It covers the following categories, as Table 1 shows:

Table 1 - Categories and elements of the database

Category	Sub-categories	Data elements
Pipeline infrastructure	Pipeline Auxiliary equipment Costs	E.g. Route, length, depth of lay, material, diameter, wall thickness Compression and dehydration Design and construction
Operation & maintenance, risk and safety	Operational characteristics Monitoring Safety	E.g. Volume, source, destination, purity, pressure, flow Inspections and monitoring Procedures, corridors and valves
Regulatory regime	Realisation process Restrictions	Spatial planning, environmental impact assessment and permits/concessions E.g. Spatial planning and location
Public concern	Public communication Decision process	Media, publications and health Environmental Impact Assessment

To make access to the collated information easier and more user-friendly, Ecofys implemented an interactive web tool based on Google Maps. It shows the location and routing of the 29 CO_2 pipeline projects investigated in this study and allows users to zoom in and access a summary of information from the database (see screenshot in Figure 1).

Operational characteristics

Volume (designed)	23.6 Mton/y
CO2 source	CO2 comes form the McElmo Dome source field
CO2 sink	CO2 hub Denver City, Texas
Phase of transported CO2	Supercritical
Pressure	74-138 bar(a)

Monitoring

Pipeline inspections	Pipeline has a 24-hour monitoring from Control Center program. Pipeline is patrolled by air 26 times per year

Figure 1 - Interactive web tool (demo version available at http://www.globalccsinstitute.com/publications/co2-pipeline-infrastructure)

From over 80 CO_2 pipeline projects worldwide, Ecofys carefully selected a subset of 29 projects covering all key regions and operating conditions in a balanced way (see Table 2). More than half of the chosen projects are operational.

Table 2 - CO_2 pipeline projects included in the assessment

	Project name	Country code[a]	Status[b]	Length (km)	Capacity (Mton/y)	Onshore / Offshore	Sink[c]
	North-America						
1	CO_2 Slurry	CA	P	Unknown	Unknown	Onshore	EOR
2	Quest	CA	P	84	1.2	Onshore	Saline aquifer
3	Alberta Trunk Line	CA	P	240	15	Onshore	Unknown
4	Weyburn	CA	O	330	2	Onshore	EOR
5	Saskpower Boundary Dam	CA	P	66	1.2	Onshore	EOR
6	Beaver Creek	US	O	76	Unknown	Onshore	EOR
7	Monell	US	O	52.6	1.6	Onshore	EOR
8	Bairoil	US	O	258	23	Onshore	Unknown
9	Salt Creek	US	O	201	4.3	Onshore	EOR
10	Sheep Mountain	US	O	656	11	Onshore	CO_2 hub
11	Slaughter	US	O	56	2.6	Onshore	EOR
12	Cortez	US	O	808	24	Onshore	CO_2 hub
13	Central Basin	US	O	231.75	27	Onshore	CO_2 hub
14	Canyon Reef Carriers	US	O	354	Unknown	Onshore	Unknown
15	Choctaw (NEJD)	US	O	294	7	Onshore	EOR
16	Decatur	US	O	1.9	1.1	Onshore	Saline aquifer
	Europe						
17	Snøhvit	NO	O	153	0.7	Both	Porous Sandstone formation
18	Peterhead	UK	P	116	10	Both	Depleted oil/gas field
19	Longannet	UK	C	380	2	Both	Depleted oil/gas field
20	White Rose	UK	P	165	20	Both	Saline aquifer
21	Kingsnorth	UK	C	270	10	Both	Depleted oil/gas field
22	ROAD	NL	P	25	5	Both	Depleted oil/gas field
23	Barendrecht	NL	C	20	0.9	Onshore	Depleted oil/gas field
24	OCAP	NL	O	97	0.4	Onshore	Greenhouses
25	Jänschwalde	DE	C	52	2	Onshore	Sandstone formation
26	Lacq	FR	O	27	0.06	Onshore	Depleted oil/gas field
	Rest of the World						
27	Rhourde Nouss-Quartzites	DZ	P	30	0.5	Onshore	Depleted oil/gas field
28	Qinshui	CN	P	116	0.5	Onshore	ECBMR
29	Gorgon	AU	P	8.4	4	Onshore	Sandstone formation

[a] Country codes: AU=Australia, CA=Canada, CN=China, DE=Germany, DZ=Algeria, FR=France NL=Netherlands, NO=Norway, UK=United Kingdom, US=United States

[b] Legend status: P=Planned, O=Operational and C=Cancelled

[c] EOR=Enhanced Oil Recovery, ECBMR=Enhanced Coal Bed Methane Recovery

The contractor used the following sources for data gathering:

- Project websites
- Environmental Impact Assessments (EIA) / Environmental Impact Statements (EIS)
- Reports and permit applications
- Front End Engineering Design (FEED) studies
- Scientific publications
- Interviews with pipeline owners and project developers

To maximise amount of data and lessons learned, Ecofys included four cancelled CO_2 pipeline projects in the scope of the study (i.e. Barendrecht, Jänschwalde, Kingsnorth and Longannet).

Findings of the Study

Availability of data

The quality, accessibility and level of detail of the data presented in the following sections varied for a number of different reasons:

- Confidentiality / commercial purposes
- Change of pipeline owner
- Lost or inaccessible data
- Lack of digitalisation
- Language

Drivers for CO_2 pipeline projects

Table 3 shows the main drivers for CO_2 pipelines and gives example projects for each category.

Table 3 - Drivers of CO_2 pipeline projects (adapted from Amann, 2010)

Motivator	Comments	Example projects
Enhanced Oil Recovery (EOR)	CO_2 is used as a tertiary recovery agent to increase oil production in depleting or old oil fields.	SACROC, Monell, Beaver Creek, Boundary Dam
CO_2 reduction targets	CO_2 is stored in deep saline formations or depleted oil or gas fields	Quest, Barendrecht, Jänschwalde, Kingsnorth, Lacq Longannet, Peterhead, ROAD, Snøhvit, White Rose, Rhourde-Nouss-Quartzite
Enhanced Coal Bed Methane Recovery (ECBMR) and Enhanced Gas Recovery (EGR)	CO_2 is used to enhance coal bed methane production from coal-beds or coal bearing formations or re-injected in suitable gas formations (depleted or for EGR)	Qinshui
Use of CO_2 for industrial purpose	CO_2 is transported to greenhouses and used to stimulate growth of plants and crops	OCAP

In case of EOR, a project can make a good return and offset the investment costs by using CO_2 to increase the oil production. However, if market conditions change the project may lose its incentive. An example is the Beaver Creek project that was abandoned due to low oil prices during the late 1980s but was revived in 2005.

In certain jurisdictions, revenue may come from generating carbon offsets. Most CCS projects in Europe focus on CO_2 storage as a mitigation option. As this does not result in additional revenues, a financial support system or carbon offset system, like the EU ETS, needs to be in place.

Sources, sinks and hubs

CO_2 pipelines connect a variety of sinks and sources. Figure 2 shows that gas processing and coal-fired power plants are the most common sources for the pipeline projects investigated in this study. Common sinks are oil fields under EOR but also depleted oil and gas fields. These storage sites generally have the benefit of existing infrastructure that can be re-used.

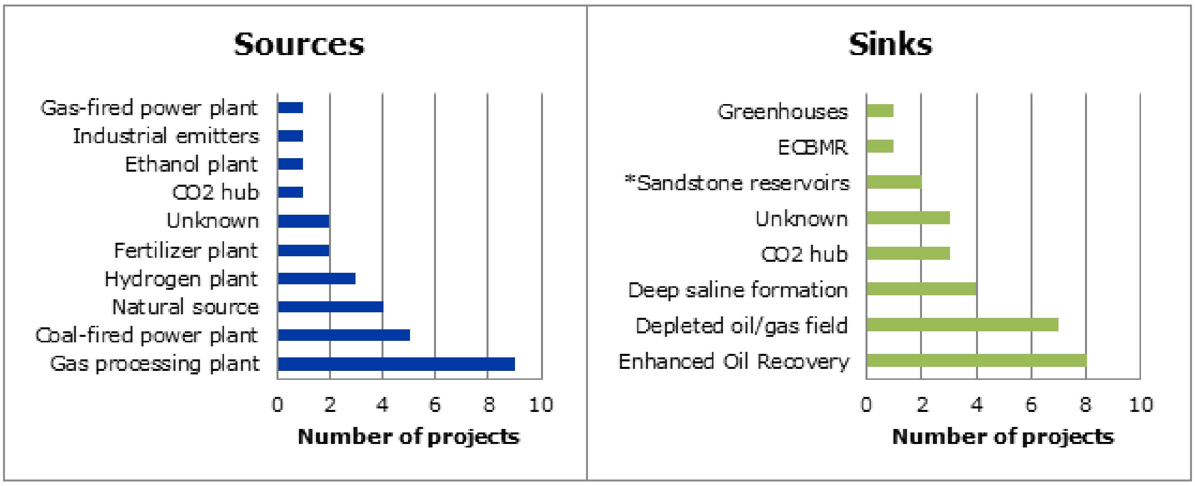

Figure 2 - Sources and sinks of CO_2 pipeline projects

The purity of the CO_2 stream depends on the CO_2 source and, if appropriate, the CO_2 capture technology. In ⅔ of the 29 pipeline projects the purity exceeds 95% and ⅓ of the projects deliver a purity greater than 99%. The main impurities in the CO_2 stream are H_2O, N_2, O_2, H_2S and CO.

Where multiple CO_2 sources and sinks exist, a gathering, transmission and distribution network - a hub - may develop. Currently operating hubs are almost all located in the US; examples are the Denver City Hub and the McCamey Hub. CO_2 hubs have no specific set of rules or lessons learned because they are usually developed ad-hoc when CO_2 sources are available and/or a viable market exists. Each hub has its own standards for CO_2 purity, acceptable impurities, pressure and temperature.

Planning, design and construction of CO_2 pipelines

The physical characteristics of the CO_2 pipelines investigated in this study vary greatly. For example, the range in length lies between 1.9 and 808 km. The following Table 4 shows the spread in other characteristics such as diameter, wall thickness, etc.

Table 4 - Physical characteristics of CO_2 pipelines

	Range
Length (km)	1.9 - 808
External diameter (mm)	152 – 921
Wall thickness (mm)	5.2 – 27
Capacity designed (Mt/y)	0.06 – 28
Pressure min (bar)	3 – 151
Pressure max (bar)	21 – 200
Compressor capacity (MW)	0.2 - 68

The inclusion of short-distance demonstration projects as well as commercial, long-distance EOR projects is the main reason for the large variation. The longest pipelines are located in

North America and the average length of CO_2 pipelines there is longer than in Europe. Another interesting point is a positive correlation between length and capacity of the pipelines. It seems that longer pipelines have to transport larger volumes of CO_2 to be economically viable.

Technical standards for CO_2 pipelines

The following dedicated standards for CO_2 pipelines currently exist:

- Unites States: CFR part 195
- Canada: CSA Z662
- Europe: DNV-RP-J202
- ISO/TC 265 (currently under development)

CO_2 pipeline project phasing

In many respects, CO_2 pipelines are comparable to natural gas pipelines but there are the following key differences:

- The properties of CO_2 lead to different design parameters.
- In many places CO_2 pipeline projects are first-of-a-kind.
- CO_2 pipelines do not transport a product that people see as directly beneficial.
- Risks associated with geological storage and the Lake Nyos incident influence the public perception of CO_2 pipelines.

Apart from this, CO_2 pipeline projects generally go through the same cycle as other gas pipeline projects. The project cycle typically takes between 3 to 6 years from concept stage to the final investment decision. The actual construction time usually lies between 1 and 4 years depending on the length and complexity of the pipeline.

Pipeline and equipment

Pipelines usually have a service lifetime that exceeds their reason for existence. If the initial design specifications allow for, than in most cases a re-use is beneficial, as this can drastically reduce the overall project costs. Offshore pipelines are a common area for re-use because they have the highest costs of all different terrain types (see Table 6 in section on CO_2 pipeline costs). There are no serious negative technical implications to operate a re-purposed pipeline in CO_2 service, as long as the capacity is lower than original.

Corrosion of the pipeline steel (which is usually carbon steel due to economic reasons) is a serious concern related to leakage and needs to be addressed during the whole project. Most CO_2 pipelines are buried under the ground, so they need both internal and external corrosion protection. The most commonly used method to prevent external corrosion is cathodic protection, sometimes in combination with a coating. Water is the main risk factor for internal corrosion. A dehydration system can keep the water content well below the allowable limit (about 840 ppmv for onshore in North America; offshore European may require below 50 ppmv). CO_2 streams from sources that produce a dry CO_2 gas (e.g. hydrogen plants, gas-processing plants) may not need additional dehydration.

The number and capacity of the compressors depend on the pipeline dimensions, transported volume and phase of the CO_2 stream. The majority of the studied pipelines transport the CO_2

in supercritical phase. To avoid phase change in practice the operators stay clear of the phase transition boundaries.

During operation, a sudden unexpected pressure drop in the pipeline can indicate a leak. For such a case, pipelines are equipped with Emergency Shutdown (ESD) valves to isolate the affected pipeline section. The distance between these ESD valves varies over the pipeline and depends on factors like population density and regulations. The selected CO_2 pipelines in this study have an average ESD valves distance of 10-20 km.

Flow meters are another important piece of equipment. They provide both a means of accurate billing and early detection of leaks.

In contrast to natural gas, high-pressure CO_2 pipelines are not self-arresting in terms of longitudinal failure and thus require the installation of crack arrestors. Crack arrestors can simply be occasional joints of pipe with greater wall thickness and improved hoop-stress properties. An alternative is the periodic wrapping with non-metallic materials.

Regulatory regime and permitting

Depending on the location of the project and the related regulatory framework, an assessment of environmental impacts might be necessary. The approaches and requirements for this vary from country to country. In general, such an assessment for a CO_2 pipeline is not fundamentally different from that for another gas pipeline.

North American regulations require an Environmental Impact Statement (EIS) when the project is complex in nature and needs consideration and analysis of environmental effects, for example under the National Environmental Policy Act (NEPA) in the US. Opinions of stakeholders and public participation play an important role in North American EISs. According to Directive 2011/92/EU, in Europe an Environmental Impact Assessment (EIA) is required for pipeline sections with a diameter of more than 800 mm and a length of more than 40 km. Most European CO_2 pipeline projects carried out an EIA because the capture and storage facilities triggered it, not the pipeline itself. By and large, there are not many EIAs or EISs that focus specifically on the pipeline part. The Kingsnorth project, for example, carried out an assessment for the offshore section of the pipeline.

In the investigated jurisdictions, CO_2 pipelines are within the regulatory framework of all pipelines that transport gaseous or liquid substances. In the US, CFR 49 Part 195 applies, which was amended in 1989 to include CO_2 in the former “Hazardous Liquid” category. Before this, CO_2 pipelines had to meet codes for natural gas pipelines. Canada has its own regulation for CO_2 pipelines, CSA standard Z662. In Europe, Directive 2099/31/EC on geological CO_2 storage states that the framework used for natural gas pipelines is adequate to regulate CO_2 as well.

The permitting and approval process plays a key role in the timeline realisation of pipeline projects. Securing permits and performing EISs/EIAs usually takes much longer than actual construction. An example for this is the 808 km Cortez pipeline in the US, which took 8 years to complete with only 2 years of construction time. Reason for the long timeline was the requirement for state-by-state approval of the pipeline routing.

Construction of CO_2 pipelines

The acquisition of necessary permits and right-of-way may be more time consuming than the actual construction of the pipeline, so they have to be done in a timely manner. In the US, CFR Section 195.248 prescribes a minimum pipeline burial depth of 1.2 m. After construction, regulations require a test of pipeline integrity. CO_2 pipelines that have passed hydrostatic testing are cleaned and dried to prevent corrosion or premature failure on start-up.

Operation, inspection and maintenance of CO_2 pipelines

Regulations require that the responsible operator prepares and follows a manual for each pipeline system. It consists of written procedures for conducting normal operations and maintenance activities but also handling abnormal operations and emergencies. In the US, this manual needs to be reviewed at least once a year.

Limited data was available on the control systems used for CO_2 pipelines. Typically, a SCADA (Supervisory Control and Data Acquisition) system monitors the key operational parameters: pressure, temperature, water content and flow rate. Very small leaks may be hard to detect with this system. The Weyburn project uses a special Leak Detection System (LDS), which monitors for leaks every 5 seconds and displays the related data on a computer screen. In combination with proprietary software, the LDS can determine the size and location of a potential leak. The flow meters integrated into SCADA and LDS help with checking the CO_2 mass balance for contract obligations.

Inspection

To minimise external influences, most pipelines are buried underground but this makes inspection more difficult. Most countries prohibit building activities within a certain range of the pipeline corridor (typically 5 m). In addition, visual corridor inspections by foot, car or helicopter take place every week.

Most operators use so-called “pig runs” to inspect the inside of their pipelines. A pig can clean the pipeline, measure wall thickness and detect leakage and corrosion. With around EUR 1 million (USD 1.4 million) for pipelines with a length between 25 - 270 km, pig runs are very costly. One reason for this is the low lubricity of CO_2, which poses a great challenge.

Besides the pipeline, inspection of auxiliary equipment takes places on a regular basis as well. This includes compressors, dehydration units, valves, cathodic protection system, monitoring systems and emergency systems.

Safety statistics

For the US, the PHMSA (Pipeline and Hazardous Materials Safety Administration) provides statistics on pipeline incidents. According to PHMSA, there have been 46 incidents involving CO_2 pipelines between 1972 and 2012. The main reasons for these incidents were:

- Relief valve failure
- Weld, gasket or valve packing failure
- Corrosion
- Outside force

Most of these incidents occurred in areas with low population density, so they did not cause any reported casualties or fatalities. In contrast, natural gas pipeline accidents injured 217 and killed 58 people over the period 1986 – 2001. However, it is difficult to make effective comparisons between CO_2 and natural gas pipelines yet because of the huge discrepancy in the number of km of pipeline (550,000 km vs. 6,500 km in the US).

In Europe, no incident reporting or analysis system exists for CO_2 pipelines, so industry gathers statistics and reports incidents on a voluntary basis. The OCAP project reported three incidents with small leakages during operation of the pipeline. Again, no human injuries or fatalities occurred.

Decommissioning and abandonment

Pipeline decommissioning is the permanent deactivation of a pipeline that leaves the pipeline in a permanently safe condition, as prescribed by a regulatory body.

The main reason for decommissioning of a pipeline is that it no longer has a commercial use. Otherwise, well-constructed and well-maintained pipelines often have a lifetime in excess of the design lifetime. CO_2 pipelines are expected to perform as well or even better than other gas pipelines if the operator carefully addresses corrosion issues.

Because the existing CO_2 pipeline projects are relatively young (40 years), there is hardly any information available about large-scale decommissioning activities.

Public concern

It is important to understand the key drivers of public concern because it can become a serious threat to a project if not handled in time and in a careful manner. During interviews many pipeline operators made clear that the CO_2 pipeline is usually not the focal point of public opposition. Most concerns relate to either the capture (building of a power plant or production plant) or the storage part of the project. In general, there is less public concern over offshore transport and storage than over onshore projects.

The Barendrecht CCS project in the Netherlands is an example where public concern led to the cancellation of the project. The developers of the ROAD project directly used the lessons learned from Barendrecht by training staff to communicate simply and clearly and to address concerns from local residents.

Most projects investigated in this study used websites, public meetings and telephone helplines as means of communication. The range of available information on the websites can vary between the different projects. Some projects (like Saskpower Boundary Dam, OCAP, Lacq) have dedicated websites while others (e.g. Kinder Morgan, Jänschwalde, Kingsnorth) just provide simple generic information. The participation in public meetings varies as well. Most North American pipeline projects have seen only limited interest in public meetings. Reasons for this are the difference in population density and the long-standing oil and gas operations that both lead to a higher acceptance of pipelines compared to Europe.

CO_2 pipeline costs

The following list gives an overview of the key costs drivers for pipelines:

- Piping (type and grade of material)
- Equipment (such as compressors, booster stations, valves, crack arrestors, etc.)
- Trenching (i.e. earthworks, excavation, backfilling)
- Distance

- Diameter
- Terrain
- Labour
- Engineering (e.g. design, project management, regulatory/permitting activities)

For some projects, cost data is publicly available and can be used as a reference to estimate future project costs. Due to commercial reasons, engineering companies sometimes keep the design and construction costs confidential. Table 5 presents actual costs for selected CO_2 pipeline projects that were available from public documents.

Table 5 - Actual costs for selected CO_2 pipelines

Pipeline	Costs for pipeline	Currency	Year	Onshore/ Offshore	International units
Canyon Reef Carriers (SACROC)	46 million	USD	1971	Onshore	D= 324 – 420 mm L= 354 km
Cortez	700 million	USD	1982	Onshore	D= 762 mm L= 808 km
Weyburn CO_2 pipeline	51 million	USD	2008	Onshore	D= 305 – 356 mm L= 330 km
Quest	140 million	USD[b]	2012	Onshore	D= 324 mm L= 84 km
Qinshui	39.35 million	USD	2006	Onshore	D= 152 mm L= 116 km
Longannet	160 million	GBP	2011	On: 100 km Off: 270 km	D= 500 to 900 mm L= 380 km
ROAD	90 million	EUR	2010	On: 5 km Off: 20 km	D= 450 mm L= 25 km
Gorgon	9 million	AUD	2011	Onshore	D= 269 – 319 mm L= 8.4 km

[a] For pipeline and associated compression stations

[b] Initial estimate in CAD (Canadian dollars). Assumed exchange rate USD 1.00 = CAD 1.00

If data is not readily available, then it is possible to estimate pipeline capital costs using credible sources, like the NETL guidelines (*Carbon Dioxide Transport and Storage Costs in NETL Studies – Quality Guidelines for Energy Systems Studies*). The related formulas reflect US dollars as of 2011 and require diameter and length as input parameters. The results of the estimation can give a first impression of possible CO_2 pipeline costs but are in no way an accurate estimate. In any case, terrain has the strongest influence on pipeline costs and accounts for the largest uncertainty in cost estimation. Table 6 shows costs for different types of terrain and it is clear that interference with bodies of water increases the costs most.

Table 6 - Pipeline cost metrics as disclosed by Kinder Morgen

Terrain	Capital Cost (USD/inch-Diameter/mile)
Flat, Dry	USD 50,000
Mountainous	USD 85,000
Marsh, Wetland	USD 100,000
River	USD 300,000
High Population	USD 100,000
Offshore (150-200 feet ~ 45–60 meters depth)	USD 700,000

Operation and maintenance costs are not readily available from the investigated CO_2 pipeline projects but again can be estimated by using the following guidelines:

- Fixed O&M costs of USD 8,454 per mile and year (NETL guidelines)
- 1.5% of initial capital costs per year (Wong 2010)
- 3-8% of initial installed capital costs (confidential source)
- EUR 1 million (USD 1.4 million) per pig run (Wevers 2013)

A number of factors differentiate CO_2 pipelines from other gas pipelines when it comes to costing. Some examples are:

- The CO_2 depressurisation characteristics dictate the use of crack arrestors.
- The carbon steel grade needs to be resistant towards brittle fracture because CO_2 can reach very low temperatures when expanded.
- CO_2 suppliers have to deliver at specified conditions which are in general:
    - 95% purity
    - Water content depending on region between 50 – 840 ppmv
    - Temperature and pressure according to single dense phase transport
- Installation of ESD valves to limit CO_2 release in case of leakage.
- Venting procedures need to include provisions for lofting and dispersing released CO_2.
- Gaskets and other non-ferrous materials must be resistant to deterioration in presence of CO_2.

Usually the CO_2 supplier(s) or the CO_2 capture project part is responsible for accounting the costs related to separation, clean-up, compression and dehydration of the raw CO_2 stream.

Expert Review Comments

Six reviewers from industry, academia and other organisations took part in the expert review of the reference manual and submitted useful comments. In general, the reviewers stated that the reference manual has a good structure and provides a valuable overview on CO_2 pipeline transport. Some reviewers asked to increase the level of detail in certain sections (especially regarding operating conditions, impurities and corrosion) and to harmonise the information presented in the two main sections of the report (i.e. lessons learned from existing projects and guidelines for CO_2 pipeline projects). Ecofys addressed most of the comments in the final version as long as they have been within the scope of the study. In some places, Ecofys regarded the addition of more information as not beneficial for the report and established a stronger reference to the database. The review of database and web tool was done by IEAGHG and the Global CCS Institute only.

Conclusions

The purpose of this study was to collect public information on CO_2 pipelines and make it available to project developers, decision makers, regulators and the interested public. The findings of the study are easily accessible in three different ways: through a reference manual, a database and an interactive web tool.

With the exception of the US, most countries have no or little experience with CO_2 pipelines or CO_2-EOR operations. Even for many of the operational projects certain information is not accessible due to commercial or other reasons. This applies especially to costs and auxiliary equipment that belongs to other parts of the process chain, like compressors and dehydration units.

Currently the main driver for CO_2 pipeline projects is EOR. CO_2 transport and storage as part of larger CCS projects can only generate revenues if a pricing or support scheme is in place.

A main result of the study is that CO_2 pipelines are both similar and different compared to other gas pipelines, natural gas in particular. They are similar to some extent, so that the regulations and standards used for CO_2 originate in natural gas pipeline codes. But they are different in terms of the physical properties of CO_2, which results in different design parameters, and the risk perception, which the public usually associates with geological storage of CO_2.

The permitting and approval processes play a large role in realisation of the project timeline. This can take much longer than expected and exceed the construction time by far. The CO_2 pipelines in the US have a 40-year history of operation with no civilian injuries or fatalities. In contrast to Europe, a sophisticated reporting system exists.

Detailed cost information was difficult to find for many projects due to confidentiality. Key factors determining the costs of a CO_2 pipeline are terrain, length and capacity. The primary means of cost reduction is the re-use of existing pipeline infrastructure. Some projects in the EU considered this approach (e.g. OCAP, Lacq, and Peterhead).

Public concern may vary from project to project, depending on the location, population density, type of project, source and sink of CO_2, etc. As public opposition can lead to cancellation of the whole project (as in the case of Barendrecht), effective communication strategies and early involvement of all stakeholders are key elements in addressing such concerns. Although important developments are expected in pipeline technology, e.g. in the fields of corrosion resistance, pigging and crack arresting, it is likely that the main area, where improvement is necessary, will be public acceptance.

Recommendations

The combination of the three deliverables (i.e. reference manual, database and interactive web tool) is a very attractive way of disseminating the results of this study to slightly different target groups and their needs. However, these tools live on being up-to-date. This is why we recommend a regular update of the web tool and database through follow-up studies (every 2-3 years).

We also think it is a good idea to use the results of this study for setting up a Wiki on CO_2 pipelines/transport to deliver information in an easily comprehendible way to the public. Likewise, an extension of the Wiki with other IEAGHG studies on CO_2 transport, capture, storage, etc. is possible.

Although CO_2 pipelines are usually not the focal point of public concern, source and sink of the CO_2 can largely influence how the public perceives them. Because of this, we aim to undertake a study focussing on the public perception on CO_2 pipelines.

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CO$_2$ PIPELINE INFRASTRUCTURE

Reference manual

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CO_2 PIPELINE INFRASTRUCTURE

Reference manual

By **Paul Noothout, Frank Wiersma (Ecofys),**
Omar Hurtado, Patrick Roelofsen and Doug Macdonald (SNC-Lavalin)

Date **13 December 2013**

Project **CESUK13551**

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Executive summary

Purpose of study

1. The aim of this CO_2 pipeline infrastructure study is to collate information from the public domain on existing CO_2 pipeline infrastructure into a comprehensive database and reference document. In particular, the study focussed on topics particular to CO_2 pipelines and where these differ from other gas pipelines. The study was commissioned by IEA Greenhouse Gas R&D Programme (IEAGHG) and the Global CCS Institute ('the Institute').

2. The present Reference Manual complements the database that captures detailed information on 29 CO_2 pipeline projects. This manual offers an overview of results and overall lessons learned. Furthermore, it can serve as a guide to enable access to the full set of information in the database. It is written to support project developers, regulators and governmental bodies that are dealing with CO_2 pipeline projects but who do not usually undertake detailed engineering calculations or cost estimates.

3. Some 6,500 km of CO_2 pipelines have been operating for years for Enhanced Oil Recovery (EOR) operations, primarily in the United States. Moreover, there are a number of CO_2 pipelines that are in use for CO_2 re-use or Carbon Capture and Storage (CCS) operations in Europe and the Americas. Valuable experience and lessons learned are available from these projects relevant for all phases of CO_2 pipeline projects: from early identification to execution and operation.

4. The information was collected based on reviews of a large number of documents and interviews with pipeline designers, builders and operators. Nonetheless, there were limitations to the availability of information in some areas and for some projects due to it being either confidential or not available for practical reasons.

Function and funding of CO_2 pipelines

5. CO_2 pipelines connect different types of sources and sinks. The most common sources are gas processing plants, fossil-fueled power stations and natural sources of CO_2. Common sinks are deep saline formations and oil fields for EOR but also depleted oil and gas fields are used when the objective is greenhouse gas emissions reduction.

6. Where multiple CO_2 sources and sinks exist a gathering, transmission and distribution network may be developed. There are some interesting examples of such hubs in the United States (US) where CO_2 from individual sources is gathered and from which various CO_2 customers are supplied.

7. CO_2 pipeline projects require large, costly investments in infrastructure. Sources of CO_2 pipeline funding will depend on the purpose of the pipeline.

8. In America enhanced oil recovery has typically been the primary driver for CO_2 pipeline infrastructure development. Private companies or consortia may join forces to develop a project as a commercial venture with the revenues from extra oil produced providing the financial justification for the project. In some cases projects have been abandoned due to changing market conditions, notably a low oil price. Carbon offsets may provide a supplemental source of revenues.

9. Most European projects are focused on CO_2 storage as a CO_2 emissions reduction option. In this case, the justification for the project relies on either a CO_2 emissions reduction mandate or cost associated with CO_2 emissions, for example under the European Emissions Trading System (ETS) or Norway's tax on carbon emissions.

10. In a number of projects existing oil or gas pipelines or infrastructure were reused for CO_2 transportation and / or injection. Where this is possible substantial savings in investment costs may be realised.

Regulatory regime and permitting of CO_2 pipelines

11. When CO_2 pipelines were new in the 1970s, designs were based on meeting codes for natural gas pipelines in the absence of specific design codes or standards. Around 1989 specific regulations were published for CO_2 pipelines in the United States, not because of the CO_2 industry's safety record — which was good — but rather the possibility of a high-consequence incident if a break in a CO_2 pipeline were to occur.

12. The European Commission concluded in the CCS directive that the framework used for natural gas transportation pipelines would be adequate to regulate CO_2 transport (European Commission, 2008). There are broad similarities between the transport of CO_2 and natural gas, "albeit without the added risk of explosion posed by natural gas".

13. Few Environmental Impact Assessments have been prepared specifically for CO_2 pipelines. Mostly, the pipeline is a part of a larger EOR or CCS project.

14. For project developers it is important to understand what the key drivers of public concern are so that focused action can be taken. Interviews with several pipeline operators (many of which are situated in America), suggest that in many cases a CO_2 pipeline itself is less of a focal point of increased public concern and is not regarded much differently from other pipeline projects. Instead, public concern is typically related to the power plant or CO_2 storage project that the pipeline is tied to. However, there are also examples of CO_2 pipeline projects that have been focus of public concern. Effective communication strategies and availability of good quality information are key elements in dealing with such concern.

15. CO_2 pipeline requirements are similar to what is needed for high-pressure natural gas transmission pipelines. The key distinguishing features fall into three specific areas:
    - Regulatory agencies and members of the public are usually not familiar with CO_2 pipelines;

- CO_2 pipelines are not separated in the public mind from the perceived risks associated with geological storage of CO_2 and arguably there are parallels.
- Properties of CO_2 gas result in different design parameters, risk contours and assessment than for natural gas;

Planning, design and construction of CO_2 pipelines

16. The design of CO_2 pipelines is governed by costs, safety and design criteria standards. Generally one or more of the standards listed below are applied in the design process. Deviations if any must be justified to regulatory authorities.

17. Commonly used standards include:
    - Canada: CAN/CSA (Canadian Standards Association) Z662 pipeline design standards.
    - US: CFR (Code of Federal Regulations) 49 part 195 and ASME B 31.4 pipeline design standards.
    - Europe: DNV-RP-J202, Recommended Practice Design and Operation of CO_2 Pipelines by Det Norske Veritas (April 2010) as well as the NORSOK standard P-001 for process design.
    - Australia: AS2885 standard is used relating to design, construction, testing, operations and maintenance of gas and petroleum pipelines.

18. Key auxiliary equipment associated with CO_2 pipelines includes booster compressors or pumps, control systems, venting equipment and valves (block valves, check valves and emergency shutdown valves). These play a key role in ensuring reliable and safe operation of the pipelines. These are essential topics from the perspective of users and producers of CO_2 and maintaining a license to operate. Primary compression and dehydration facilities for bringing the CO_2 from its source to pipeline inlet conditions are usually considered as part of the capture facility rather than the pipeline.

19. After construction, commissioning and testing are key steps towards operation. Carbon dioxide pipelines that have been hydrostatically pressure tested are cleaned and dried upon completion of testing to prevent corrosion that can otherwise occur on start-up of the system (Canadian Standards Association, 2012). The presence of residual water following a hydrotest could contribute to rapid pipeline corrosion and potential premature failure, so dry-out procedures must be carefully designed and followed.

20. The particular properties and phase envelope of CO_2 as a gas result in procedures for start-up, routine inspection, shutdown and venting that differ considerably from those for natural gas pipelines.

Operation and safety statistics of CO_2 pipelines

21. Typically the CO_2 pipeline will be the most operationally reliable of the components of a CCS project. The pipeline can usually accommodate and flexibly handle the operational needs of both supplier and user.

22. Typically, each operator must prepare and follow, for each pipeline system, an up to date manual of written procedures for conducting normal operations and maintenance activities and handling abnormal operations and emergencies as a regulatory requirement.

23. Abnormal pressure drops, temperature and content of water and other impurities are key operational parameters that are monitored using a Supervisory Control And Data Acquisition (SCADA) system. Pressure drops are likely to indicate possible leaks and such deviations would trigger alarms.

24. Minimising external influences is an important focus for the design and burying pipelines is one of the options to achieve this. Still, it is possible that a pipeline would be impacted by construction activities such as digging. In most countries, construction activities are prohibited within a certain distance of the corridor (typically 5 meters from the pipeline). Still, every week the pipeline corridors are visually inspected to determine if construction activities have taken place near the corridor.

25. The condition of the pipeline is inspected using a tool that passes through the pipeline (a “pig run”), supplemented by external examination via specific digs. The pig cleans the inside and takes measurements of wall thickness or diameter and detects possible corrosion. Special provisions or pig design factors may be necessary to accommodate CO_2’s physical characteristics (including lack of lubricity, interaction with certain non-metallic materials).

26. Incident frequency statistics for CO_2 pipelines provide no indication that these would be materially different from the frequency of incidents with natural gas pipelines. However, the hazards associated with such incidents for natural gas pipelines tend to be more severe than for the case of CO_2 pipelines, both in terms of human injuries and casualties as with property damage. Due to the limited number of kilometres of CO_2 pipelines and likely sampling error in the incident statistics it is not possible to draw robust conclusions about whether or not the incident rate with CO2 pipelines would be systematically different from other gas pipelines.

Costs of CO_2 pipelines

27. Little information is publicly available on the costs of specific CO_2 pipelines. This information is treated confidentially for commercial reasons.

28. In the absence of public data, pipeline capital cost can be estimated based on credible sources. A recent source is the National Energy Technology Laboratory 2013 study entitled Carbon Dioxide Transport and Storage Costs in NETL Studies. Such an approach should be used as an indicator of possible costs for a project and never as an accurate estimate.

Table of contents

1 Introduction

1.1 Background

Currently, there is over 6,500km of CO_2 pipeline in North-America, Europe, the Middle East, Africa and Australia. Some of these pipelines have been operating for many years, mostly to transport CO_2 for enhanced oil recovery (EOR) operations in the Americas. Some pipelines are linked to Carbon Capture and Storage (CCS) projects and a number of new pipelines associated with CCS are under development at the time of publication.

This CO_2 Pipeline Infrastructure Reference Manual has been prepared as part of the “CO_2 pipeline infrastructure” study commissioned by IEA Greenhouse Gas R&D Programme (IEAGHG) and Global CCS Institute (the Institute). The aim of this study is to collate information from the public domain on existing CO_2 pipeline infrastructure into a comprehensive database and reference document.

The database captures detailed information on a selection of twenty-nine CO_2 pipeline projects. This manual offers an overview of results and overall lessons learned.

1.2 Purpose of the study

The purpose of this study was to collect public information on CO_2 pipelines and to make this available to project developers, decision makers and regulators working on current and future CO_2 pipeline projects. An extensive amount of information was collected and organised in a comprehensive CO_2 pipeline database.

This Reference Manual complements the database. On the one hand it serves as a summary of the information in the database to assist project developers, decision makers and regulators. On the other hand it is intended as a guide to accessing the database, pointing to relevant examples in the database where further information can be found. This Reference Manual highlights key design, construction, operational and regulatory learnings from existing work on CO_2 pipeline infrastructure.

This reference manual was written primarily for project developers that are interested in building a CO_2 pipeline but who do not cover detailed engineering calculations or cost estimates. Secondly, the reference manual provides valuable information for governments and regulators, addressing different phases of a CO_2 pipeline project, including permitting and regulations.

The reference manual and database cover the following topics:

- Regulatory regime and permitting;
- Public concern and safety statistics;
- Pipeline infrastructure and related equipment;
- Pipeline operation, inspection and maintenance;
- CO_2 pipeline capital and operating costs;
- CO_2 pipeline FEED studies;
- Design and construction of CO_2 pipelines;
- CO_2 Pipeline decommissioning and abandonment;
- Research and centres of excellence.

1.3 Methodology

There are over 80 CO_2 pipeline projects around the world - a list is provided in Appendix A. Providing detailed information about all these projects in one report is not necessarily helpful towards the overall aim. Therefore, a carefully selected subset of twenty-nine CO_2 pipelines was compiled by the project team covering all key regions and different conditions in a balanced way. In this process the following criteria were considered:

- Geographical coverage;
- Onshore and offshore;
- Time of construction covering both recent and older projects;
- EOR and storage projects;
- Existing and planned;
- Conventional and new concepts;
- New-built and reuse of pre-existing pipelines.

Another key criterion was the extent to which public information was available. Figure 1 (see next page) presents an overview of the projects that were covered in the present study.

In parallel with selecting projects, a detailed list was prepared with key content topics of interest. This was used as a checklist during the data collection phase. For each of these pipelines a database was populated, using publically available sources.

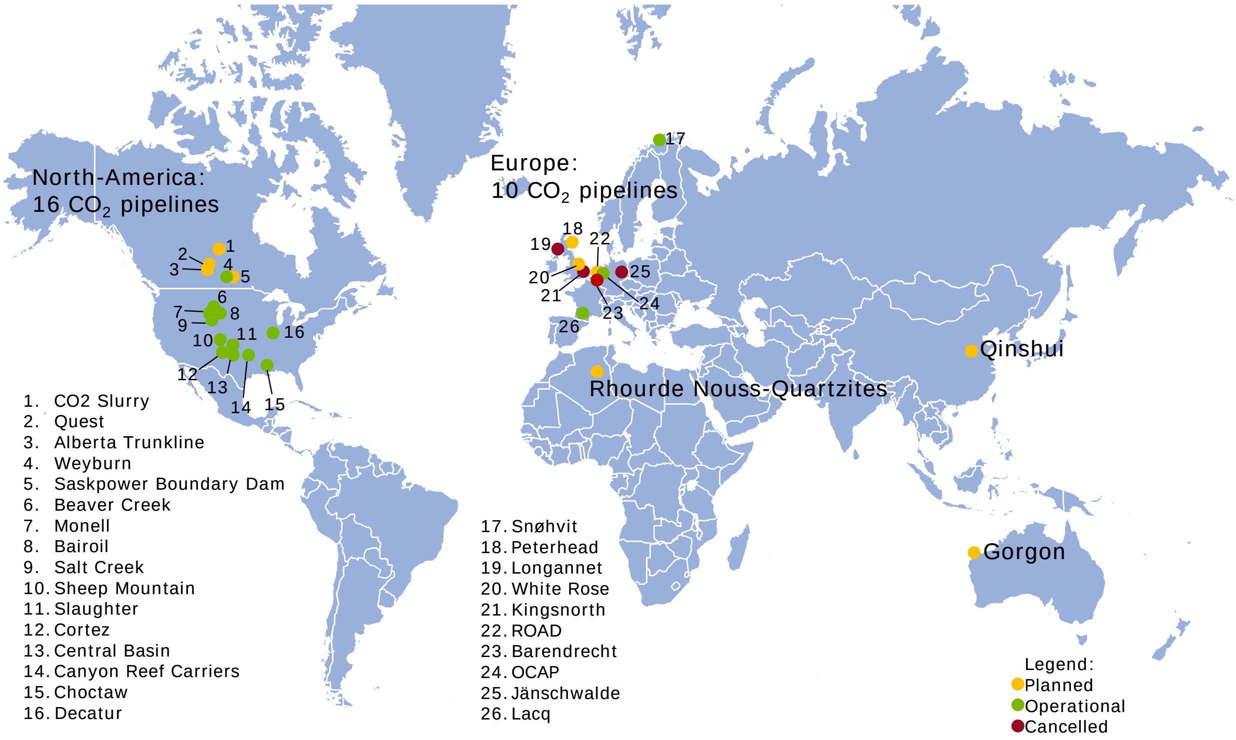


Figure 1 – Overview of CO_2 pipelines included in the study.

The first step in data gathering was to carry out a literature survey of the selected CO_2 pipeline projects. The following sources were consulted:

- Project websites;
- Environmental Impact Assessments or Environmental Statements;
- Reports on pipeline routes (sometimes as part of a permit application);
- FEED-studies;
- Journal articles, including scientific articles.

Next, pipeline owners were contacted to seek additional information. The combined networks of Ecofys, SNC-Lavalin, IEAGHG and the Institute allowed key contact persons to be identified. Contacts were established by telephone, e-mail and face-to-face meetings at offices and conferences. A large number of interviews were conducted and supplemental information was obtained that could not be retrieved from literature.

To maximize the amount of information presented in the study, the project team decided to also include four CO_2 pipelines that have been cancelled. For these projects (Barendrecht, Jänschwalde, Kingsnorth and Longannet), FEED-studies were available, containing detailed information that is valuable for the purpose of this study.

Table 1 - Overview of CO_2 pipeline projects included in the assessment

	Project name	Country code[a]	Status[b]	Length (km)	Capacity (Mton/y)	Onshore / Offshore	Sink[c]
	North-America						
1	CO_2 Slurry	CA	P	Unknown	Unknown	Onshore	EOR
2	Quest	CA	P	84	1.2	Onshore	Deep saline formation
3	Alberta Trunk Line	CA	P	240	15	Onshore	Unknown
4	Weyburn	CA	O	330	2	Onshore	EOR
5	Saskpower Boundary Dam	CA	P	66	1.2	Onshore	EOR
6	Beaver Creek	US	O	76	Unknown	Onshore	EOR
7	Monell	US	O	52.6	1.6	Onshore	EOR
8	Bairoil	US	O	258	23	Onshore	Unknown
9	Salt Creek	US	O	201	4.3	Onshore	EOR
10	Sheep Mountain	US	O	656	11	Onshore	CO_2 hub
11	Slaughter	US	O	56	2.6	Onshore	EOR
12	Cortez	US	O	808	24	Onshore	CO_2 hub
13	Central Basin	US	O	231.75	27	Onshore	CO_2 hub
14	Canyon Reef Carriers	US	O	354	Unknown	Onshore	Unknown
15	Choctaw (NEJD)	US	O	294	7	Onshore	EOR
16	Decatur	US	O	1.9	1.1	Onshore	Deep saline formation
	Europe						
17	Snøhvit	NO	O	153	0.7	Both	Sandstone reservoir
18	Peterhead	UK	P	116	10	Both	Depleted oil/gas field
19	Longannet	UK	C	380	2	Both	Depleted oil/gas field
20	White Rose	UK	P	165	20	Both	Deep saline formation
21	Kingsnorth	UK	C	270	10	Both	Depleted oil/gas field
22	ROAD	NL	P	25	5	Both	Depleted oil/gas field
23	Barendrecht	NL	C	20	0.9	Onshore	Depleted oil/gas field
24	OCAP	NL	O	97	0.4	Onshore	Greenhouses
25	Jänschwalde	DE	C	52	2	Onshore	Deep saline formation
26	Lacq	FR	O	27	0.06	Onshore	Depleted oil/gas field
	Rest of the World						
27	Rhourde Nouss-Quartzites	DZ	P	30	0.5	Onshore	Depleted oil/gas field
28	Qinshui	CN	P	116	0.5	Onshore	ECBMR
29	Gorgon	AU	P	8.4	4	Onshore	Sandstone reservoir

[a] Country codes: AU=Australia, CA=Canada, CN=China, DE=Germany, DZ=Algeria, FR=France NL=Netherlands, NO=Norway, UK=United Kingdom, US=United States

[b] Legend status: P=Planned, O=Operational and C=Cancelled

[c] EOR=Enhanced Oil Recovery, ECBMR=Enhanced Coal Bed Methane Recovery

The CO_2 pipelines included in this study and database are presented in Table 1 (see previous page). These twenty-nine projects are located in five continents, of which sixteen are in North America, ten in Europe and one each in Australia, Asia and Africa. More than half of the CO_2 pipeline projects covered are operational, mostly located in North-America. Ten projects are still in the planning phase and four of the projects included are cancelled.

1.4 Availability of data

The quality and level of detail of the available data varied. For example, the availability of public information depends on the period in which the project took place. The oldest projects, stemming from the 1970s, had good information availability. These projects were first-of-a-kind, and many parties were interested in publishing information on these or carrying out research. This resulted in a number of conference papers providing valuable information. However, projects that started somewhat later (1980s) were considered less interesting and/or more commercially sensitive and much less information was published. Moreover, from this period most of the information is archived as hard copy — if at all available — and certainly not available in digital format. Such older projects tend to have switched owners once or multiple times. This has negatively impacted the availability of information from the design and construction stages to the current owners. More recent pipeline projects on the other hand tend to have good information available. Most of these projects have a degree of government funding and a lot of information is publicly available. For some of these projects detailed information was available from Environmental Impact Assessments and FEED-studies.

However, for other projects fewer sources of information were available for a number of different reasons:

- Confidentiality of information: Some parties contacted indicated that parts of the information sought are not public and could not be disclosed. This played an important role in the limited success in collecting information on costs;
- Information from older projects that had been archived, was lost or otherwise inaccessible;
- Another party had become the Owner of the pipeline changed and the current owners did not have all information from the time that the project was developed and built;
- In some cases key people involved are no longer working for the pipeline owners;
- No digital copies of reports or assessments were available. In some cases only hard copies and / or information in local language was available;
- Pipelines with a strictly commercial purpose and no government funding were less likely to be forthcoming with specific technical and cost information.

1.5 Database and web-viewer complementing this Reference Manual

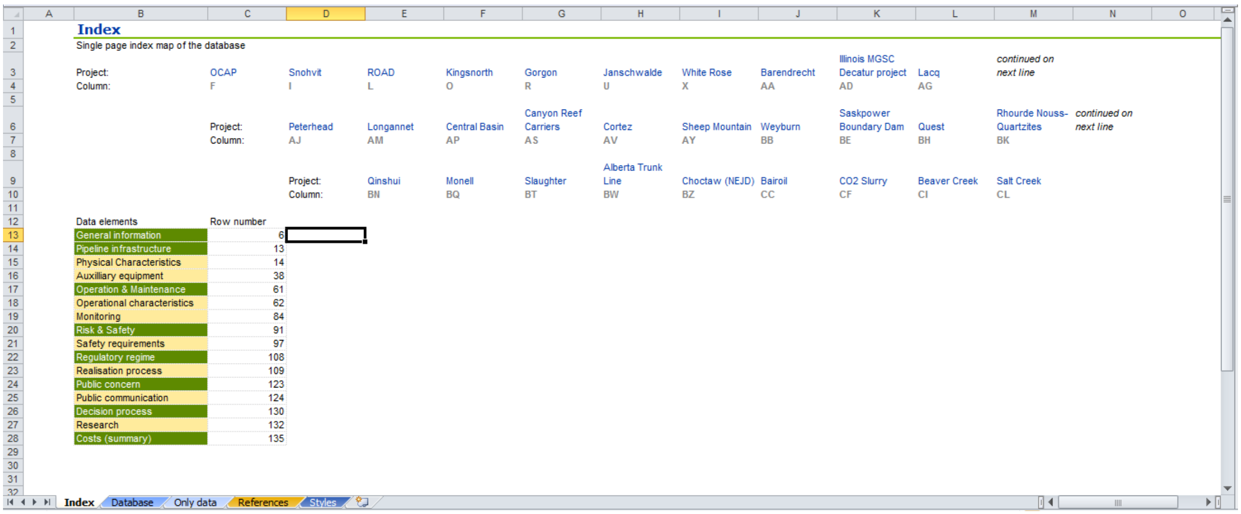
For the selection of CO_2 pipeline projects we gathered information on more than hundred data elements. Table 2 gives an overview of the categories and sub-categories used in the database, including a selection of data elements. Appendix B provides a detailed overview of all data elements that are included in the database. Two screenshots (Figure 2 and Figure 3 on the following page) give an first impression of the database.

Access to the database can be found on the following website or by contacting the Global CCS Institute: http://www.globalccsinstitute.com/publications/co2-pipeline-infrastructure

In addition to the main database, a web-viewer was created that provides a convenient way to access the information on CO_2 pipelines in a Google-maps environment. The web-viewer provides an overview of the routes of selected CO_2 pipeline projects, including a summary of the data per project. Furthermore, it presents centres of excellence – a selection of key institutes and companies that play a role in the development of CO_2 pipelines. Figure 4 and Figure 5 show screenshots of the web-viewer. The web-viewer will be accessible at both the websites of IEAGHG and the Global CCS Institute.

Table 2 – Setup of database with detailed information on CO_2 pipeline projects

Category	Sub-categories	Data elements
Pipeline infrastructure	Pipeline	E.g. Route, length, depth of lay, material, diameter, wall thickness
	Auxiliary equipment	Compression and dehydration
	Costs	Design and construction
Operation & Maintenance, risk and safety	Operational characteristics	E.g. Volume, source, destination, purity, pressure, flow
	Monitoring	Inspections and monitoring
	Safety	Procedures, corridors and valves
Regulatory regime	Realisation process	Spatial planning, environmental impact assessment and permits/concessions
	Restrictions	E.g. Spatial planning and location
Public concern	Public communication	Media, publications and health
	Decision process	Environmental Impact Assessment



Index

Single page index map of the database

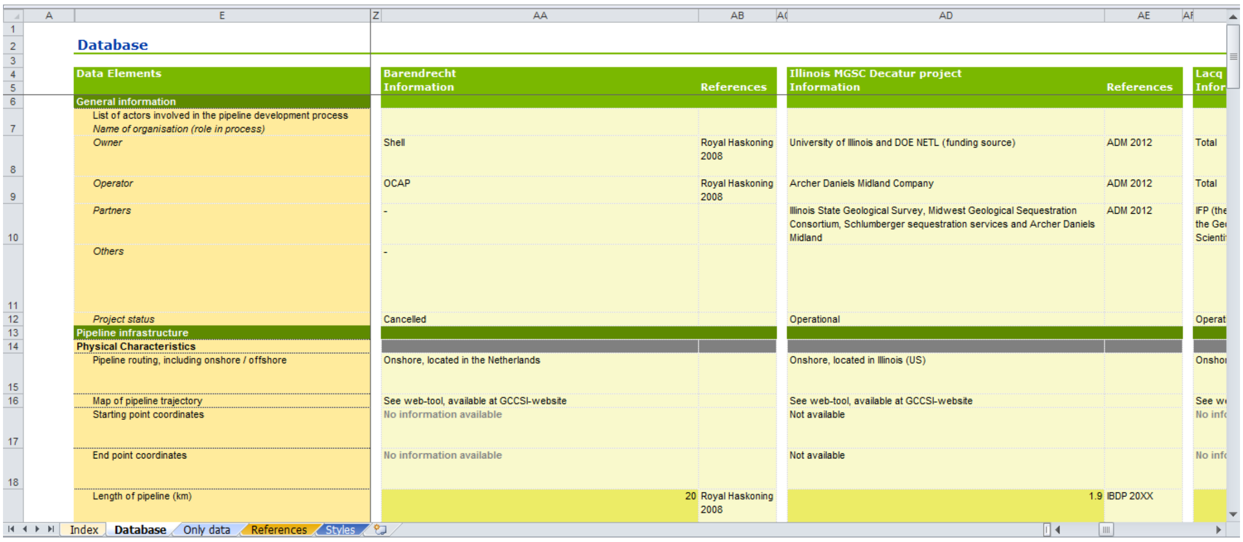
Project:	OCAP	Snohvit	ROAD	Kingsnorth	Gorgon	Janschwalde	White Rose	Barendrecht	Illinois MGSC Decatur project	Lacq	*continued on next line*
Column:	F	I	L	O	R	U	X	AA	AD	AG	

Project:	Peterhead	Longannet	Central Basin	Canyon Reef Carriers	Cortez	Sheep Mountain	Weyburn	Saskpower Boundary Dam	Quest	Rhourde Nouss-Quartzites	*continued on next line*
Column:	AJ	AM	AP	AS	AV	AY	BB	BE	BH	BK	

Project:	Qinshui	Monell	Slaughter	Alberta Trunk Line	Choctaw (NEJD)	Bairoil	CO2 Slurry	Beaver Creek	Salt Creek
Column:	BN	BQ	BT	BW	BZ	CC	CF	CI	CL

Data elements	Row number
General information	6
Pipeline infrastructure	13
Physical Characteristics	14
Auxilliary equipment	38
Operation & Maintenance	61
Operational characteristics	62
Monitoring	84
Risk & Safety	91
Safety requirements	97
Regulatory regime	108
Realisation process	109
Public concern	123
Public communication	124
Decision process	130
Research	132
Costs (summary)	135

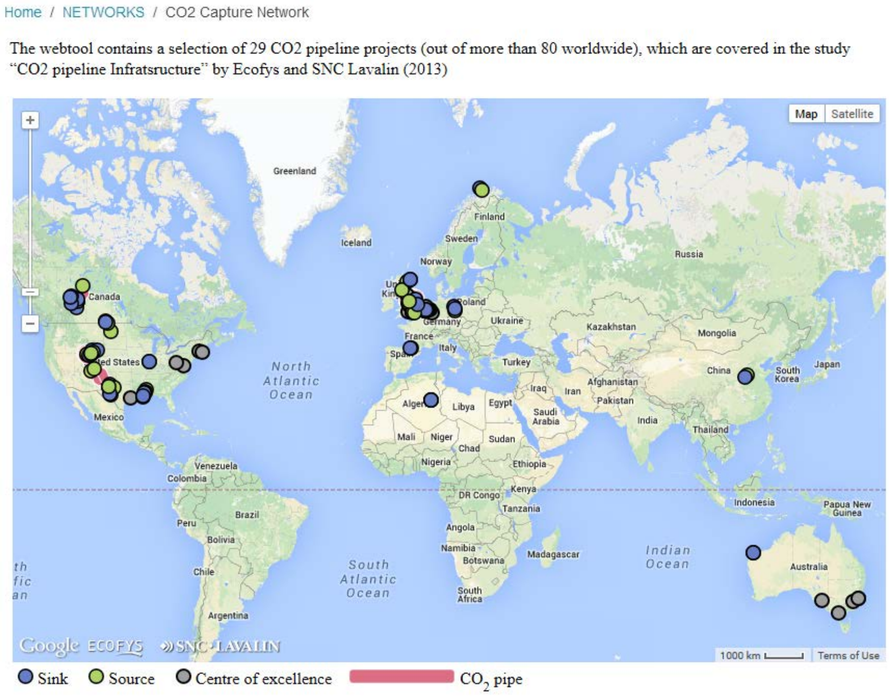
Figure 2 – Index map of the CO_2 pipeline database



Database

Data Elements	Barendrecht Information	References	Illinois MGSC Decatur project Information	References	Lacq Infor
General information					
List of actors involved in the pipeline development process *Name of organisation (role in process)*					
Owner	Shell	Royal Haskoning 2008	University of Illinois and DOE NETL (funding source)	ADM 2012	Total
Operator	OCAP	Royal Haskoning 2008	Archer Daniels Midland Company	ADM 2012	Total
Partners	-		Illinois State Geological Survey, Midwest Geological Sequestration Consortium, Schlumberger sequestration services and Archer Daniels Midland	ADM 2012	IFP (the the Ge Scienti
Others	-				
Project status	Cancelled		Operational		Operat
Pipeline infrastructure					
Physical Characteristics					
Pipeline routing, including onshore / offshore	Onshore, located in the Netherlands		Onshore, located in Illinois (US)		Onsho
Map of pipeline trajectory	See web-tool, available at GCCSI-website		See web-tool, available at GCCSI-website		See w
Starting point coordinates	No information available		Not available		No inf
End point coordinates	No information available		Not available		No inf
Length of pipeline (km)	20	Royal Haskoning 2008	1.9	IBDP 20XX	

Figure 3 – Screenshot of the CO_2 pipeline database

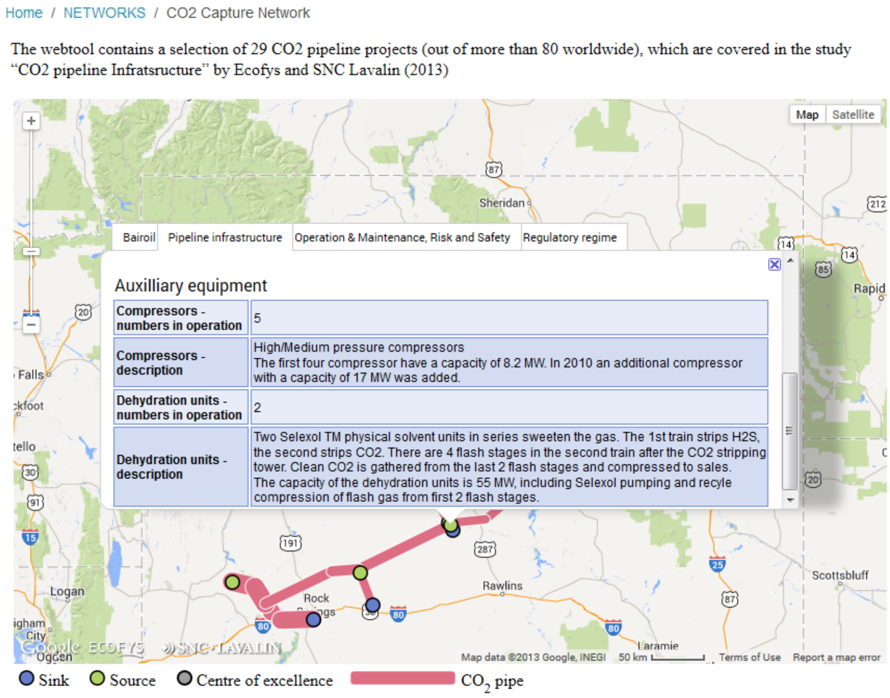


Home / NETWORKS / CO2 Capture Network

The webtool contains a selection of 29 CO2 pipeline projects (out of more than 80 worldwide), which are covered in the study "CO2 pipeline Infratsructure" by Ecofys and SNC Lavalin (2013)

● Sink ● Source ● Centre of excellence ▬ CO_2 pipe

Figure 4 – Screenshot of the CO_2 pipeline web-viewer.



Home / NETWORKS / CO2 Capture Network

The webtool contains a selection of 29 CO2 pipeline projects (out of more than 80 worldwide), which are covered in the study "CO2 pipeline Infratsructure" by Ecofys and SNC Lavalin (2013)

Auxilliary equipment

Compressors - numbers in operation	5
Compressors - description	High/Medium pressure compressors The first four compressor have a capacity of 8.2 MW. In 2010 an additional compressor with a capacity of 17 MW was added.
Dehydration units - numbers in operation	2
Dehydration units - description	Two Selexol TM physical solvent units in series sweeten the gas. The 1st train strips H2S, the second strips CO2. There are 4 flash stages in the second train after the CO2 stripping tower. Clean CO2 is gathered from the last 2 flash stages and compressed to sales. The capacity of the dehydration units is 55 MW, including Selexol pumping and recyle compression of flash gas from first 2 flash stages.

● Sink ● Source ● Centre of excellence ▬ CO_2 pipe

Figure 5 – Screenshot of the CO_2 pipeline web-viewer

1.6 Setup of this manual

The reference manual is organised in three sections:

Section A **Lessons learned from existing projects**

Section A summarises the results from the CO_2 pipeline projects, including the important lessons learned. The section is organised into several topics. Each topic is covered in a dedicated chapter, aligned with the sections used in the database.
This section includes the following chapters:

2. Drivers for CO_2 pipeline projects
3. Pipeline infrastructure and related equipment
4. Regulatory regime and permitting
5. Public concern and safety statistics
6. Research and centres of excellence

Section B **Project guideline**

Section B draws on the information presented in Section A to provide guidance for the development of a CO_2 pipeline project. The phases from project concept to the actual construction and operation of a CO_2 pipeline are described. Each of the chapters in this section is devoted to describing a particular stage or aspect in more detail.
This section includes the following chapters:

7. CO_2 Pipeline project phasing
8. CO_2 Pipeline cost
9. CO_2 Pipeline permitting
10. CO_2 Pipeline FEED studies and design
11. Construction of CO_2 pipeline
12. CO_2 Pipeline operation, inspection and maintenance
13. CO_2 pipeline decommissioning and abandonment

Section C **Overall findings and conclusions**

Finally, Section C describes the overall findings and conclusions and some discussion, including a discussion of the results. This section includes the following chapter:

14. Key findings and conclusions

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SECTION A

Lessons learned from existing projects

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2 Drivers for CO_2 pipeline projects

2.1 CO_2 pipeline drivers

CO_2 pipeline projects are motivated by the need to transport CO_2 to a certain destination. Drivers are identified and govern all subsequent project activities. Generally, there are three reasons to transport CO_2 (not mutually exclusive):

- Use CO_2 to enhance hydrocarbon production (tertiary recovery);
- Store the CO_2 in order to achieve a greenhouse gas reduction target;
- Use of CO_2 for an industrial purpose.

Some examples of drivers are summarised in Table 3. The largest portion of costs in a CCS development involving CO_2 transmission by pipeline is usually associated with CO_2 capture. The exceptions to this occur in the South-West United States where most CO_2 is sourced at very low cost from naturally occurring deposits or is required to be separated from raw natural gas to meet natural gas pipeline shipping specifications. The design parameters such as volume and flow are determined based on the amount of CO_2 to be captured and stored.

Table 3 – CCS pipeline project drivers. Adapted from: (Amann, 2010)

Motivator	Comments	Example projects
Enhanced Oil Recovery (EOR)	CO_2 is used as a tertiary recovery agent to increase oil production in depleting or old oil fields.	SACROC, Monell, Beaver Creek, Boundary Dam
CO_2 reduction targets	CO_2 is stored in deep saline formations or depleted oil or gas fields	Quest, Barendrecht, Jänschwalde, Kingsnorth, Lacq Longannet, Peterhead, ROAD, Snøhvit, White Rose, Rhourde-Nouss-Quartzite
Enhanced Coal Bed Methane Recovery (ECBMR) and Enhanced Gas Recovery (EGR)	CO_2 is used to enhance coal bed methane production from coal-beds or coal bearing formations or re-injected in suitable gas formations (depleted or for EGR)	Qinshui
Use CO_2 in greenhouses	CO_2 is transported to greenhouses and used to stimulate growth of plants and crops	OCAP

By contrast, in the Texas Permian Basin large natural and industrial CO_2 volumes are produced inexpensively and shipped to multiple customers, so design considerations look more like that of a large natural gas gathering/transmission/distribution operation.

Other uses of CO_2, such as in the food industry, are usually quite small in volume and transported (in liquid phase) by truck, or in the case of the fertilizer industry the ammonia plant (CO_2 source) and the Urea plant (CO_2 user) are generally located in the same plant so the CO_2 can be transported at low pressure and with less quality constraints over very short distances.

2.2 Source, destination and purity of CO_2 stream

CO_2 pipelines connect a variety of sinks and sources with each other, as summarised in Figure 7. The most common sources are gas processing plants, fossil-fuelled power stations and natural sources of CO_2. The latter source is commonly used in the United States. These natural sources were developed in the 1970s to provide CO_2 for EOR in Texan oil fields located in the Permian Basin.

Common sinks are oil fields for EOR, but also depleted oil and gas fields are used. The benefit of these storage sites is that there is existing infrastructure in place that may be reused for CO_2 transportation. In some of the European projects (OCAP, Barendrecht, Lacq, Peterhead CCS and Longannet) the reuse of existing infrastructure has been seriously considered.

The purity of the CO_2 stream depends on the CO_2 source and the technology used to capture the CO_2. For instance, hydrogen plants produce an almost pure CO_2 stream (>99.0%), while flue gases from coal-fired power plants contain a substantial percentage of impurities. Figure 6 (on the following page) presents CO_2 concentrations in the selected pipeline projects. In two-thirds of the 29 projects investigated for this study the CO_2 concentration of the stream exceeds 95% and in one-third of the projects it is greater than 99%. Besides CO_2, the stream often contains water, nitrogen and oxygen. The database provides a more detailed overview of constituents in the CO_2 stream per project. The concentration of other various impurities varies among the projects. The concentration of water is important for preventing corrosion or hydrate formation when operating in colder environments or offshore (sections 3.5 and 3.7 provide more information on this issue).

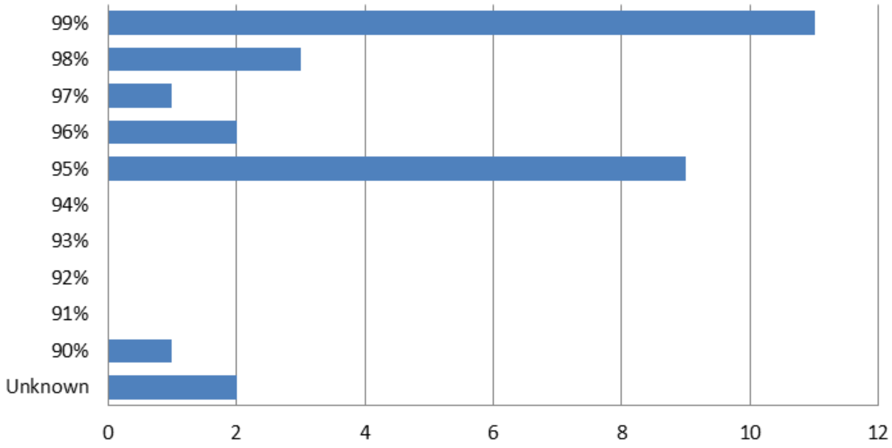

Figure 6 – CO_2 concentration of CO_2 streams in the pipeline projects studied.

In most cases the concentration of the other substances in the CO_2 stream is not specifically regulated, except for substances such as H_2S, CO and others that pose health hazards in themselves. However, when CO_2 is used for specific purposes, such as growing plants in the case of the OCAP-project, the CO_2 stream must meet the strict specifications of food grade CO_2. This means that it can still contain some other components (such as oxygen, nitrogen, hydrogen, methane and ethanol), but only in very low concentrations. The composition of the CO_2 stream flowing into the pipeline is monitored continuously and if the stream does not meet the requirements - for example in case water content is too high - an alarm will be triggered.

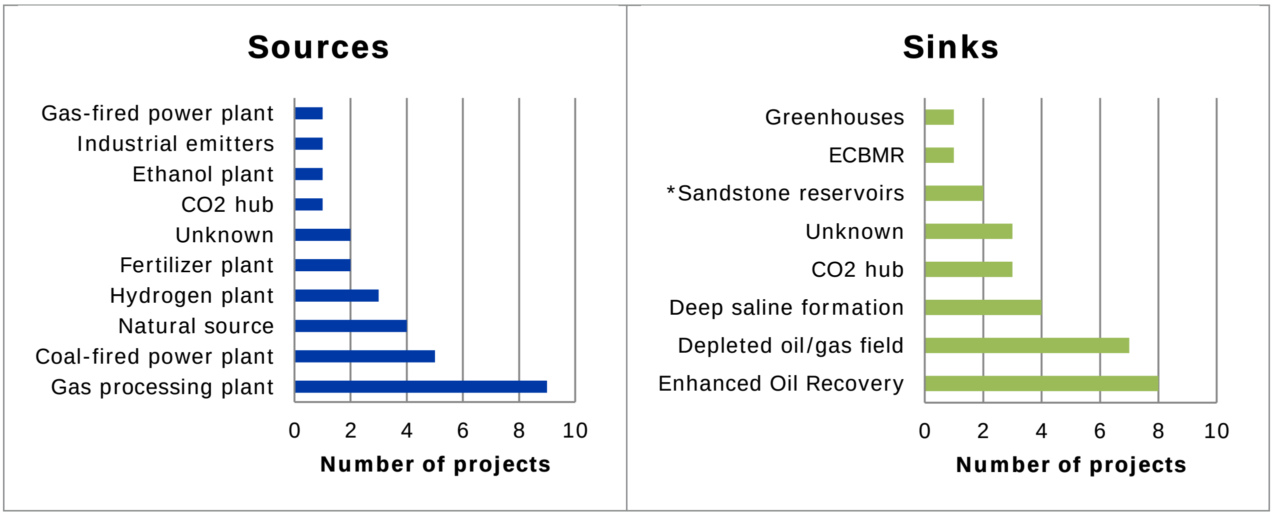

Figure 7 –Current sources and sinks of CO_2 pipeline projects.

* Some of these sandstone formations are likely to be deep saline formations, but this cannot be confirmed based on the gathered information. Therefore, these have therefore been classified as “Sandstone reservoirs”.

2.3 CO_2 hubs and networks

Where multiple CO_2 sources and sinks exist, a gathering, transmission and distribution network may develop. Hubs may be developed where individual CO_2 sources are gathered and from which various CO_2 customers are supplied. Existing CO_2 hub systems are almost all located in the Southwest Unites States. The Denver City and the McCamey Hubs in West Texas (Figure 8) bring CO_2 from three major pipelines as summarised in the Table 4 and Table 5 below. It is then redistributed to clients.

Figure 9 (the second figure on the following page) shows a CO_2 network in Wyoming. This Exxon CO_2 system is not a CO_2 Hub per se as there is only a single CO_2 source. However, it distributes CO_2 from the La Barge gas plant to several clients in Wyoming. Pipelines that receive CO_2 from the Bairoil pipeline include Monell and Salt Creek (operated by Anadarko) and Beaver Creek (operated by Devon energy) among others. The original intent of the pipeline was to transport CO_2 from Wyoming to North Dakota. The record of decisions by the Bureau of Land Management indicates that a right-of-way was granted pending further protests from interested parties for this extended pipeline once an environmental impact statement (EIS) was issued (BLM, 1986).

Development of CO_2 hubs has no specific set of rules, nor are there crucial lessons to be learned from previous installations that would help in future designs. The configuration has been developed in an ad-hoc fashion, driven by the operator's perception of what CO_2 sources will be available, what commercially viable markets exist and what their requirements are for CO_2 purity. Each hub system is a mini-"Common Carrier" that has its own standard for CO_2 purity, maximum concentrations of permitted contaminants and delivery pressures and temperatures.

In Europe there are a number of plans to develop CO_2 networks and hubs. Two plans have been developed in the United Kingdom to capture CO_2 from several industrial sources which would link into one (common carrier) pipeline: the Humber cluster (UK) and the Teesside cluster (UK). Furthermore, in the Netherlands a CO_2 hub is proposed for the Rotterdam harbour area (Figure 10).

Table 4 - Denver City Hub CO_2 sources

Pipeline	CO_2 source	Type	Source
Cortez (operated by Kinder Morgan)	McElmo Dome	Natural	(Holtz, et al., 1999)
Sheep Mountain (operated by BP)	Sheep Mountain	Natural	(Holtz, et al., 1999)
Bravo (operated by Occidental)	Bravo Dome	Natural	(Holtz, et al., 1999)

Table 5 - McCamey Hub CO_2 sources

Pipeline	CO_2 source	Type	Source
Canyon Carrier Reef (SACROC)	4 adjacent gas processing plants: Terrell, Grey Ranch, Mitchell, Puckett	Anthropogenic	(Gill, 1982)
Central Basin (Kinder Morgan)	Denver City Hub	Natural	(Holtz, et al., 1999)

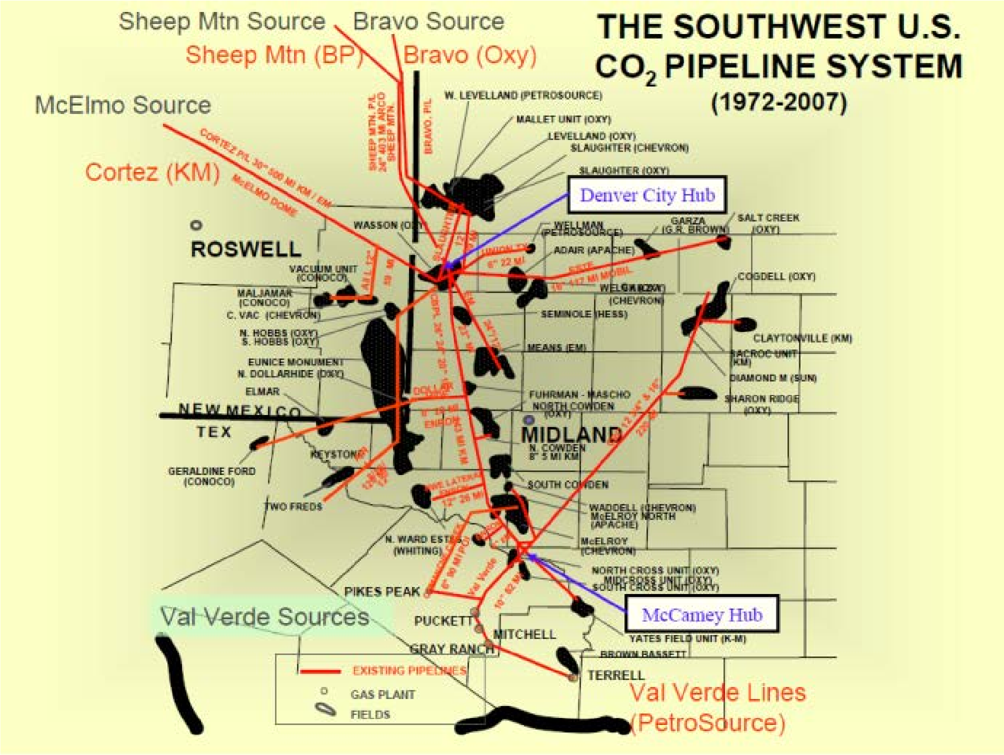

Figure 8 - Denver City and McCamey CO_2 Hubs (Melzer, 2007)

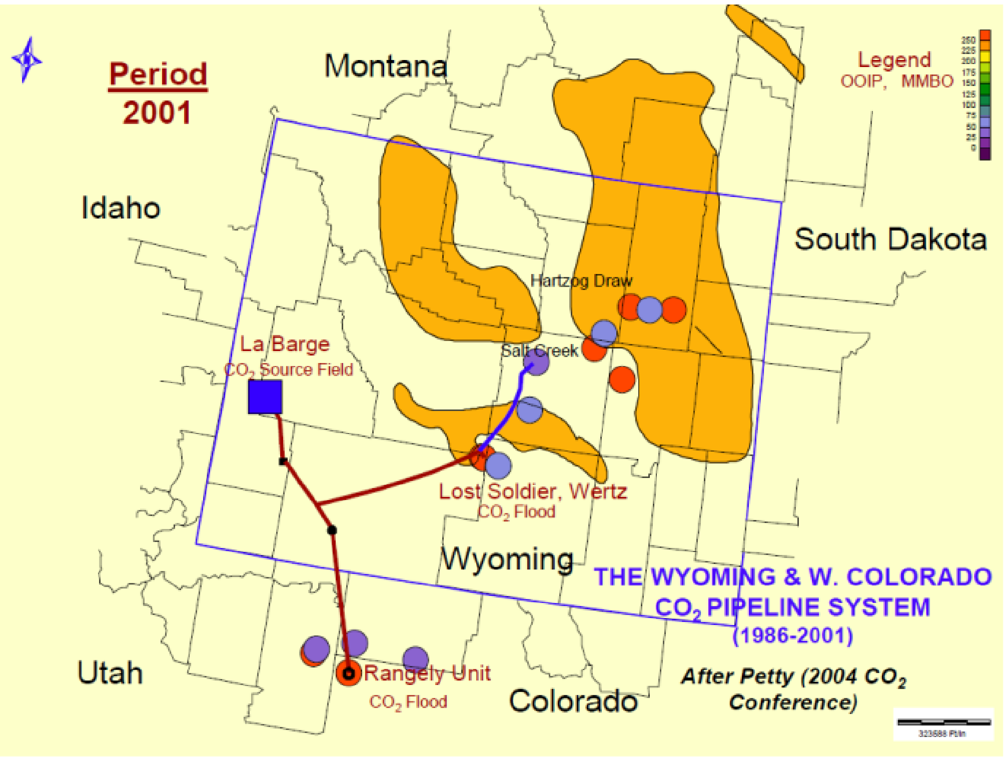

Figure 9 - Exxon (Bairoil) CO_2 system in Wyoming (Melzer, 2007)

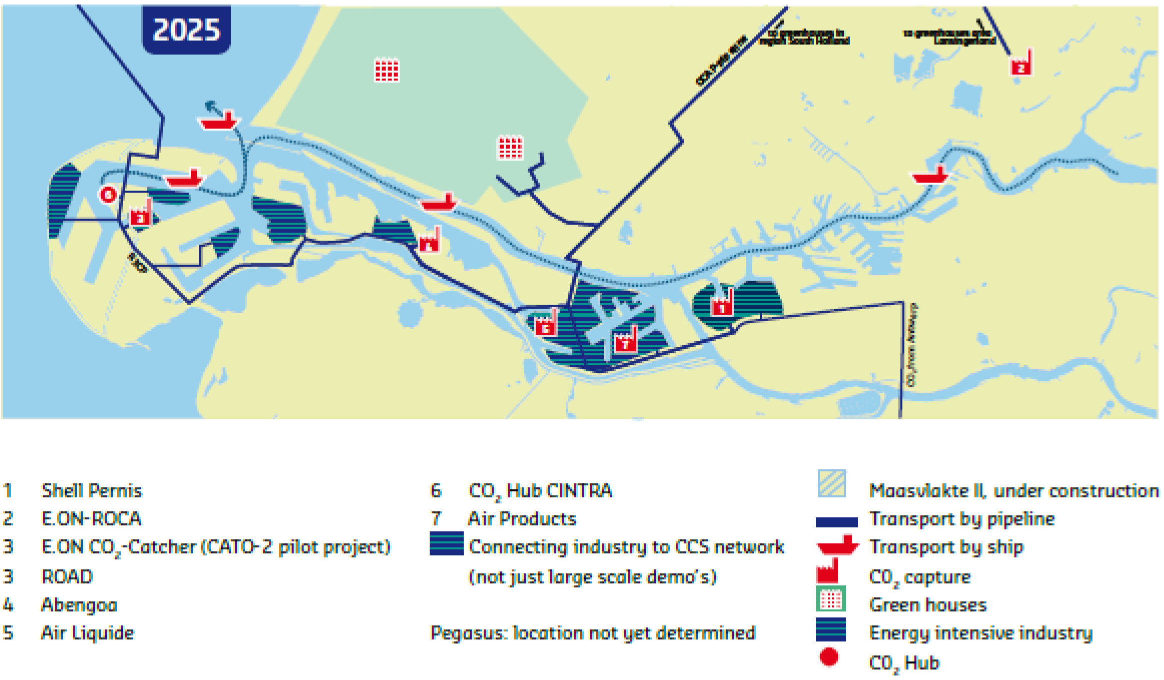

Figure 10 – Proposed Development of the Rotterdam CO_2 hub (Rotterdam Climate Initiative, 2011). In three phases, CO_2 capture should be extended from three current sources (Shell Pernis, Abengoa and E.On RoCa) to seven. In illustrates the anticipated outcome is depicted.

2.4 Commercial drivers for CO_2 pipeline projects

Sources of funding for CO_2 pipelines will depend on the user and operator as well as possible motivations that are not directly financial. Some pipelines and related feasibility studies are funded through public entities or governments as well as by private companies or organisations.

In the case of EOR, private companies, consortia or groups may join forces to develop a project. By using the CO_2 to increase the production of oil fields, the project can make a good return, offsetting the investment costs for CO_2 infrastructure. In some cases a project may appear attractive but market conditions can change and the project loses its appeal. For example the Beaver Creek project was conceived in 1987 but abandoned due to low oil prices and lack of data to mitigate risk (Peterson, 2008). In 2005 the project was revived and by February 2007 the US Bureau of Land management carried out an Environmental Assessment as well as a scoping exercise and approved the project. From 2007 to 2008 construction commenced and operations began shortly after to inject into Beaver Creek's Madison Field.

In some jurisdictions revenue may come from generating carbon offsets. The generation of carbon offsets follows a cycle in which the project is approved by a governing body. Typically, a project is validated and thereafter annual verifications occur. In the United States, Monell and Salt Creek are two EOR projects that have generated carbon offsets under the American Carbon Registry. In Canada, the intention of the Quest project is to generate carbon offsets under the Alberta Offset System.

Most current European CCS projects are focused on CO_2 storage as a CO_2 emissions reduction option. In contrast to EOR, CO_2 storage does not result in additional revenues and is therefore only of interest when a financial support scheme is available or under some form of carbon offset system. In the European Union, the Emissions Trading System (ETS) is used for, but other systems for non-EU countries exist as well. For example, Norway imposes a sufficiently high direct carbon tax on all CO_2 emitted that preventing these emissions makes some CCS projects economically viable.

Table 6 presents an overview of CO_2 values for both EOR and European carbon offsetting in recent years.

Table 6 – EU ETS and EOR (US) prices of the last five years

Additional revenue	**CO_2 price range (lowest-highest) of the last five year)**	**Reference**
EOR	15 - 50 USD/ton CO_2	Anecdotal information
EU-ETS	3 - 25 EUR/ton CO_2 *(*4-34 USD/ton CO_2*)*	(Reuters Thompson Point Carbon, 2013)

Case studies Examples of commercial drivers for CO_2 pipeline projects[1]

Cortez

The Cortez pipeline project was fully funded by Shell, who contracted an engineering firm to design and build the 808 km pipeline (Willbros, 2013).

Canyon Reef

The Canyon Reef Carriers CO_2 pipeline is a commercial venture of several oil companies that formed the SACROC committee to explore EOR in the Kelly Snyder Field of the SACROC Unit in Scurry County, Texas, United States.

Quest

Similar to the Cortez project described above, the estimated CAD 1.35 billion Quest project in Alberta was funded by oil companies and the Canada and Alberta Governments:

- Shell Canada Energy (project operator and constructor of all facilities including the pipeline)(60% stake);
- Chevron Canada (20% stake);
- Marathon Oil Canada Corporation (20% stake).

The project includes an 80km CO_2 pipeline. Government funding includes CAD 745 million (Canadian dollar) from the Government of Alberta, Department of Energy (from a CAD 2 billion CCS support fund) and a supplemental and CAD 120 million from the Canadian federal government.

Snøhvit

In Norway, the Norwegian government supported CO_2 capture, transport and storage for the Snøhvit project. Besides financial support amounting to some 180 million 2011 NOK (Pöyry Management Consulting, 2012), the Norwegian government decided that CCS was an obligatory part of this project. Without CCS, the Norwegian government would not approve the permits for the Snøhvit LNG-plant (Koeijer, 2013).

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[1] More information on these projects can be found in the database.

2.5 Additional funding sources

CO_2 pipeline projects require large, costly investments in infrastructure. Depending on the purpose of the pipeline it may be eligible for financial support as part of the funding of the project. However, such financial support rarely applies to the pipeline project per se, but rather to an overall scheme that may include CO_2 capture and storage or re-use.

In Europe, the development of CO_2 pipelines is often directly related to CO_2 capture and storage. In the current economic condition with the low ETS-price of CO_2 emissions and regulatory climate it is almost a given that a CCS project is not feasible in the absence of external funding. Early engagement of governments at the political level (and of development banks if the project is in a recipient country) should be undertaken to establish the possibility of external financial assistance. These activities relate to the entire CCS project and are not specific to the pipeline.

Table 7 provides other examples of sources of financing for CO_2 pipelines. In practice, a combination of these funding sources is usually needed to make a project financially viable.

Table 7 – Financial drivers

Financial Driver	Comments	Example (may appear in more than one category)
Positive: Enhanced Oil Recovery (EOR) or enhanced coal Bed Methane recovery (ECBM)	CO_2 is used to increase oil production in depleted or old oil fields. CO_2 is largely naturally sourced and relatively inexpensive or is already being produced industrially (e.g. by-product of gas processing) and requires low additional investment.	SACROC, Monell, Beaver Creek, Boundary Dam, Qinshui
Negative: Cost of not meeting CO_2 reduction targets	CO_2 is stored in deep saline formations or depleted oil or gas fields; carbon trading schemes place a value on avoided CO_2	Quest, Barendrecht, Jänschwalde, Kingsnorth, Lacq Longannet, Peterhead, ROAD, Snøhvit, White Rose, Rhourde-Nouss-Quartzite
Additional incentives provided by Governments	Projects that come close to being economically justified are helped by various means, including subsidies, to meet target investment goals.	Boundary Dam, Quest, OCAP

Case-studies Government support schemes

European EEPR programme

In 2009 the European Energy programme for Recovery (EEPR) was set up to co-finance projects that would increase reliability of energy supplies while decreasing CO_2emissions. The total budget of EUR 4 billion has been used to support 59 projects, six of which are CCS-projects: Don Valley (UK), ROAD (the Netherlands), Jänschwalde (Germany), Belchatow (Poland), Compostilla (Spain) and Porto Tolle (Italy) (European Commission, 2013).

European NER300 programme

Under the New Entrants' Reserve (NER) 300 million Allowances (each representing the equivalent value of emitting 1 tonne CO_2) are made available as a financial support scheme for the installations of innovative renewable energy technologies and CCS. The value of the financial support depends on the value of CO_2 under the ETS. This scheme operates through a series of calls for expressions of interest in participating. The first call attracted several CCS projects, but none of these have been awarded (NER300.com, 2013).

In several European countries national governments support CCS projects, sometimes as part of a European financial support scheme. Both NER300 and EEPR schemes require co-funding, which is often made available (partly) by the national government.

Alberta Provincial programme

Alberta has made funds available totalling CAD 2 billion (Canadian dollars) to support CCS projects. It is understood that as of July 2013, two CCS projects will be receiving funding from the Government of Alberta:

- Shell Canada Energy Quest;
- Enhance Energy Inc. Alberta Carbon Trunk Line (ACTL);
- Two others were initially announced as receiving funding but both have dropped out following preliminary work.

Other jurisdictions may offer some form of financial aid, particularly if the project is first-of-its–kind in the area.

3 Pipeline infrastructure and related equipment

3.1 Dimensions of pipelines

The physical characteristics of the CO_2 pipelines included in this study vary greatly. For each of the pipeline projects, information can be found in the database. Table 8 presents a summary of the results and the spread of the physical characteristics.

Where applicable, the results have been grouped in ranges: “low”, “medium” and “high”. These three ranges have been tentatively defined such that approximately 1/3rd of the pipeline projects fall within each category. For some of the characteristics these clusters are very clear, as for instance with pressure and compressor capacity. For other characteristics, such as length and capacity of the pipeline, clusters are less distinct. In the following paragraphs, the physical characteristics are described in more detail.

Table 8 - Physical characteristics of CO_2 pipeline projects

	Low	Medium	High	Number of data points available
Length (km)	1.9 - 97	116 - 380	656 - 808	28
External diameter (mm)	152 - 270	305 - 508	600 - 921	26
Wall thickness (mm)	5.2 – 9.5	10 - 13	19 - 27	12
Capacity designed (Mt/y)	0.06 - 2	2.6 - 7	10 - 28	26
Pressure min (bar)	3 - 10	31 - 35	72 - 151	14
Pressure max (bar)	21 – 40	98 - 145	151 - 200	17
Initial feed Compressor capacity (MW)	0.2 - 8	15 - 17	43 - 68	16

3.2 Length and capacity of pipelines

Table 8 shows that there is a wide variety in the physical characteristics of the pipeline projects. The range in length alone of pipelines is large: between 1.9 and 808 km. This is caused by the inclusion of demonstration projects (typically covering comparatively short distances) as well as commercial EOR projects over long distances. The longest pipelines are located in North-America, where half of the pipelines included in the analysis exceed 200 km in length. European pipelines tended to be shorter with an average length of 130 km.

The length of a pipeline depends on the number of “obstacles” between the CO_2 source and sink, such as cities, roads, railways, archaeological heritage or sensitive natural areas that need to be avoided (for more information see Section 3.4). It may also be that existing infrastructure such as other hydrocarbon pipelines and pipeline-alleys are a key driver in determining the route. Typically, in the planning phase, several pipeline routes are developed and proposed. For example, in the Gorgon project (Australia) five different pipeline routes were considered, while in the Peterhead CCS project (UK) as many as twenty routes were considered. Figure 11 presents an overview of the length and capacities of the pipelines included in the study. The positive correlation between these two factors is driven by basic economics: longer pipelines need larger volumes transported to be economically viable.

Most of the pipelines analysed (22 out of 29 projects in total) are situated entirely onshore. In 7 projects the plan is to capture the CO_2 onshore and then transport it to an offshore sink. The planned offshore pipelines are all situated in Europe.

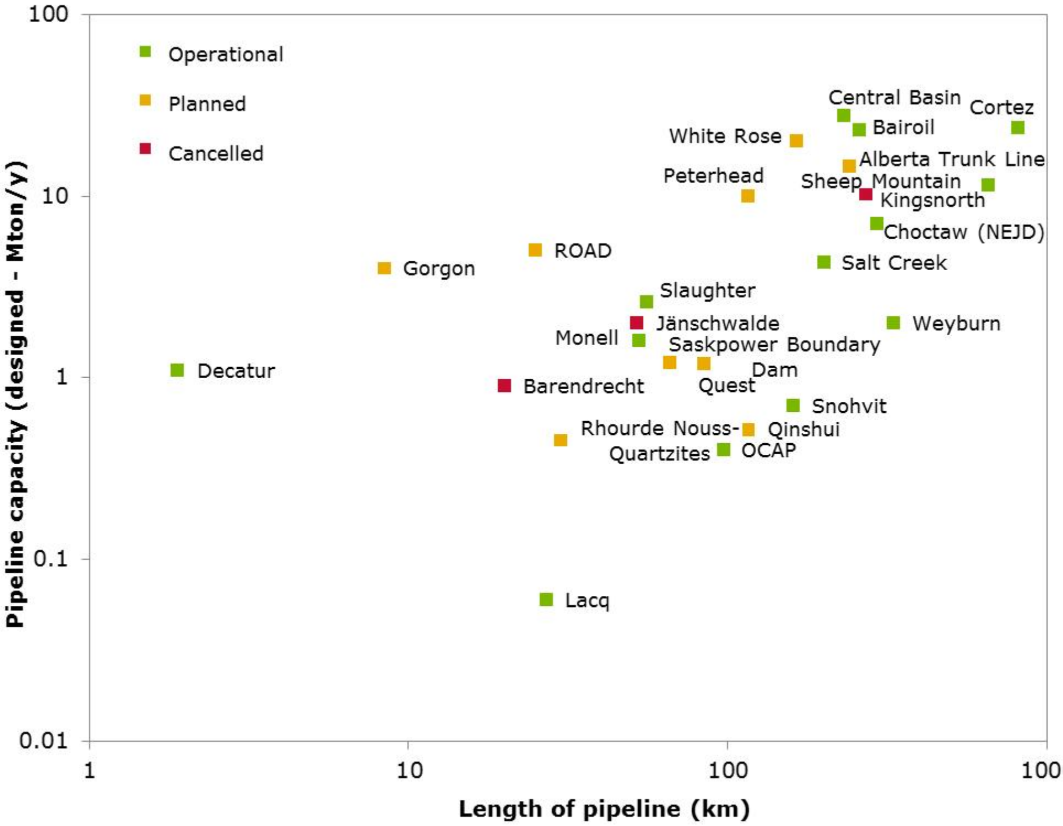

Figure 11 - Length of pipeline and pipeline capacity[2]

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[2] Note: only the CO_2 pipeline projects for which data was available on both length of pipeline and pipeline capacity are included.

3.3 Reuse of existing pipelines

As is discussed elsewhere in the manual, pipelines commonly have service lifetimes that exceed their primary reason for existence. Re-purposing a pipeline for CO_2 use can drastically reduce overall CCS project costs and in fact may make the difference between success and failure of a CCS project. Usually but not always, use of an existing pipeline for CO_2 transport involves reversal of flow. As long as the initial design (as modified to take into account any loss of pressure rating over the life of the line in its initial service) can support the pressures, volumes, compositions and design operating parameters required in CO_2 service, there is every reason to re-use the line. Two areas commonly experiencing existing pipeline re-use are offshore where pipeline costs are very large, and in onshore acid gas re-injection (a mixture of CO_2 and H_2S is injected into a depleted gas reservoir).

There are no serious negative technical implications to operating a re-purposed pipeline in CO_2 service at capacities much lower than its original capacity in another service. In an oversized line, pressure drops will be less so it is possible that the inlet CO_2 compressor can be designed for a lower discharge pressure. It could be speculated that if the volume of CO_2 were drastically less it could be shipped as a subcritical gas.

Case studies Reuse of existing pipelines[3]

Reusing existing natural gas pipeline in the Longannet Project

The planned Longannet CO_2 pipeline would have been one of the longest European pipelines (350 km) and largest in diameter (900 mm over a length of 280 km). Despite the large capacity a relatively small volume of CO_2 (1.8 Mton/y) was planned to be transported to this pipeline. The reason why this pipeline has such “overcapacity” is that part of the pipeline consists of a reused natural gas pipeline that was dimensioned for transporting a much higher volume of natural gas.

Reusing existing oil pipeline in the OCAP Project

In the OCAP project a former oil pipeline is used as a main pipeline for transporting CO_2 from the Shell hydrogen plant in the Rotterdam area to greenhouses in the Southwest of the Netherlands. In 2004, before OCAP took over the pipeline, the 97 kilometres long pipeline (diameter 305-660mm) was cleaned, inspected and tested for durability and strength. For the inspection a pig-run and ultrasonic testing were performed. Based on the outcomes, the pipeline was improved where it was needed. After the improvements the pipeline was thoroughly checked once more. To ensure safe operation, the maximum operating pressure was lowered from 56 bar to 21 bar (Veenstra, 2013).

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[3] More information on these projects can be found in the database.

3.4 Pipeline crossings

A pipeline is likely to cross existing infrastructure (roads, railway or waterways) and challenging natural features. These crossings are made either underground or overhead, depending on the situation and costs. Typically, each individual crossing is evaluated to determine whether specific or additional measures must be taken to ensure the safety of operation and minimise the probability of leakage. In the textbox below some examples are presented to illustrate the above.

Case-studies: Pipeline crossings[4]

Waterway crossing (ROAD)

Crossing waterways is often complicated. For example, the crossing of the 35 meter-deep Maasgeul channel by the pipeline of the ROAD-project in the Netherlands. For this crossing a 1.7 kilometre long tunnel is planned to be drilled ten metres under the Maasgeul using Horizontal Directional Drilling. Subsequently, the CO_2 pipeline will be placed in this tunnel(GCCSI, 2013; Wevers, 2013)

Crossing of the river Forth (Longannet)

One of the crossings in the pipeline route of the Longannet project was the river Forth. The original plan was to use Horizontal Directional Drilling (HDD) for the crossing, but results from boreholes revealed that ground conditions were unsuitable for HDD. This made tunnelling the preferred option. As this option would increase both costs and risks, National Grid organised an independent tunnelling design study to analyse this (Scottish Power CCS consortium, 2011). The outcome of this study was not available.

Pipeline-alley (ROAD)

To protect pipelines from third party interference, safety corridors are defined around the pipeline. In some pipeline routes, such as the ROAD-project, the corridor is part of a dedicated “pipeline-alley” in which also other pipelines are laid.

Offshore corridor (Snøhvit)

In the Snøhvit-project, a big section of the part of the pipeline that is laid offshore is located in important fishing grounds. Safety zones were established by the government surrounding the underwater pipeline in order to protect the pipeline from potentially hazardous fishing equipment. These zones may not be accessed by unauthorised vessels, such as fishing vessels. In some zones fishing is still allowed, but only with certain equipment that is not interfering with the petroleum activities (Snohvit Environmental Impact Assessment, 2001).

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[4] More information on these projects can be found in the database.

3.5 Corrosion protection

A key safety consideration in CO_2 pipelines is to prevent the release of CO_2 due to leakage or incidents. One of the possible causes for leakage is corrosion of the pipeline steel wall. As CO_2 pipelines are usually buried under the ground, both internal and external corrosion protection measures should be implemented as part of the pipeline design, before the pipeline is constructed. Pipelines are inspected on a regular basis, to measure wall thickness and check for corrosion (see operation and maintenance, section 12).

There are many factors involved in assessing the risks of internal corrosion of a pipeline in CO_2 service. Research is on-going to better define corrosion factors. Water content is an important risk factor for internal corrosion in CO_2 pipelines. This is handled by use of dehydration equipment upstream of the pipeline. More information on this is presented in section 3.7.

Although not specific to pipelines for CO_2, the most commonly used method for protection against external corrosion is cathodic protection (CP) in combination with a coating. CP systems make use of either anodes consisting of a “sacrificial material” or an electrically driven impressed current system. For coatings, typically polyethylene (PE) is used, but polypropylene (PP) and concrete coatings also occur in the pipelines reviewed. For offshore pipelines, concrete coating is used to stabilise the pipeline on the seafloor.

Ultimately, if the combination of water content and other contaminants cannot be effectively controlled at the point where the CO_2 enters the pipeline, more resistant metallurgies such as stainless steel may need to be considered. In most applications, however, the cost of such a change is prohibitive, such that it would only be considered in very short sections of pipeline.

3.6 Auxiliary equipment - Compression

To transport CO_2 from a source to a sink, the CO_2 is pressurised with compressors. The number of compressors and their capacity depend on amongst others things, the pipeline dimensions, volume transported and the phase of the CO_2 stream. Figure 12 presents a diagram that shows how the combination of pressure and temperature determines the phase of pure CO_2 (in case of impurities – such as in most streams - this diagram changes). In all but the shortest CO_2 pipelines, it is transported in super-critical phase. Subsequently, this desired phase governs the compression (and if needed booster[5]) capacity required.

The operator will try to keep the CO_2 phase constant and avoid phase changes of the CO_2 in the pipeline. As external conditions, such as temperature, can influence the CO_2 phase, the operator

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[5] Booster stations are required when the desired flow rate in the line results in pressure drops that bring the operating conditions close to the subcritical range (below approximately 100 bar). Because of the high density of CO_2 at these pressures the booster can be a pump rather than a compressor.

reacts by adapting the pressure. Therefore, the operator should prevent sudden pressure or temperature swings, maintain the flow of CO_2 flow within pre-defined limits and react to these changes by adjusting the pressure in the CO_2 pipeline (JRC, 2011). In practice, most pipeline operators make sure to stay clear of the phase transition boundaries.

CO_2 phase change is a complex issue and topic of research for many years in different institutes. Also IEAGHG is currently involved in research on this topic of which the results are expected in 2014. In the database more information about operating pressure, temperatures and CO_2 phase can be found.

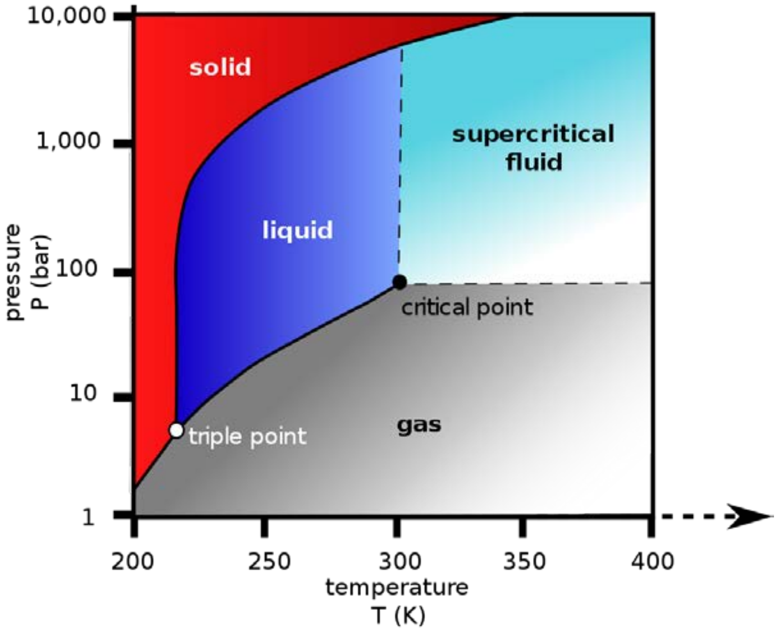

Figure 12 - Thermodynamic phases of pure CO_2 at various pressures and temperature (The Young Engineer, 2012)

3.7 Auxiliary equipment - Dehydration

CO_2 pipelines are typically made of carbon steel as this is the most economic option. However, this material is vulnerable to potentially high rates of corrosion when the CO_2 stream includes water. To prevent this, the water content in the CO_2 stream should be kept as low as possible. Although there is no official standard, the water content is generally kept well below about 840 ppmv or 40 lb/MMCF[6] (theoretical limit, based on conditions typically encountered in North-America). For the projects analysed in this study the water content in the CO_2 stream covers a wide range: between <50 ppm (e.g. OCAP, Snøhvit, Kingsnorth, Lacq and Weyburn) up to 630 ppmv (e.g. Central Basin, Sheep

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[6] 1 lb/MMCF = 21 ppmv (Taylor and Francis Group, LLC, 2006)

Mountain, Monell, Slaughter, Bairoil and Salt Creek). The database includes more information on the specified maximum water content in the different CO_2 pipelines studied.

To prevent corrosion, the pipeline operator aims to keep the water content as low as possible, based on what is technically and economically practicable (see also section 8.7.1). Typically, a dehydration system is used to control the water content in the CO_2 stream. An alternative way of preventing corrosion would be to use specialised types of steel (such as stainless steel) that is not vulnerable to this type of corrosion, but this is likely to come at a substantially higher cost. Another benefit of dehydration is that it also reduces the risk of hydrate formation in the CO_2 stream. This phenomenon can occur in colder regions, where the water content could form solid hydrates that can damage equipment (more information presented in the textbox below).

Case study Hydrate formation

Hydrates are solid, crystalline compounds formed by water ("host molecules") and small molecules ("guest molecules"). Typical guest molecules are CO_2, CH_4 and H_2S. Highly soluble gases, such as ammonia and hydrogen chloride do not form hydrates, regardless of their size. Hydrates form at temperatures higher than the freezing point of water and are very much like common ice in both their appearance and their properties. In a pipeline it is the accumulation of the hydrates that causes problems. These accumulations can block the line and plug and damage equipment. The formation of hydrates requires the following three conditions (de Visser, et al., 2007):

- The right combination of temperature and pressure. Hydrate formation is favoured by low temperatures and high pressure;
- Hydrate forming molecules must be present;
- A sufficient amount of water to form the cage-like structure, but note that free water is not always required.

CO_2's ability to hold water at varying temperatures and pressures means that dehydration is usually implemented inter-stage in the main CO_2 compressor(s) so that the absolute minimum water content can be achieved, before the CO_2 stream flows into the pipeline. Depending on the water concentration allowed in the CO_2 stream, supplemental dehydration stages may be required. Dehydration is not always needed, for instance when the source produces a dry CO_2 stream, for example in the case of CO_2 produced from a hydrogen plant (Barendrecht and OCAP) or gas processing plant (Monell and Salt Creek from LaBarge).

After compression and dehydration, the CO_2 stream is monitored for water content. However, water content monitoring systems tend to be unreliable. To be safe, water content is often kept at low levels: below 50 ppmv (2.4 lbs/MMSCF) as for instance in the Longannet, Kingsnorth and ROAD projects, or below 40 ppmv (1.9 lbs/MMSCF) in other projects. The database includes more information on the specified maximum water content in the various CO_2 pipelines.

Case-studies Dehydration technologies

Silica gel

Silica gel is a solid absorbent used for dehydration. The product, SiO_2, is highly porous. Depending on the pores in the gel (ranging from 10 to 1000 Angstrom), silica gel can be used for the removal of a wide range of different compounds. Silica gel can be used in sour gas service and is relatively easy to regenerate (AMEC, 2013). At the Abengoa ethanol plant in Rotterdam (OCAP-project), the CO_2 stream contains ethanol residues, which are removed with water. Subsequently, silica gel is used to absorb the water from the CO_2 stream. After offline drying, the silica gel can be re-used.

Tri-Ethylene Glycol (TEG)

Based on a small assessment performed on a limited number of vendors, TEG is the preferred CO_2 dehydration method (AMEC, 2013). TEG removes water from the CO_2 stream by means of absorption. The CO_2 stream passes through a scrubber column where water, other incidental liquids and solids are removed from the gas stream. After this treatment, the CO_2 contains 150 ppmv of water (AMEC, 2013).

Molecular sieves

Molecular sieves consist of a solid absorbent. These are crystalline in structure, highly porous and have a large surface area. Depending on the size of the pores, molecular sieves can be used for the absorption of different compounds such as water (AMEC, 2013).

Joule-Thompson Valves

In situations where the wet CO_2 stream is at higher pressures (e.g. naturally-produced CO_2) another approach is to let the pressure down through a valve that utilized the Joule-Thompson effect under controlled conditions. As the gas depressurizes it cools and the water condenses out of the CO_2.

More information on dehydration can be found in the AMEC-study “Evaluation and analysis of the performance of dehydration units for CO_2 capture” (AMEC, 2013)

Figure 13 – Example of typical block valve in natural gas pipeline (Gazprom, 2011)

3.8 Auxiliary equipment - Valves

During the period that the CO_2 is flowing through the pipeline, the pressure is the most important parameter that is checked to ensure that the pipeline functions normally. A sudden unanticipated pressure drop may be used as a proxy for leakage. In such a case, Emergency Shutdown (ESD) block valves are used to isolate the pipeline section where the leakage occurs. This contributes to the safety of operation and prevents the entire pipeline from being vented.

The distance between ESD valves varies over the pipelines and depends amongst others on factors such as population density and regulations. The average distance of block valves of the projects included in the database is 10 to20 km. Typically, the spacing is determined with the use of atmospheric dispersion models to calculate a safe maximum volume of CO_2 that could be released in case of an accidental rupture. For offshore pipelines, by default block valves are installed at the beach and at the injection platform. It is technically possible to install block valves at sea as well, but this is not standard procedure. One of the issues is that block valves require regular maintenance, which would be a complex, costly and potentially hazardous operation at sea (Read, 2013)

3.9 Flow Metering

As with all pipelines, CO_2 flows are metered into and out of the pipeline, providing both a means for accurate billing of users and payment of suppliers, and also to provide early warning of leaks. Flow metering is not generally accurate enough to detect very small leaks.

3.10 Crack Arrestors

With most gases including natural gas, the result of a longitudinal failure of a pipeline will result in depressurization so rapid that the propagation of the crack will stop. This is not the case with high-concentration CO_2, which depressurizes more slowly, causing the conditions promoting crack propagation to persist. As a result, an initial small longitudinal crack in a high pressure CO_2 pipeline may propagate over long distances. This is addressed in the design by installing crack arrestors in a CO_2 pipeline. Typically they are simply occasional joints of pipe with a greater wall thickness and better hoop-stress properties. Other methods have been used (periodic wrapping with non-metallic materials) and research is on-going into other systems.

4 Regulatory regime and permitting

CO_2 pipeline projects are often part of a larger project. These projects typically include carbon capture from natural or artificial sources, transportation of the CO_2 via pipelines and injection underground (for storage or EOR). These capture, transportation and storage activities can have environmental impacts of a project that warrant an assessment. Depending on the project and the regulatory framework in place, such environmental impact assessments may be required. Approaches and requirements vary from country to country and environmental impacts are a subject field by itself. A detailed discussion is beyond the scope of the present study.

This chapter presents an overview of the typical approaches followed in Europe and the United States. Furthermore a set of case studies is discussed. In many respects such assessments purely for the CO_2 pipelines are not fundamentally different from other gas pipelines. The details of EIA requirements will differ among jurisdictions but the only major difference related to CO_2 will be in the area of what characteristics of the CO_2 pipeline will trigger the need for an EIA.

4.1 Europe - Environmental Impact Assessment

According to Directive 2011/92/EU of the European Parliament an Environmental Impact Assessment (EIA) is required for projects "which are likely to have significant effects on the environment by virtue, inter alia, of their nature, size or location, before development consent is given" (European Union, 2013). The Directive includes a list of projects that require an EIA based on their type and size. For CO_2 pipelines, an EIA is required for pipeline *sections* with a diameter of more than 800 mm and a length of more than 40 km (European Union, 2013). For shorter and smaller CO_2 pipelines EU Member States can still decide whether an EIA must be carried out on a case-by-case basis or when certain threshold values are exceeded as set by the respective EU Member State (European Union, 2013).

Figure 14 (on the following page) presents an overview of the total pipeline length and maximum external diameter of existing European CO_2 pipelines. The pipelines in the blue box have the dimensions for which an EIA might be mandatory. It should be noted that the figure presents the total length of the pipeline. However, whether or not an EIA is required depends on the length of individual pipeline sections. Many pipelines have developed in such sections and an EIA will be mandatory only if new sections have a length exceeding 40 km and a diameter exceeding 800 mm diameter. Correspondingly, information on section length, diameter and whether the sections are new or reused is presented in Table 9 (on the next page). As an example, based on this information, only the offshore pipeline section in the Kingsnorth project would require an EIA.

For the Kingsnorth project, an Environmental Scoping Report has been prepared for the onshore pipeline with the aim to inform stakeholders about the nature of the potential impacts of the offshore pipeline (RSK Environment, 2010). This scoping report was the first step in the permit application of the pipeline section. Before the subsequent steps could be taken (including the preparation of an EIA and Environmental Statement), the Kingsnorth project was cancelled (Read, 2013).

Although not mandatory for the pipeline section, for most of the European CO_2 pipeline projects, EIAs have been carried out because the capture and storage facilities did exceed the threshold requirements for a mandatory EIA. In these EIAs, the pipeline is only described as part of a wider scheme.

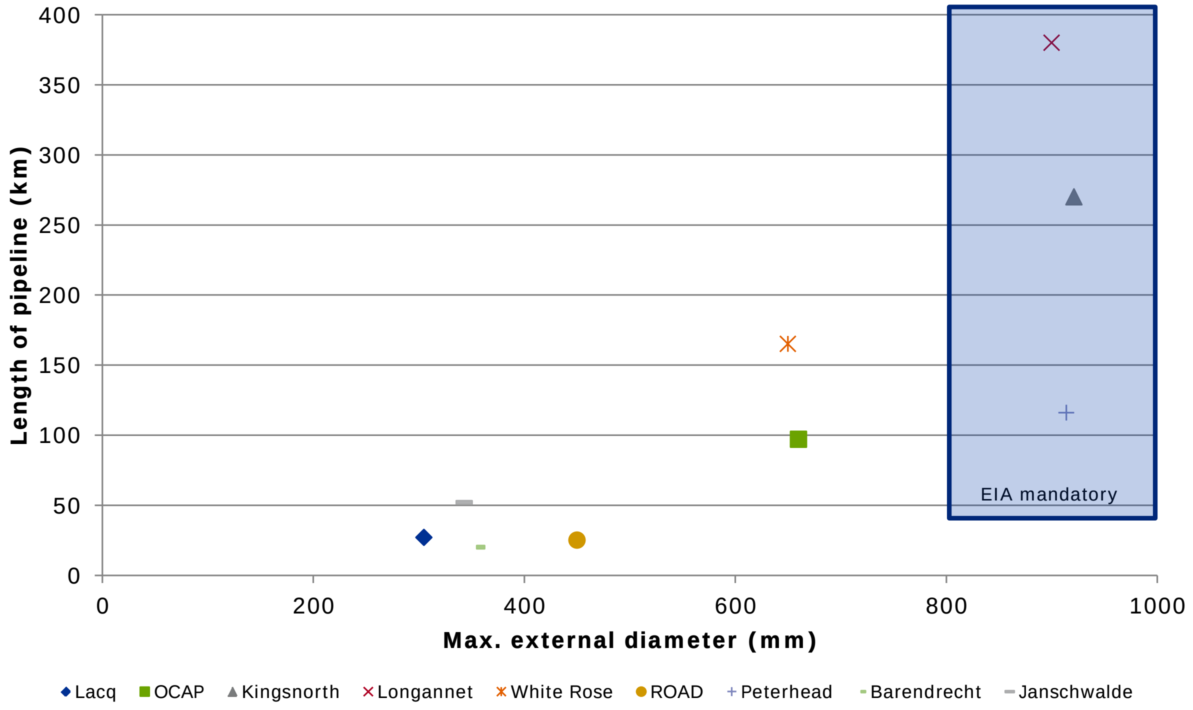

Figure 14 – Total pipeline length (km) and maximum external diameter (mm) for European CO_2 pipelines

Table 9 - Examples of recent UK projects with their respective EIA requirements.

Project	Section length (km)[a]	Section diameter (mm)	New or reuse	EIA mandatory
Kingsnorth	10	921	New	No
	270	914	New	Yes
Longannet	25[b]	900	New	No
	280	900	Reuse	No
Peterhead	16	914[c]	New	No
	100	660	Reuse	No

[a] Note that indicated section length are likely to differ from total pipeline lengths presented in Figure 14 as pipelines may consist of multiple sections.

[b] Estimated based on distance between Valleyfield and Dunipace in Google Maps

[c] The exact diameter of the Peterhead onshore pipeline has not been determined yet. The range available in the literature is between 457 – 914 mm (Petrofac, 2012).

4.2 North America: Environmental Impact Statement

In North-America the process is referred to as Environmental Impact Statement and the Requirements are not appreciably different. Similar to the EIA, first it is assessed whether or not it is necessary to prepare an EIS based on how the project influences the National Environmental Policy Act (NEPA). To determine this, an Environmental Assessment (EA) will be carried out. The EA is a concise document providing evidence and analysis whether or not is necessary to prepare an EIS (U.S. EPA, 2013). There is a strong requirement in North American EISs to include the opinions of stakeholders and demonstrate public participation.

When an EIS is needed, a more detailed analysis is performed of the effect and impact of the project on the quality of the human environment. This should include a discussion on the significant environmental impacts and alternatives, including a “No Action alternative” (U.S. EPA, 2013).

As an example, in Alberta, Canada the need for an EA is triggered when the complexity and scale of a proposed project, technology, resource allocation, or siting considerations create uncertainty about the exact nature of environmental effects, or result in a potential for significant adverse environmental effects (AESRD, 2013). Therefore an EA or EIA is triggered when a project is complex in nature and requires considerations and analysis of environmental effects.

4.3 Content of environmental assessments

As mentioned, there are not many Environmental Impact Assessment reports focused specifically on CO_2 pipelines. Therefore, as a starting point, the scoping report of the offshore section of the Kingsnorth project is used (RSK Environment, 2010). Table 10 shows the typical contents of this assessment.

Table 10 – Typical contents of an Environmental Impact Assessment (RSK Environment, 2010).

Part	Description
Physical environment	The environment of the proposed development and identification of the potential impacts.
Ecology	Flora and fauna living in the area where the pipeline is planned.
Cultural heritage	Buildings, objects and other structures of historical, artistic or archaeological significance.
Navigation	Existing infrastructure interfering with the pipeline route.
Emissions	Among which noise, air quality and marine discharges.
Human environment	Impact of the pipeline on economic, social and recreational activities.
Nature conservation designation	Protection of specific habitats and species.

Case studies Permit and EIA requirements

Voluntary Environmental Impact Assessment (Barendrecht)

In 2008, there were no specific guidelines for EIA procedures concerning CO_2 storage. CO_2 was considered a non-dangerous gas and therefore an EIA was only mandatory when it concerned >500,000 m3 CO_2. Shell insisted on performing the EIA as they found it a necessary step in the route towards public acceptance and for learning (Royal Haskoning, 2008).

Requirement for CCS (Snøhvit)

The CO_2 pipeline that connects the Snøhvit LNG-plant with an offshore gas-field was required by the Norwegian government. They would only approve the permits for extraction from the LNG-field in the Barents Sea under the condition that the CO_2 was captured and stored (Koeijer, 2013).

Redirect planned pipeline route (OCAP)

For the new parts of the pipeline distribution network of the OCAP-project, a new pipeline was planned near the municipality of Zoetermeer. The project developer filed a permit application for building this new section. The municipality did not approve the building permit, leading to a redirection of the pipeline (Veenstra, 2013).

Environmental Assessment requirements for project funding (Quest CCS Project)

The Quest CCS project has received funding in part from the Government of Canada Clean Energy Fund- a program created as part of the federal Economic Action plan and administered by Natural Resources Canada (NRCan). NRCan is the responsible party and determined that a screening-level environmental assessment is required under the Canadian Environmental Assessment Act (CEAA). At a provincial level, the Quest project triggers the need for an Environmental Impact Assessment (EIA) for the CO_2 storage component (Quest, 2010).

4.4 Regulatory framework for CO_2 pipelines

In all jurisdictions studied the implementation of CO_2 pipeline projects happens within the regulatory framework that applies to all pipelines that transport liquid or gaseous substances, including natural gas, CO_2 and chemicals. What differs is the extent to which CO_2 pipelines may be considered as distinct from other classes of pipeline.

United States

The design of CO_2 pipelines was new in the 1970s. Designs were based on meeting codes for natural gas pipelines in the absence of design codes or standards. ANSI B 31.8 Gas Transmission and Distribution Piping Systems and other Department of Transportation regulations were used to design the very first CO_2 pipeline, the Canyon Reef Carriers or SACROC (West, 1974).

As of 1989, 16 CO_2 pipelines were operating in the United States and the regulations in US DOT CFR (Code of Federal Regulations) title 49 part 195 prescribed safety standards and accident reporting requirements for pipeline facilities used in the transportation of hazardous liquids. “Hazardous liquid” at that time was defined to include petroleum, petroleum products, or anhydrous ammonia. Therefore, part 195 of the CFR did not apply to the transportation of CO_2 by pipeline at that time (Federal Register, 1989). A proposed rulemaking notice was posted in October 1989 in the Federal Register to require the Department of Transportation (DOT) to regulate CO_2 pipelines. The CO_2 pipeline industry had experienced a good safety record at the point in 1989 when the proposed rulemaking notice came out. At that time the CO_2 industry was considered a new one compared to other established industrial sectors. It was not a question of the CO_2 industry’s safety record that caused the requirement for safety regulation, but rather the possibility of a high-consequence incident if a break in a CO_2 pipeline were to occur. The notice proposed the Subparts that are not part of section CFR 49 Part 195. Changes to other related codes (ASME codes (B31.4 and 31.8) relevant to the design of pipelines; SSPC dealing with protection coatings; ASTM for mechanical testing of steel products etc.) followed as a direct result of the October 1989 rulemaking notice.
See section 5.4, for more information on CO_2 pipeline safety performance since 1989.

Canada

In Canada, CSA standard Z662 contains a section on CO_2 pipeline design. More detailed information is presented in Section 10.4.

Europe

The European Commission concluded in Directive 2009/31/EC on the geological storage of CO_2 that the framework used for natural gas transportation pipelines would be adequate to regulate CO_2 transport. Since potential hazards posed by CO_2 transport are broadly comparable to those of natural gas transport (albeit without the added risk of explosion posed by natural gas) (European Commission, 2008). The European Commission had therefore good reasons to believe that the natural gas framework would be suitable for CO_2 transport as well and did not consider other options (European Commission, 2008).

Case-studies Pipeline situation[7]

The information in this section is applicable to most gas pipelines, not limited to CO_2 pipelines.

Pipeline corridors

In almost all projects a safety corridor (typically 5 meters on both sides of the pipeline) is defined. Within this corridor, no construction activities or digging is allowed, unless a specific exemption or permit is granted.

Burial depth

There are different standards for burial depth of pipelines, depending on parameters such as operating pressure and soil type. The lower limit for community soil is 0.8 meter, while in open land the minimum depth is 0.6 meter. Most countries have increased this minimum depth in their local legislation: often 1.2 meters or even 1.5 meters is used as a minimum depth.

Almost all pipelines that have reported information on burial depths, the minimum depth is found at 1 meter. Only the burial depth for the Rhourde Nouss-Quartzites project is less (0.8 meters). In some cases pipelines or sections are not buried, for instance in the case of the Decatur pipeline and some of sections of the offshore pipelines. These sections are laid on the sea floor. For these pipelines offshore corridors are determined, that prohibit activities that could damage the pipelines, such as fishing (also refer to textbox in section 3.4 on the Snøhvit project).

Third party interference

According to pipeline operators interviewed for this study, the main risks of leakage arise from third-party interference. Safety corridors are normally indicated and legislation exists to prohibit construction activities without permits within this corridor. Nonetheless, there are still incidents caused by unreported works in the proximity of the pipeline. Therefore, pipeline operators conduct regular visual inspections of the corridor, to check on activities near the corridor and prevent activities within the corridor.

In Europe, the regulatory framework varies between countries. A consortium led by COWI (2011) did a survey on the requirements in national legislation regarding the requirements for pipelines. The following topics were covered within legislation of most of the EU-member states:

- Hazard identification and risk assessment;
- Inspection and maintenance plans;
- Surveillance of the pipeline route;
- Protection against third party interference;

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[7] For more detailed information on these projects, please refer to the database.

- External emergency plans;
- Technical standards should be followed (majority) or at least be used as a guidance.

Typically, national legislation also includes requirements on the implementation of safety measures based on Quantitative Risk Assessment analysis. The following measures are required in most of the Member States (COWI, 2011):

- Location specific requirements (to avoid third party risks);
- Pipeline integrity monitoring equipment;
- Location specific requirements for burial depth;
- Leak detection equipment;
- Remotely operated safety valves;
- Location specific requirements for wall thickness.

4.5 Timeline for permitting of CO_2 pipeline projects

Permitting and approval play a key role in realisation timeline for these projects. As an example, the following Table 11 and Table 12 illustrate the timeline for the Quest project in Alberta, Canada and the Cortez project in the United States.

The Quest project (Table 11) will take 6 years to complete. Actual construction time is less than two years for this 80 km pipeline that is located on flat prairie land in Alberta, Canada. However, the need to secure permits and approvals in addition to the input from public participation extended the actual construction timeline.

In another example (Table 12), the Cortez pipeline took 8 years to complete. Actual construction took about 2 years. The Cortez CO_2 pipeline is 808 km long. Some of the long timeline was due to the requirement in the United States for state-by-state approval of the pipeline routing.

Other examples for the ROAD and Jänschwalde projects are presented in Table 13 and Table 14.

Table 11 - Important milestones for Quest CCS project (not exclusive to the pipeline; dates focus on pipeline activities).

Date	Milestone
2008	Project was disclosed to public
January 2010 - present	Stakeholders involved in decision making and regulatory process incl. 3 rounds of Information Requests (200+individual requests) by provincial regulator ERCB.
March 2012	Public hearing chaired by the ERCB
July 2012	Decision Report received
August 2012	Upgrader Environmental Plan update approved
September 2012	Final Investment Decision
2013	Project approved for construction.
2015	Expected commissioning and start operation

Table 12 - Important milestones for Cortez CO_2 Pipeline

Date	Milestone
1976	Bureau of Land Management environmental impact statement started
1980	Environmental impact statement completed
1982	Private land acquisition commences
1982	Commencement of construction
1984	Completion of construction and start-up of operations

Table 13 - Important milestones for the ROAD CO_2 Pipeline

Date	Milestone
2009	Application and award for EEPR-subsidy
2011	Submission of IEA and permits
2015 (planned)	CCS chain mechanically complete
2016 (planned)	Start of operation
2016 – 2020 (planned)	Demonstration phase
2021 (planned)	Start of commercial phase

Table 14 - Important milestones for Jänschwalde CO_2 Pipeline

Date	Milestone
2004	First work commenced on the feasibility of CCS operations in Germany
2006	Start of negotiations with GdF, owner of the Altmark site
2008	Pilot oxyfuel plant at Schwarze Pumpe was developed
2009	CCS law failed to pass in German parliament
2009	Start of planning Jänschwalde CCS plant (despite of failed CCS law)
2010	Projects get awarded €180 mln EEPR grant
2011	NER300 application submitted
2011	CCS law procedure stopped for second time
2011	Vattenfall announced to cancel the project due to regulatory uncertainties

5 Public concern and safety statistics

5.1 Drivers of public concern

For project developers it is important to understand what the key drivers of the public concern are so that focused action can be taken. Interviews with several operators made clear that the CO_2 pipeline is seldom the focal point of public concern. Most concerns relate to the building of a new coal-fired power plant (Kingsnorth) or gas treatment/production facility (Snøhvit) or CO_2 storage (as in the Barendrecht-project). Furthermore it is of importance whether the pipeline and the storage site are situated onshore or offshore. There is less public concern on CCS-projects that are planning to use offshore storage sites, such as Kingsnorth and ROAD (Read, 2013; Wevers, 2013). Only in the Snøhvit project, the pipeline route was an important topic, as it crosses important fishing grounds (Koeijer, 2013).

Public concern can become a serious threat to a project if not handled in time and in a careful manner. Effectively dealing with public concern is a challenging task, as often there is not a single “right” way. Actions and strategies are most effective when tailor made. Still, lessons from previous approaches can be learned. An important driver for public concern is anxiety, not being able to understand risks and consequences and dissatisfaction on information flow and answers given by decision makers and the project developer.

The Barendrecht CCS project in the Netherlands is a notable example which has had to deal with public concern, leading to the cancellation of this project (refer to the following textbox). Many project developers consider public concern as a serious potential threat and thus take it into account in their development strategy. Public communication plays an important role and is discussed further in section 5.3.

Case study Public hearings for the Barendrecht-project

A perceived lack of good information was one of the major reasons that the public concern in the Barendrecht CCS project grew quickly. Citizens were not satisfied with how their concerns were addressed, with little information available for example on the potential effects of CO_2.

Two public hearings were held in 2008. The first meeting (February 2008) attracted about 60 people, of which most were actively involved in local politics. During the meeting some concerns were raised but no significant debate was held, according to interviewees that attended these meetings. It was decided to organise a second meeting to answer questions and inform more people. At the second meeting (April 2008), more people attended (180) and a much greater number of questions and concerns were raised.

In November 2009 the responsible Ministers approved the plans for the Barendrecht project, despite the public opposition. In December 2009 the responsible Ministers came to Barendrecht to explain their decision to the citizens. The meeting was attended by 600 people. The Ministers were continuously interrupted by many boos, whistles, cries of disapproval and insults (ECN, 2010). A small number of very vocal attendees managed to influence the audience (Prangnell, 2013). A late attempt to deal with the questions and concerns of citizens by the companies involved and the responsible Ministers failed to change the situation.

The outcome of the public hearings, in combination with concerns raised by opposition parties in parliament harmed the political support for the Barendrecht-project. Elections took place half a year later, in June 2010. The newly elected government decided not to pursue the plans for onshore CO_2 storage in the Netherlands. This led to cancellation of the project in 2010 (ECN, 2010).

For a detailed description and analysis of the events in Barendrecht, please refer to the ECN-report (2010): "What happened in Barendrecht?"

5.2 Addressing public concern

Lessons learned from the Barendrecht project were directly used in the communication of the new ROAD project in the Netherlands. Everyone speaking on behalf of the project was trained in how to communicate simply and clearly and how to address concerns from worried citizens. Furthermore, facilitating one-on-one conversations appeared to work better than addressing a large audience in a single session. In the Kingsnorth-project E.ON has organised many events with local groups, such as Parish Councils, Hoo Community First Responders and Action with Communities in Rural Kent, as well as hosting a number of community information events and regular newsletters delivered to local residents (E.On, 2010; Read, 2013). More information about public concern in other CO_2 pipeline projects is included in the database.

The United States has dealt with public concern in a similar way as in Europe. For the Salt Creek projects town hall meetings have been held in Howell periodically since 2003, the most recent in October of 2011, to present the proposed development and to answer questions regarding development. Topics discussed included future phase development within Salt Creek Oil Field, monitoring plans for the towns of Midwest and Edgerton, and emergency sirens erected in the towns by Natrona County Emergency Management and with financial support from Howell Petroleum. It turned out that the public had only limited interest in these meetings for reasons that are unclear. Due to the limited attendance of the public meetings, Howell will update project progress and plans via city council meetings. Public meetings will be held as needed (BLM, 2012).

5.3 Public communication

Public communication has become increasingly important in CCS projects. For one, the Barendrecht-project has been cancelled, largely because of public opposition. Several studies about the impact of public opposition in CCS projects have been published over the years. These pointed to the fact that public engagement at an early stage and clear communication are essential. In various CCS projects[8], a range of communication media have been used to inform the public, as illustrated in Table 15.

Table 15 – Communication media used in CO_2 pipeline projects

	Alberta Carbon Trunk Line	Beaver Creek	Canyon Reef Carriers	Central Basin	Choctaw	Cortez	Decatur	Monell	Quest	Salt Creek	Saskpower Boundary Dam	Sheep Mountain	Slaughter	Weyburn	Barendrecht	Jänschwalde	Kingsnorth	Lacq	OCAP	ROAD	Snøhvit
Flyers and folders			🟩	🟩		🟩						🟩	🟩	🟩		🟩			🟩	🟩	
Website	🟩		🟩	🟩		🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩		🟩	🟩	🟩
Documentary																					🟩
Public meetings							🟩		🟩	🟩	🟩				🟩	🟩	🟩	🟩		🟩	🟩
Informative letter																	🟩	🟩			
Telephone helpline		🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩		🟩	🟩	🟩			🟩				
Local information centre							🟩								🟩	🟩					
Training and education							🟩														
Local press																		🟩			

There are various ways to communicate with stakeholders and to inform people about the projects. Websites, public meetings and telephone helpline are the most common media used. However, none of the projects have used all types of communication media. Most of the communication media listed in the table represent one-way communication: these inform people, without a direct opportunity for questions or a dialogue. This is useful and straightforward, but often not sufficient to convince stakeholders. Public meetings, local information centres, training and education are examples of

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[8] The table does not include all selected CO_2 pipeline projects, as for some of the projects no information on the use of public communication was known.

two-way communication. These forms are more complex, require knowledgeable people, but are essential in the success of the project. The selection of channels for communication is important as it should meet the information need of the stakeholders. Based on the table and the information available on communication to stakeholders, the following observations have been made:

1. The use of media to inform the public of the earliest CO_2 pipeline projects (started in the 1970s and 1980s – Cortez, Canyon Reef Carriers, Central Basin, Slaughter, Choctaw and Bairoil) was limited;
2. Most of the new initiatives have a website where information about the project is presented. The range of information available through these websites varies between projects. For most projects, the pipeline project is mentioned on the website of the operator, including a small description (e.g. pipelines from Kinder Morgan, Anadarko, Jänschwalde and Kingsnorth), while other projects have a dedicated website on the project (e.g. Saskpower Boundary Dam, OCAP and Lacq);
3. Telephone helplines are used in almost all North-American projects. These helplines are intended specifically for emergencies and thus for projects that are already operational. The Kingsnorth project also used a helpline, but there it was meant for requesting information about the project;
4. Public meetings have been organised for almost all European projects and for most recent North American projects. The number of people attending these meetings varied. In the Salt Creek project there was very limited attendance at the public meetings (see textbox case studies below), while public meetings in the Barendrecht-project drew a crowd of six hundred people (see textbox in section 5.1);
5. A key difference between the past United States/Canada experience and present and future European experience is the difference in population density between western United States/Canada and Western Europe. Additionally the areas of North America containing CO_2 pipelines are subject to extensive long standing existing oil and gas operations. Therefore, the concept of multiple pipelines is somewhat more accepted. This could explain the reduced use of communication and limited interest in attending to public meetings (see textbox below).

Case studies Use of communication media in CO_2 projects

Documentary (Snøhvit)

Statoil invested in a massive media campaign. Several media have been used in the Snøhvit project, among which television documentaries of its progress. The documentary was made for the Discovery Channel for the programme Discovery Channel Extreme Engineering under the title: The Snøhvit Arctic Gas Processing Platform and Kings of Construction. The documentary was shown all over Europe (Create Acceptance, 2006).

Regional outreach through the National Sequestration Education Centre (Decatur)

The Decatur project is integrated into the larger Illinois Industrial CCS Project (ICCS). Part of this project is the National Sequestration Education Centre (NESC). From this centre, a project team is conducting an integrated communication, outreach, training, and education initiative. The purpose is to engage stakeholders in understanding CCS and the Illinois ICCS project. Knowledge sharing and training in CCS and related technologies are the prime objectives.

Part of the outreach activities are provided through the state-of-the-art interactive visitor's centre. These outreach activities are (Gallakota & McDonald, 2012):

- Disseminating state-of-the-art and safe CCUS practices based on the demonstration of the industrial-scale, integrated CO_2 capture, transportation, storage, and MVA technologies in the Illinois ICCS project;
- Providing an opportunity to ask questions to improve understanding of the CCUS technologies;
- Engaging the general public to discuss concerns and to present the benefits of the CCUS technologies, and give a general overview of the CCUS technologies and MVA of stored CO_2. The project progress and results will be made available through websites, conference presentations, press releases, etc.;
- Providing valuable information on the process, tools, and technologies needed to implement a large scale CCS project which can be shared with other developers.

Limited public interest (Salt Creek)

Howell has held town meetings periodically in Midwest since 2003, the most recent in October of 2011, to present the proposed development and to answer questions regarding development. Topics discussed included future phase development within Salt Creek Oil Field, monitoring plans for the towns of Midwest and Edgerton, and emergency sirens erected in the towns by Natrona County Emergency Management and subsidized by Howell Petroleum. Going forward, due to the limited attendance of the public meetings, Howell will update project progress and plans via city council meetings. Public meetings will be held as needed (BLM, 2012).

Other informative websites

Information on CO_2 pipeline projects can also be found through websites of interest organisations or research platforms that gather information on CCS projects. These websites form a good starting point to find out more about CCS and CO_2 pipeline projects, for example:

- Global CCS Institute (http://www.globalccsinstitute.com/projects/browse);
- IEAGHG (http://ieaghg.org/);
- Zero (http://www.zeroco2.no/projects/);
- The Carbon Capture and Sequestration Technologies website from MIT (http://sequestration.mit.edu/tools/projects/).

5.4 Safety measures, requirements and statistics

Incidents with CO_2 pipelines

The Pipeline and Hazardous Materials Safety Administration (PHMSA, part of the US Department of Transportation) provides extensive data and analysis of pipeline incidents, including CO_2 pipelines.

US Pipeline and Hazardous Materials Safety Administration dataset on CO_2 pipeline incidents

The entire data set for pipeline safety can be accessed on their Distribution, Transmission, and Liquid Accident and Incident Data website. The information includes data on failure mechanisms that led to these incidents, such as valve failures, compression failures, corrosion, leaks and ruptures, among others.

http://www.phmsa.dot.gov/portal/site/PHMSA/menuitem.ebdc7a8a7e39f2e55cf2031050248a0c/?vgnextoid=fdd2dfa122a1d110VgnVCM1000009ed07898RCRD&vgnextchannel=3430fb649a2dc110VgnVCM1000009ed07898RCRD&vgnextfmt=print

This information indicates that in the United States for the time period 1972 – 2012 there have been no fatalities and 46 reported incidents involving CO_2 pipelines. There are no reported civilian injuries or casualties associated with these incidents. The fact that these incidents have typically occurred in areas with very low population density is likely to have played a role

Furthermore, based on older records from the Office of Pipeline Safety (US Department of Transportation), ten incidents have been reported between 1990 and 2001 (Gale & Davison, 2004). These incidents were caused by relief valve failure (four occasions), weld/gasket/valve packing failure (three occasions), corrosion (two occasions) and outside force (one occasion). The property damage as a result of these incidents is estimated at a total of USD 469,000 (Gale & Davison, 2004).

Some small scale incidents with CO_2 pipelines have been reported in Europe as well, but again no personal injuries or casualties (see textbox). In contrast to the United States, there is no incident reporting or analysis system in Europe from which safety trends and statistics could be evaluated (COWI, 2011). Industry itself gathers statistics on a voluntarily basis.

Case-studies Some reported incidents in CO_2 pipelines[9]

OCAP

During operation of the OCAP pipeline, three incidents with small volumes of leakage were reported. None of the incidents caused civilian injuries or casualties. In the towns of Berkel en Rodenrijs some ducks died from exposure to CO_2. It should be noted that this specific pipeline is operating at a relatively low pressure and has a small capacity (0.4 Mton/y). Therefore, risks for large damage and injuries may be expected to be lower compared to higher pressure CO_2 pipelines as would typically be used in CCS projects. The leakages that occurred were all evaluated by OCAP and lessons learned were drawn accordingly (Veenstra, 2013). There is no public information available on leaked quantities.

Canyon Reef Carriers

Five Incidents with loss of containment have been reported since 1982, with no injury to persons.

Incidents with natural gas pipelines

Discussion of incident statistics for CO_2 pipelines begs comparison with natural gas pipelines. However, it is difficult to make effective comparisons because of the huge discrepancy in the number of km of pipelines on each category.

For natural gas in the United States, a total of 217 people were reported as injured and 58 killed as a result of accidents with natural gas pipelines over the period 1986 to 2001. For CO_2 pipelines there are no known reports of people having been injured or killed. Incidents with natural gas pipelines resulted in damage costs amounting to an average of USD 37,000 of annually per 1000 kilometres of pipeline (Gale & Davison, 2004).

To interpret such information correctly with respect to CO_2 pipelines, incidents should be compared per km of pipeline. There are over 2,000,000 kilometres of natural gas pipelines in Europe (both high- and low-pressure (COWI, 2011). In contrast, the existing European CO_2 pipeline infrastructure (OCAP and Lacq) is limited to 230 kilometres (Total, 2013) (OCAP, 2012). The relative number of incidents per 1,000, km of pipelines appears to be slightly higher for CO_2 (0.32), than for natural gas (0.17). However, the hazards associated with these incidents tend to be much more severe in the case of natural gas pipelines, both in terms of human injuries and casualties as with property damage (Gale & Davison, 2004). Moreover, due to the limited number of kilometres of CO_2 pipelines and likely sampling error it is not possible to draw robust conclusions about whether or not the incident rate with CO_2 pipelines would be systematically different from other gas pipelines.

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[9] More information on these projects can be found in the database.

Case-studies Incidents with natural gas pipelines

Carlsbad (United States), 2000

In New Mexico, a 30-inch (762 mm) diameter underground natural gas transmission pipeline ruptured as a result of internal corrosion. The released gas ignited causing the death of twelve people (COWI, 2011).

Ghislenghien (Belgium), 2004

After the detection of a leak in a gas pipeline with a diameter of 1,000 mm, the gas ignited and caused an explosion, killing twenty four people and injuring another 132. This has been the worst natural gas accident in Europe (COWI, 2011).

San Bruno (US), 2010

In the residential area of Bruno California nine people were killed after a gas pipeline ruptured. The cause was identified as faulty welding in the pipeline and complications as a result of a local power outage (COWI, 2011)

6 Research and centres of excellence

Globally, the development of technology for pipeline design, construction, inspection and maintenance continues at a range of research institutes, universities and private businesses. There are several research programmes focusing on CCS in general, pipelines or specific topics such as corrosion and materials. Most of these topics are addressed in a broader context than CO_2 pipelines, but in most of the programmes specific attention is paid to CO_2 pipelines.

Besides these, various private businesses are actively involved in the development of pipeline technology. Several large companies such as Kinder Morgan (North-America) or consortia of pipeline companies (European Pipeline Research Group and Pipeline Research Council International) have research programs to develop the knowledge on pipelines and pipeline issues.

This chapter highlights some examples of these initiatives. A longer list is presented in Table 16 at the end of the chapter (please note that this list is not intended to be complete).

6.1 Research programmes

Energy Pipelines Cooperative Research Centre (EPCRC)

The main focus of the EPCRC is the extensive network of high pressure gas transmission pipelines around Australia. These pipelines are responsible for the safe and continuous supply of natural gas from production sources to the range of industry, retail and domestic customers. The Energy Pipelines CRC is conducting research into a wide range of topics covering:

- Materials and welding;
- Corrosion and its control;
- Design and construction; and
- Human factors in relation to pipeline safety.

Although this work is mainly focused on natural gas carrying pipelines, much of the work is also directly applicable to CO_2 pipelines and for specific areas the research is extended from natural gas pipelines to both CO_2 pipelines and pipelines carrying other hydrocarbon fluids. EPCRC is a collaboration between the Australian Commonwealth Government, the fifty member companies of the Australian Pipeline Industry Association and the Universities of Adelaide, Deakin, Wollongong and the Australian National University.

More information on this topics is available at: https://www.epcrc.com.au/

Carbon Storage Program (NETL)

The Carbon Storage Program of National Energy Technology Laboratory (NETL) received USD 70 million from the American Recovery and Reinvestment Act of 2009 (Recovery Act). These funds are being used for (1) Geologic Storage Site Characterisation projects (USD 50 million), and (2) to provide training opportunities through R&D at universities and establish regional training centres with the goal of creating a qualified carbon storage workforce in the United States (USD 20 million). These efforts complimented the existing goals for the program. Sixty projects were awarded with the Recovery Act funds. The details about individual projects are provided through the contents of the Storage Program's web pages within the Core R&D and Infrastructure components of the program.

Although not specifically focusing on CO_2 pipelines, the Program is an important driving force for the development of CCS in general and is therefore mentioned in this context. At least two of NETL's studies have been used in this manual as bases for cost estimation. More information can be found at: http://www.netl.doe.gov/technologies/carbon_seq/index.html

CATO-2

The CATO-2 programme is a Dutch R&D programme that focuses on facilitating and enabling integrated development. Representatives of Industry, CCS platforms, NGOs and scientists of research institutes and universities take part in the CATO-2 programme.
More information is available at: http://www.co2-cato.org/cato-2/themes.

The CATO-2 programme is divided into five sub-programmes, all representing the full chain of CCS, including transport and infrastructure. The sub-programmes should result in a quantified blueprint for the deployment of CCS, its impacts, required infrastructure and implementation strategies for the Netherlands and in the larger European and global setting. The main elements of the sub-programme are:

- Technical aspects of CO_2 transport infrastructure;
- Techno-economic chain analysis and cost-benefit assessments;
- National and international policy analysis;
- Chain integration and development of a CCS implementation plan.

CO_2Europipe

This project aims at enabling the transition from initial small-scale, local CO_2 transportation towards large-scale CO_2 transport and storage that is expected to start around 2020. Based on scenario studies and a business case, a roadmap was developed to guide the transition towards a large-scale CO_2 infrastructure in Europe. The CO_2Europipe consortium consists of 19 partners that together cover the CO_2 capture, transport and storage chain.
More information can be found at: http://www.co2europipe.eu/

COMET

The objective of the COMET project is to study the techno-economic feasibility of integrating CO_2 transport and storage infrastructures in Portugal, Spain and Morocco. The feasibility study takes into account several scenarios of energy system development for the time period 2010-2050, the location

and development of the major CO_2 point sources and the available potential for geological storage in each of those countries. It is expected that the results will generate insights that can contribute significantly to the deployment of CCS in the region. The consortium consists of 17 partners.
More information can be found at: http://comet.lneg.pt/

CO_2 PipeHaz
The CO_2PipeHaz consortium is made up of 7 partners from 5 different countries involved in diverse but complementary aspects of what is a complex project. This includes experts in the fields of thermodynamic and transport properties, CO_2 purification, multi-phase heterogeneous flows, and dispersion at both small and large scales (near- and far-field).
More information can be found at: http://www.co2pipehaz.eu/index.php

COCATE
The aim of the study is to assess the potential for flue gas or other fluid pooling so as to devise common emission collection systems for industries within the area around Le Havre and to design a CO_2 export system for transporting the emissions to the Rotterdam hub, from where they will be sent to an eventual storage location in the North Sea. For both the local CO_2-emissions transport/collection networks and the cross-border CO_2 export systems, a range of technical options are proposed and assessed from risk, economic, and network management standpoints. The COCATE consortium includes nine project partners, representing all essential stakeholders of the technology supply chain for CCS.
More information can be found at: http://projet.ifpen.fr/Projet/jcms/c_7861/cocate

6.2 Pipeline technology development

EPRG - European Pipeline Research Group
EPRG's technical activities are directed by the Plenary Group and coordinated through three Technical Committees, concerned with materials, corrosion and design respectively. The main focus of recent and on-going research activities is to provide understanding, guidance and engineering application methods in the three areas listed below. More information is available at:
http://www.eprg.net/home:

- Materials and manufacturing;
- Corrosion and corrosion protection;
- Design and operation.

Pipeline Research Council International (PRCI)
PRCI is a community of the world's leading pipeline companies, vendors, service providers, equipment manufacturers and other organisations. More information is available at:
http://prci.org/index.php

In their 2013 Research Program, the following topics have been identified:

- Corrosion;

- Compressor and Pump Station;
- Design, Materials and Construction;
- Long Term Research Committee;
- Measurement;
- Operations & Integrity;
- Underground Storage.

Kinder Morgan

Kinder Morgan is the largest midstream and the third largest energy company (based on combined enterprise value) in North America. They own an interest in and/or operate approximately 80,000 miles of pipelines and 180 terminals. Kinder Morgan is the largest natural gas pipeline and storage operator in the United States and are the largest transporter and marketer of CO_2 in the United States. More information is available at: http://www.kindermorgan.com

6.3 Standardisation

ISO – International Organisation for Standardisation

ISO is the world's largest developer of voluntary International Standards. It has published more than 19,500 International Standards covering almost all aspects of technology and business. ISO is currently pursuing a proposed program (ISO/TC-265) of work that includes the full lifecycle of a CCS system, including CO_2 transportation. A specific working group on CO_2 transport (IS/TC 265/ WG2 'CO_2 Transportation') has started in June 2013 and will include many different aspects of the CO_2 pipelines, among which material, wall thickness, internal corrosion protection, construction, testing, operation, maintenance and abandonment of pipeline systems. The extensive work on international standards for CO_2 pipelines is expected to be completed in 2015.
More information is available at: http://www.iso.org/iso/iso_technical_committee?commid=648607

INGAA - Interstate Natural Gas Association of America

The Interstate Natural Gas Association of America (INGAA) is a trade organisation that advocates regulatory and legislative positions of importance to the natural gas pipeline industry in North America. More information is available at: http://www.ingaa.org/

DNV GL

DNV GL has developed a Recommended Practice (RP) which provides guidance and sets out criteria for the concept development, design, construction and operation of steel pipelines for the transportation of CO_2. More information is available at:
http://www.dnv.com.au/industry/energy/news/2011/designandoperationofco2pipelines.asp

6.4 Overview of key centres of excellence

Table 16 presents an overview of relevant research programs at universities and institutes. A short description of the research is provided for each. This list provides a first impression and is not intended to be exhaustive. There are on-going research projects on specific topics at a wide range of institutes.

Table 16 – Centres of excellence

University or institute	Region / Country	Description
Research programmes		
MIT	North-America	The Carbon Capture and Sequestration Technologies Program at MIT conducts research into technologies to capture, utilise and store CO_2 from large stationary sources. A major component of the program is the Carbon Sequestration Initiative, an industrial consortium launched in July 2000.
CATO 2	Europe	The CATO-2 programme is a Dutch demand driven R&D programme and focuses on facilitating and enabling integrated development. Representatives of Industry, CCS platforms, NGOs and scientists of research institutes and universities take part in the CATO-2 programme.
Energy Pipelines CRC	Australia	The Energy Pipelines Cooperative Research Centre (EPCRC) is a collaboration between the Australian Commonwealth Government, the fifty member companies of the Australian Pipeline Industry Association and the Universities of Adelaide, Deakin, Wollongong and the Australian National University.
CO_2Europipe	Europe	This project aims to enable the transition from initial small-scale, local CO_2 transportation towards large-scale CO_2 transport and storage that is expected to start around 2020. A roadmap was developed to guide the transition towards a large-scale CO_2 infrastructure in Europe based on scenario studies and a business case.
COMET	Europe	The objective of the COMET project is to study the techno-economic feasibility of integrating CO_2 transport and storage infrastructures in Portugal, Spain and Morocco.
CO_2 PipeHaz	Europe	The CO_2PipeHaz consortium is made up of 7 partners from 5 different countries involved in complementary aspects of this complex project. It includes experts in the fields of thermodynamic and transport properties, CO_2 purification, multi-phase heterogeneous flows, and dispersion at both small and large scales (near- and far-field).
COCATE	Europe	The aim of this study is to assess the potential for flue gas or other fluid pooling so as to devise common emission collection systems for industries within the area around Le Havre and to design a CO_2 export system for transporting the emissions to the Rotterdam hub, from where they will be sent to an eventual storage location in the North Sea. For both the local CO_2 emissions transport/collection networks and the cross-border CO_2 export systems, a range of technical options are proposed and assessed from the points of view of risk, economic, and network management.
Carbon Storage Program (NETL)	North-America	NETL's Carbon Storage Program received USD 70 million from the American Recovery and Reinvestment Act of 2009 (Recovery Act).

University or institute	Region / Country	Description
		Key areas of work Geologic Storage Site Characterisation projects, creation of a qualified carbon storage workforce in the United States.
Topic		**Corrosion**
University of Adelaide *Energy Pipelines CRC*	Australia	A focal point of the program is welds and one goal is to produce a user friendly industry tool for the prevention of weld metal hydrogen assisted cold cracking. Another project aims to develop an integrated solution for online quality monitoring and non-destructive testing of steel pipeline girth welds. The program is also being used to support the use of higher strength steels by providing expertise on methods of manufacture, specification, joining and repair.
Deakin University *Energy Pipelines CRC*	Australia	Cost effective extension of the life of pipeline infrastructure by mitigating corrosion and environmentally assisted degradation of pipelines. One major area of research concerns coating selection, application and testing, supported by a National Facility for Pipeline Coating Assessment (NFPCA) hosted by Deakin University. Other research themes include cathodic protection and stress corrosion cracking.
Topic		**High pressure dispersion modelling**
DNV/KEMA	Europe	DNV has developed a Recommended Practice (RP) which provides guidance and sets out criteria for the concept development, design, construction and operation of steel pipelines for the transportation of CO_2.
UK Atmospheric Dispersion Modelling Liaison Committee	Europe	Review current understanding of atmospheric dispersion and related phenomena for application primarily in authorisation or licensing of discharges to atmosphere resulting from industrial, commercial or institutional sites.
Topic		**Materials**
MATTRAN	Europe	Materials for Next Generation CO_2 Transport Systems (MATTRAN) is a consortium of Newcastle University, Imperial College London, The University of Nottingham, Cranfield University and UCL - University College London
Newcastle University *MATTRAN*	Europe	CO_2 stream specification, Pipeline specification, Internal stress corrosion cracking investigation
Imperial College London *MATTRAN*	Europe	Synthesis and dissemination
The University of Nottingham - *MATTRAN*	Europe	Phase and dew point determination
Cranfield University *MATTRAN*	Europe	Internal corrosion and degradation investigation
UCL - University College London - *MATTRAN*	Europe	Fracture control
Topic		**Safety**
Deakin University *Energy Pipelines CRC*	Australia	Extension of Safe Operating Life of New and Existing Energy Pipelines
Wollongong University *Energy Pipelines CRC*	Australia	Advanced Design and Construction of Energy Pipelines
Australian National Univ. *Energy Pipelines CRC*	Australia	Public Safety and Security of Supply of Energy Pipelines

SECTION B

Guideline for assessment of CO_2 pipeline projects

The information provided in this document is not intended to be a comprehensive and detailed description of all aspects of CO_2 pipelines; rather, it is a basic outline that can be used by individuals and organisations that do not possess extensive skills and knowledge in the areas of engineering, permitting, construction and operation of CO_2 pipelines. For a more comprehensive description, please refer to “Recommended Practice DNV-RP-J202, Design And Operation Of CO_2 Pipelines” (Det Norske Veritas, 2010).

Moreover, the materials presented are more detailed for the conceptual or project definition stage, as the subsequent phases of project development are increasingly the same as for all gas pipelines.

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7 CO_2 pipeline project phasing

7.1 Project phases

In many respects CO_2 pipeline projects are comparable to other gas pipeline projects. Figure 15 illustrates a typical project cycle for large projects, from initial idea to operation. This will be used in this Chapter to discuss the various stages of a CO_2 pipeline project. In particular, it will highlight some key issues that are specific to CO_2 pipelines.

Planning and preparing for construction and operation of a CO_2 pipeline is quite similar to what is needed for a high-pressure natural gas transmission pipeline. The key distinguishing features fall in four specific areas:

1. The properties of CO_2 gas result in different design parameters than for natural gas;
2. Regulatory agencies and members of the public who are not familiar with CO_2 pipelines are inclined to perceive them quite differently, as unlike natural gas infrastructure they do not deliver a product that is directly beneficial on a household level and in many places represent first-of-a-kind projects;
3. A single high-profile incident involving a large number of fatalities from concentrated CO_2 emissions (Lake Nyos, Cameroon) while not in any way related to pipelines, has created a - arguably exaggerated - perception of public risk from releases of concentrated CO_2 from pipelines;
4. CO_2 pipelines are not separated in the public mind from the perceived risks associated with geological storage of CO_2.

The result of these differences, particularly the last three, is that the level of effort invested in public awareness, education and consultation as well as working with regulatory authorities is in most jurisdictions likely to need to start sooner than for natural gas pipelines, be much more extensive and may result in longer-than-normal timelines.

On the other hand, like all gas pipelines, the project phases that CO_2 pipeline projects go through are generally the same as for gas pipelines and constitute what is known as the “project cycle”. Typically, the project cycle takes between 3 to 6 years from the project concept stage to the final investment decision. The actual construction of the pipeline depends on the length and the complexity of the pipeline and takes between 1 to 4 years.

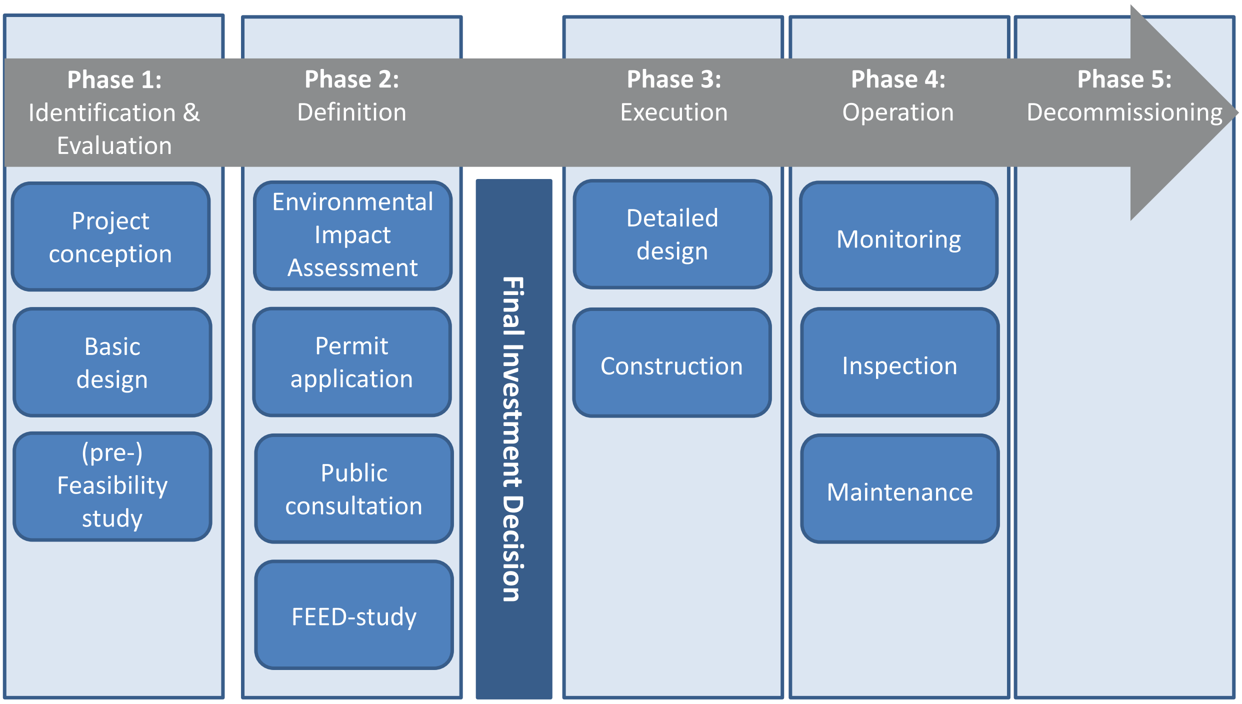

Figure 15 – Project cycle and phases

7.2 Phase 1 - Identification and evaluation

The main activities in this phase are:

1. Qualitatively define the project concept, including motivation and financial driving forces;
2. Establish basic parameters: starting point, end point, CO_2 source(s), CO_2 sink(s);
3. Define design CO_2 transport capacity;
4. Establish regulatory requirements, particularly any directly related to $CO_{2;}$
5. Establish rough pipeline routing;
6. Plan public consultation process;
7. Make preliminary contact with possible sources of additional funding;
8. Establish conceptual design, costs and preliminary economics;
9. Develop an overall business plan / pre-feasibility study covering all issues.

7.2.1 Project concept

In Phase 1 the project concept is elaborated. The purpose of the project is defined, the source of CO_2 used, the quantity and quality of CO_2 transported and to which sink. Also in this phase the possibilities of reusing existing pipelines or connecting to an existing pipeline network are assessed. Based on the choices made, several scenarios are developed including different routes, lengths, pipeline diameters, materials selection and capacity.

In all cases some financial driving force either exists or must be created to justify the considerable investment costs for CO_2 transportation. It may be positive (the value of additional hydrocarbon recovered in an EOR operation), or negative (avoidance of penalties imposed if greenhouse gas reduction targets are not met). At the present stage of CCS development worldwide both of these drivers may be present to some degree, along with some form of positive government incentive (grants, tax breaks, etc.) specific to the project. As is noted elsewhere such incentives usually but not always apply to the entire CCS project rather than to the pipeline as a separate entity.

7.2.2 Basic design parameters and design capacity

The design parameters for a CO_2 pipeline, particularly one associated with a single CCS project, are usually entirely dependent on the designs for the CO_2 capture equipment and identification of the likely use/sink for the CO_2.

A general principle of all pipeline projects is that establishing the right-of-way and opening the trench figure more prominently in total pipeline costs than the cost of the pipe itself. So, if prospects of additional CO_2 volume from one or more sources seem good and the assessment of CO_2 storage / utilisation capacity appears able to support expansion, it is likely prudent to build some additional capacity into the pipe itself. Greater compression capacity, booster stations, etc. can be added later to accommodate increased volumes. A reasonable scenario might involve designing the pipeline to handle a base initial project capacity without booster pump stations, but allow a doubling of that capacity with no modifications to the pipe itself but with the addition of booster stations and feed compressors. More detail on pipeline design is provided in Chapter 12.

Details of the conceptual design and technical aspects of CO_2 pipeline are elaborated in Section 11.

7.2.3 Pipeline route selection

Beyond general route definition and potential problem area identification, most of the detailed work on route selection will come in later project phases. Very little distinguishes route selection for CO_2 pipelines from that for other gas pipelines. The basic principles are:

1. Minimise interference with or proximity to current or potential other infrastructure; avoid human habitation where possible;
2. Avoid sites of archaeological interest or ecologically sensitive areas;
3. Choose terrain assessed to be relatively easy for pipeline construction;
4. Follow existing pipeline routes or other transportation corridors; take advantage of established rights-of-way;
5. Avoid difficult watercourse and highway crossings where possible;
6. Avoid areas earmarked for future developments that may be incompatible with the presence of pipelines;
7. For CO_2 pipelines it is necessary to establish in the specific jurisdiction and applicable regulations whether any differences from natural gas pipelines exist for offsets from existing developments or human habitation. In the absence of regulatory differences, technical considerations do not result in different proximities to human habitation for CO_2 than for natural gas. However, public perception and lack of public experience may make it prudent to use greater separations for CO_2.

7.2.4 CO_2 hubs and main pipelines

A different set of early-stage decision criteria are used where multiple CO_2 sources and sinks exist. The model is identical to that for natural gas gathering, transmission and distribution networks. Hubs may be developed where individual CO_2 sources are gathered and from which various CO_2 customers are supplied. These hubs are connected by main transmission lines. Once the basic network is in place, it is relatively easy to add new CO_2 sources and sinks that in themselves involve small individual CO_2 pipeline projects. Just as with natural gas transmission systems, allowing CO_2 to be shipped from multiple sources requires that the operator strictly define the required CO_2 purity, pressure and volume conditions that each shipper must meet. The decision criteria for hub definition are substantially more complex than for a single-project pipeline, and beyond the scope of this guideline. Even the hub location may be subject to multiple location choices. The overall objective remains the same: within the physical constraints imposed by generally prudent pipeline route selection, minimise the unit cost of moving CO_2 through the system.

More information on existing CO_2 hubs is presented in section 2.3 .

7.2.5 Conceptual design, costs, preliminary economics

With the information gathered up to this point, rules of thumb and publicly available cost estimating techniques can be used to develop simple preliminary project economics. Chapter 8 provides more detail on how that can be accomplished. The results of this economic analysis must be considered to be preliminary only and to have a very wide confidence interval; perhaps +/- 50% or greater at best. Economic analysis at this stage can be carried out using a full-cost, no-inflation base, to avoid obscuring the real cost of the project and to be used as a base of comparison for alternate technical and financial configurations.

7.2.6 Business plan development

Preparation of a conceptual business plan is common to all projects. In the case of a CO_2 pipeline that is likely part of a CCS project it will answer such questions as:

- Who will the owners of the pipeline be? Will it be integrated into the CCS project or handled as a separate entity?
- How will the pipeline generate and account for revenue?
- What proportion of an overall CCS project costs is represented by Transportation?
- Will the nature of the CO_2 utilisation be such that demands for transporting CO_2 are relatively constant, or will they be variable?

7.3 Phase 2 - Project definition

This Phase takes place if the results of the Phase 1 pre-feasibility study are sufficiently positive to encourage additional expenditures to further develop the project. Activities include:

- Environmental Impact Assessment;
- Initial permit application;
- FEED study to advance the level of confidence in all aspects of the project design, providing a basis for a cost estimate at +/- 10% accuracy as a basis for final investment decision;
- Public participation.

7.3.1 Environmental Impact Assessment

In Phase 2, an Environmental Impact Assessment (EIA) is performed according to the prevailing law and regulations. Depending on the size of the project and local regulations, an EIA is likely mandatory. For a first-of-its-kind project in a particular jurisdiction a greater level of information might be expected. EIA contents for a CO_2 pipeline would generally not be expected to be materially different from those for a natural gas pipeline, except as related to the characteristics of CO_2 if released into the atmosphere. The expected environmental benefits of CO_2 transport (Less Greenhouse Gases released to the atmosphere) would typically be addressed in the capture and storage aspects of a CCS project.

7.3.2 Initial permit application

Phase 2 includes submission of the initial permitting application, based on the results of the EIA. The length of the permitting procedure varies between projects and depends on different factors, such as the complexity of the project, presence of existing regulations and the public's opinions. As noted above, first-of-a-kind activities may occasion more lengthy public participation processes and increase the probability that a formal public hearing may be required. The length of permitting procedures can vary from a few months to several years. The degree of overlap of these activities with more detailed engineering design and right-of-way acquisition processes is highly dependent on an organisation's assessment of how certain a successful outcome might be, and the financial capacity of the organisation to sustain lengthy delays or ultimate failure. The outcome of the EIA and permitting activities is not likely to be a full permit at this stage, but rather an informal acknowledgement from regulatory authorities that subject to no material changes in the plans as they exist, appropriate permits would be issued at the time of full financial commitment by the sponsor organisation.

7.3.3 Public participation

While public participation is unlikely to be required at this stage for natural gas pipelines, for CO_2 it would be prudent to initiate the process.

7.3.4 Other activities

As for all pipelines, the process of improving project definition and establishing the pipeline right-of-way continues through Phase 2 in parallel with EIA and permitting activities. At this stage, the biggest uncertainty in cost estimates is still associated with lack of full knowledge of exactly what will be built. A key part of Phase 2 is a FEED study that improves the accuracy of the pipeline design and reduces uncertainty associated with the cost estimate (more information on FEED-studies is available in section 10).

7.4 Phase 3 – Execution: detailed design, construction and start-up

Very little in this phase is unique to CO_2 pipelines. Pre-construction, it is aimed at carrying out sufficient detailed design and right-of-way acquisition to arrive at a cost estimate with a confidence interval of +/- 10%, generally required for a final investment decision. Chapter 11 provides additional detail, building on the FEED study content as related to CO_2 pipelines.

Depending on the outcomes of the permitting process, adjustments to the original plans must be made and cost effects assessed. Two projects that were included in this study are currently under construction: Quest and the Alberta Carbon Trunk Line. Links to the respective project websites are included in the textbox below.

Start-up of a CO_2 pipeline presents a set of different complexities than for a natural gas pipeline of similar operating conditions. For example, with natural gas a major concern involves avoidance of explosive mixtures when the pipeline is being filled. For CO_2 no such issue exists, but the ability of CO_2 to achieve extremely low temperatures when expanded from a compressor discharge into a pipe at low pressure can result in pipeline steel temperatures below allowable tolerances unless pressures are brought up gradually. Also the presence of water in the line at any time CO_2 is present is intolerable.

Case-studies Projects under construction[10]

Adjusting pipeline route (Quest)

To come to the final pipeline route, 30 changes were made to the initially planned route for the Quest pipeline. These changes were the result of Quest's commitment to respond to community input. Len Heckel (Business Opportunity Manager at Shell Canada): “Upfront community consultation had tangible benefits for our project, with mostly positive responses from the community during our public hearing” (Global CCS Institute, 2012).

Besides the Quest project, two other Canadian projects are under construction. More information can be found at their respective websites:

- Saskpower Boundary Dam (Cenovus) http://www.cenovus.com/operations/oil/docs/rafferty-landowner.pdf;
- Alberta Carbon Trunk Line (Enhance) http://www.enhanceenergy.com/.

7.5 Phase 4 – Operation

During the operational phase the project not only has to perform technically as expected, but also financially and commercially. Moreover, the performance in terms of safety and minimising incidents

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[10] For more detailed information on these projects, please refer to the database.

plays an important role in maintaining the project's license to operate. Again, in most aspects this phase for CO_2 pipelines is comparable to other gas pipelines. This document focusses on monitoring, inspection and maintenance activities during this phase. These are elaborated in some detail in chapter 12.

7.6 Phase 5 – Decommissioning

At the end of either the technical or the commercial life of the project, it is decommissioned and abandoned. Often, decommissioning requirements are part of the conditions of the initial project permit.

No specific information was found on the specifics of decommissioning of CO_2 pipelines. However, the Lacq project in France, for one, has a CO_2 pipeline that was decommissioned. Chapter 13 presents some key topics relevant for this concluding project phase.

8 CO_2 pipeline cost

8.1 Key cost drivers

General initial pipeline capital costs are divided into two main categories: (a) materials and labour and (b) engineering. Material costs will be determined by the specific nature of the CO_2 pipeline as summarised in Table 17.

Table 17 - Summary of key cost drivers

Costs driver	Description	Comment
Equipment requirements	• Compression or booster pump station requirements and associated energy sources such as electricity or fuel supply; • Block valves, check valves, control valves, ESD valves; • Instrumentation and auxiliary equipment.	Customised equipment may cost more than commercially available equipment
Trenching	• Includes earthworks, excavation and backfilling.	Cost may rise if drilling or blasting is needed. Not appreciably different than for Natural Gas pipelines.
Piping, valves and equipment	• Type of material and grade to be used; • Wall thickness; • Crack arrestors to prevent crack propagation; • Emergency Shutdown valves to limit releases in case of a rupture; • Specialized non-ferrous components.	Costs may rise for thicker wall pipes needed in areas with existing infrastructure /population; Costs for offshore pipelines will be higher, due to specific pipeline requirements for offshore construction; Other equipment is similar to that for Natural Gas.
Distance	Distance determines pressure drop and related requirements for intermediate compression or booster pump requirements	Longer pipelines will translate into higher – per unit length material costs to allow for higher pressures and/or booster equipment
Diameter	Determines the costs related to size of pipe	
Terrain	Determines building of access routes or temporary camps to host work force	Costs may rise if there are river crossings or highways that need to be traversed
Labour	Determines the necessary labour force and salaries	Needs to account for indirect costs such as transportation of labour, camp costs, etc.

Engineering costs are a combination of the following items:

- engineering design from conceptual design to detailed engineering;
- project management;
- regulatory, permitting and supporting activities.

Other costs include:

- miscellaneous and head office expenses;
- contingencies for potential unforeseen events.

8.2 Pipeline costs background

Depending on the CO_2 pipeline, costs may be publicly available and can be used as a reference to estimate future CO_2 pipeline projects. Design and construction costs may be difficult to acquire due to confidentiality and cannot be disclosed by the design firm. Also, pipelines may have been designed and built by the operator as opposed to an engineering design firm and after selling off the pipeline to other interested parties, cost information is misplaced or not easily available. Table 18 presents a summary of selected pipelines with actual costs information available from public documents.

Table 18 Actual costs for selected pipelines. Refer to the accompanying database for available information on operating conditions such as flow rates, temperatures, pressures, etc.

Pipeline	Costs for pipeline	Currency	Year	Dimensions	Onshore / Offshore	International units
Canyon Reef Carriers (SACROC)	46 million	USD	1971	D= 26 to 16 inches L= 220 miles	Onshore	D= 324 – 420 mm L= 354 km
Cortez	700 million	USD	1982	D= 30 inches L= 502 miles	Onshore	D= 762 mm L= 808 km
Weyburn CO_2 pipeline	51 million	USD	2008	D= 14 to 12 inches L= 205 miles	Onshore	D= 305 – 356 mm L= 330 km
Quest	140 million	USD[a]	2012	D= 12 inches L= 49.7 miles	Onshore	D= 324 mm L= 84 km
Qinshui	39.35 million	USD	2006	D= 6 inches L= 72 miles	Onshore	D= 152 mm L= 116 km
Longannet	160 million	GBP	2011	D= 500 to 900 mm L= 380 km	On: 100 km Off: 270 km	D= 500 to 900 mm L= 380 km
ROAD	90 million	EUR	2010	D= 450 mm L= 25 km	On: 5 km Off: 20 km	D= 450 mm L= 25 km
Gorgon	9 million	AUD	2011	D= 269 – 319 L= 8.4 km	Onshore	D= 269 – 319 mm L= 8.4 km

[a] Initial estimate in CAD (Canadian dollars). Assumed exchange rate USD 1.00 = CAD 1.00

8.3 Estimate of pipeline costs

In the absence of actual data, pipeline capital cost can be estimated from credible sources. Such sources include actual data or studies. A simple approach to estimating costs for onshore CO_2 pipelines can be found in the National Energy Technology Laboratory 2013 study entitled *Carbon Dioxide Transport and Storage Costs in NETL Studies; Quality Guidelines for Energy Systems Studies, DOE/NETL 2013-1614* (NETL, 2013). Costs are based on formulas that require diameter (D) and length (L) as input, and are based on data from the United States. Costs are reflective of US dollars (USD) for the year 2011. This approach should be used as a rough indicator of possible costs for a project and never as an accurate estimate. In evaluating the usefulness of this cost estimating approach particular attention should be paid to the assumptions used by the authors and to Table 19below, which illustrates the extremely wide range of unit costs for CO_2 pipelines experienced by Kinder Morgan, the largest CO_2 pipeline operator in the world. Implicit in the paper is that carbon steel is being used for the pipeline. Also of interest in this exhibit is the suggested unit cost for offshore CO_2 pipeline segments, more than twice the cost of onshore river crossings and almost seven times the cost of any of the example calculations provided. It would appear from this that the largest uncertainty in pipeline cost is the nature of the geography and geology traversed by the pipeline. More accurate costs estimates can only be carried out once vendors and service providers make costs available.

For other countries it may be possible to use country factors to adjust the estimates, but a better approach may be to identify studies based on the alternate location (e.g. Europe) and use them.

The NETL study also provides a summary of costs based on Kinder-Morgan pipeline experience. Table 19 summarises pipeline capital costs based on terrain characteristics rather than detailed generic costs from Table 20 (both on the following page).

None of these cost numbers, either quoted or derived, will produce estimates than can be used for any purpose other than to a first impression of possible CO_2 pipeline costs. A project proponent will usually follow a cost estimating standard such as AACE International Recommended Practice No. 18R-97 (AACE, 2011), which if followed and is based on a realistic physical scope of work, will yield cost estimates with predictable confidence intervals. While this document and the accompanying 17R-97 (AACE, 2011) are not specific to pipelines, the nomenclature and estimate class interval descriptions of 18R-97 and the process industry context are appropriate to the pipeline industry.

Table 19 - Kinder-Morgan pipeline representative cost metrics. Source: (NETL, 2013)

Terrain	Capital Cost (USD / inch-Diameter / mile)
Flat, Dry	USD 50,000
Mountainous	USD 85,000
Marsh, Wetland	USD 100,000
River	USD 300,000
High Population	USD 100,000
Offshore (150-200 feet ~ 45–60 meters depth)	USD 700,000

Table 20 - Pipeline capital cost estimates as established by the NETL

Cost Type	Units	Cost
Pipeline Capital Costs		
Materials (assumes Carbon steel)	Diameter (inches), Length (miles)	USD 70,350+USD 2.01*L*(330.5*D^2+686.7*D+26,960)
Labour	Diameter (inches), Length (miles)	USD 371,850+USD 2.01*L*(343.2*D^2+2,074*D+170,013)
Miscellaneous	Diameter (inches), Length (miles)	USD 147,250+USD 1.55*L*(8,471*D+7,234)
Right of Way	Diameter (inches), Length (miles)	USD 51,200+USD 1.28*L*(577*D+29,788)
Other Capital Costs		
CO_2 Surge Tank	USD	USD 1,244,724
Pipeline Control System	USD	USD 111,907
Pipeline O&M Costs		
Fixed O&M	USD/mile/year	USD 8,454

8.4 Costs and crossings with other infrastructure

Costs are strongly influenced by terrain. Typically, trenching is required to install a pipeline. However, offshore pipelines or interference with existing infrastructure or bodies of water can increase project costs quite significantly as can be ascertained from Table 19.

8.5 O&M costs

Operation and maintenance costs are not readily available. Annual O&M costs can be estimated using one or more of the following guidelines:

- Fixed O&M costs assumed to be USD 8,454 per mile-year (based on North-American pipelines, without details of terrain specified, but likely low population density) (NETL, 2013);
- 1.5% per year of initial capital costs (excluding costs for compression) (Wong, et al., 2010);
- 3% to 8% of initial installed capital cost (based on multiple pipelines, from different parts of the world) (confidential source);
- Estimated cost for pipeline pigging for a pipeline of some 10s km length is EUR 1 million (approximately 1.4 million USD) per run (as part of the percentage estimates noted above) (Wevers, 2013).

It is assumed that O&M costs cover expenditures related to electricity usage for booster compression if it exists, dehydration, control systems (SCADA), labour for inspectors and people in control rooms, overhead consumables and operating supplies as well as regular maintenance along the pipeline. Dehydration is a small cost usually associated with initial compression, which is not normally included with the pipeline cost.

8.6 Estimated and actual pipeline costs comparison

Although actual costs are the best source of information, factored cost estimates can provide helpful information, albeit with significantly reduced accuracy. Table 21 provides a summary of actual pipeline and estimated costs based on the NETL study mentioned in earlier sections.

The equations from the NETL study are a regression analysis based on a suite of pipelines in the United States. Some terrain-related costs are implicit in the formulas provided in the study but they are not specifically defined. While the formulas provide an estimate of costs, they will deviate from actual data and need to be adjusted for the relevant price level. Here these are estimated as 2011 costs using a nominal 3% annual inflation as indicated in the third column as specific indices applicable to pipelines were not available.

Table 21 - Cost comparison using actual and NETL study assumptions

Pipeline	**Actual or estimated** [a]	**Cost escalation to 2011 at 3% per year USD**	**Using NETL study formulae (2011 USD)**
Weyburn-Souris	110 million allocated for pipeline (1997)	166 million	192 million
Quest	140 million for pipeline (2012) [b, c]		45 million
Qinshui	39.35 million for pipeline capital costs (2006) [d]	48 million	45 million
ROAD	124 million for pipeline capital costs (2010)	128 million	158 million
Longannet	247 million for pipeline capital costs (2011)	247 million	233 million
Gorgon	9.1 million for pipeline capital costs (2011)	9.1 million	4.8 million

[a] Unless otherwise indicated;

[b] Costs in Canadian dollars (see footnote below), assumes parity with US dollar for simplification;

[c] Total cost of Quest is CAD 1.4 billion Canadian dollars and includes pre financial investment decision, capital and 10 year operating costs. Capital costs ratio is 80% for capture system, 10% pipeline and 10% wells; hence estimated USD 140 million for pipeline costs;

[d] For Qinshui a country factor of 0.8 was used for a China location.

8.7 CO_2 pipeline capital cost analysis and commentary

This section presents an approach to early conceptual estimating of CO_2 pipeline costs and a commentary on some of the factors that may influence the results. In addition, it includes material on estimating CO_2 compressor costs. The designs, cost estimates and source data comparisons were compared in an indicative way. Results should not be considered as an accurate estimate and should not be used for budgeting purposes.

Additional data is presented related to primary CO_2 compression, although such equipment is normally considered to be part of the cost of CO_2 delivery to the pipeline.

8.7.1 Pipeline costs

The initial costs of the CO_2 pipelines catalogued in the database are factual but not practical to those planning to construct a CO_2 pipeline today. Important factors that differentiate CO_2 pipelines from other gas pipelines when costing a CO_2 project include:

1. Relative constancy of CO_2 pipeline design. Other than differences in physical geography and to some extent local climate, the basics of long distance, high volume CO_2 pipeline design

are similar in most cases. The pipeline will be designed to move a specific volume of CO_2 with a purity exceeding 95% maintaining dense-phase (supercritical) conditions over distances ranging up to 300 km, at least initially without the need for booster pumps/compressors While this is not a given, arguably this represents the most likely design strategy for a new CO_2 pipeline (see point 2 below). The NETL study uses a nominal specified inlet pressure of 2,200 PSI (150 bar), 100 km length and outlet pressure of 1,200 psi (82 bar). For some conceptual work SNC-Lavalin has done in the past, inlet design pressures in the neighbourhood of 175 bar and outlet pressures of approximately 105 bar were used - similar pressure differentials to what is reported by NETL but starting and finishing at slightly higher pressures.

2. As noted in Section 7.2.2 above, at a conceptual level design CO_2 volumes are a function of project philosophy. For example, if the CO_2 supply and potential CO_2 storage capacity are both capable of much greater capacities than the initial project, one strategy would be to design the pipeline itself for initial project CO_2 volumes with no pipeline booster stations, but with capacity to double CO_2 flow rates in future through addition of a booster station. This is what was done with the 300km Dakota Gasification/Weyburn pipeline (Dakota Gasification Company, 2009). In the absence of additional specific information this is a reasonable way to generate conceptual CO_2 pipeline designs.
3. The nature of CO_2's depressurisation characteristics will dictate use of periodic joints of pipeline material with increased hoop strength[11].
4. The pipeline will be constructed of carbon steel, with the grade and wall thickness determined as part of the design process. Because CO_2 when expanded can reach very low temperatures the steel grade is chosen to resist brittle fracture.
5. CO_2 suppliers to the line will be obliged to deliver CO_2 at specified delivery composition, pressure and water content that will permit safe, corrosion-free operation of the line for 25 years or more. In general this means:
   a. 95% CO_2 purity. Irrespective of the CO_2 end use this provides for the ability to maintain a single (dense or supercritical) phase in the line. Within that constraint, end use, desire for common specifications for multiple CO_2 supply streams and concerns about corrosion rates will be taken into account by the designer in setting specifications.
   b. water content less than 30 lb/MMCF[12] (630 ppmv). The issue of water content is a complex one. Theory suggests that a water content for the CO_2 stream of less than about 40 lb/MMCF (840 ppmv) is sufficient to avoid corrosion issues. However, water content measurement devices are not considered to be reliable in that range and dehydration equipment is subject to upsets so a typical designer's response is to design the equipment to yield as low a water content as is technologically and

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[11] In this case Hoop Strength is defined as the ability of a pipe to resist propagation of a longitudinal rupture

[12] 1 lb/MMCF = 21 ppmv (Taylor and Francis Group, LLC, 2006)

economically practicable; in the range of 7 lbs/MMSCF (150 ppmv) and in some cases even below 2.4 lbs/MMSCF (50 ppmv).

   c. system conditions maintain the CO_2 in single dense phase throughout.

6. Concerns regarding the nature of CO_2 as a heavier-than-air asphyxiant will dictate use of periodic Emergency Shutdown (ESD) valves that would limit the volume of CO_2 released in case of a pipeline rupture.
7. Pipeline venting procedures need to include provisions for lofting and dispersing released CO_2.
8. Non-ferrous materials such as gaskets must be resistant to deterioration in the presence of CO_2, which among other things possesses very low lubricity.

The NETL study provides an analysis of 2011-base CO_2 transport and storage costs and a series of formulas to be used for conceptual CO_2 pipeline design as indicated in pervious sections. The report does not state confidence intervals for the cost estimates.

The case study also relates to SNC-Lavalin's review of internal work on CO_2 pipeline design carried out over the past 6 to 7 years. The review used conceptual estimating techniques developed internally as a cross check on the NETL report. SNC-Lavalin would evaluate its conceptual capital cost estimating techniques to also have an accuracy of +/- 50% (Class 5) at best. It would appear that in general SNC-Lavalin's internal techniques yield capital cost estimate results that are in most cases within +/-20% of those generated by NETL. As the basis of the NETL formulas is described in more detail and the details are fully public SNC-Lavalin recommends use of this report as a conceptual cost estimating basis.

Operating and Maintenance costs show greater divergence. NETL uses a fixed O&M cost of USD 8,454 per mile of pipeline, irrespective of its size and length. Some parties prefer to use a percentage of the pipeline's initial capital cost. Nominally that number can be a fixed percentage of initial installed capital cost, plus labour of another percentage of fixed O&M, but this yields O&M cost estimates between two and ten times those estimated by the NETL study, depending on the pipeline configuration of the specific case.

After considerations and analysis of design and costing aspects presented in this reference manual, a series of steps are recommended for estimating conceptual costs for a CO_2 pipeline and are presented in Table 22.

Table 22 - Summary of recommended steps to estimate conceptual costs for single non-hub onshore (95%+ pure) CO_2 pipelines without boosters.

Cost	Description
Capital	Use a standard process design program such as Pro-II or similar to estimate the physical parameters of the pipeline, bearing in mind that the inlet pressure should be in the neighbourhood of 150-170 bar and the discharge pressure should remain at or near super critical (e.g. Weyburn and Central Basin pipelines). Use the NETL 2013 study parameters to estimate base capital costs for the pipeline. Update cost escalation factors to the desired year using standard cost escalation indices such as Nelson-Farrar or other similar.
O&M	Develop annual operating and maintenance costs using the NETL suggested formula.

8.7.2 Compression and dehydration costs

Typically CO_2 raw stream separation/clean-up, compression and dehydration are carried out by the CO_2 supplier and are considered a cost of product delivery to the pipeline. Compressor costs are not included in the conceptual pipeline cost estimates discussed above. It should also be noted that in many cases, the CO_2 supplier is not the same corporate entity as the pipeline operator. In such cases, a CO_2 supply contract must be in place.

In order to generate Compression and dehydration equipment costs, another NETL report entitled **“**Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity” (NETL, 2010) was used. This study reports costs for a range of power plants equipped with CO_2 capture equipment (2007 base), including compression and dehydration. Case 14, Natural Gas Combined Cycle compression and dehydration equipment costs (pages 477-499) from the reference study were used as a base for scaling compression cases. Some assumptions used in comparisons are:

- Multi-stage centrifugal compressors constructed largely of stainless steel are the norm in high volume, high pressure CO_2 applications;
- Two compressors – no spare capacity;
- Availability 85% (used for operating costs, not for design flows);
- Scaling Power factor for compression and dehydration equipment costs: 0.6.

Some internal information on CO_2 compressor costs generated from a vendor quotation was also used as a cross check against NETL data. The NETL base case was scaled to the size of the internal study. In both cases the accuracy of the resulting estimates is assumed to be +/- 50% (Class 5) at best. Reasonable agreement was observed between the two cost estimates derived from the different estimating bases. The following Table 23 and Table 24 indicates several CO_2 projects where CO_2 compressor cost information was available and SNC-Lavalin was able to cross-check it against the cost method described. Reasonable agreement was achieved.

Table 23 - CO_2 suppliers and sources

CO_2 Pipeline	Location	Operator	CO_2 Source	Location	Operator
Rafferty	Saskatchewan, Canada	Cenovus Energy	Boundary Dam-coal-fired power generation, Unit 3	Saskatchewan, Canada	SaskEnergy
Monell	Wyoming, US	Anadarko	La Barge gas field	Wyoming, US	ExxonMobil
Beaver Creek	Wyoming, US	Devon	La Barge gas field	Wyoming, US	ExxonMobil
Snøhvit	Barents Sea (Norway)	Statoil	LNG production facility	Snøhvit	Statoil
Lacq	Rousse, France	Total	Lacq industrial Pilot Plant	France	Total
Decatur	Decatur	Archer Daniels Midland	Ethanol fermentation plant	Decatur	Archer Daniels Midland

Table 24 - Base Case: Compressor and Dehydration costs

Location: United States Midwest, Scaled NETL data	
CO_2 design flow (2 compressors)	1.6 Mton/y
Compressor power consumption	15.2 MW
Compressor outlet Pressure:	153 bar
Compressor and Dehydration Equipment cost (2007 USD)	USD 14,251,000
Labour, Head Office and fee	USD 4,471,000
Engineering, Head Office & Fees	USD 1,604,000
Contingency	USD 4,065,000
Total	USD *24,391,000*
Gross up to Total Overnight Cost	USD 5,391,000
Total Overnight Cost	**USD 29,782,000**

9 CO_2 pipeline permitting

9.1 Regulatory requirements

While the major effort regarding permitting occurs in later stages of design, it is worth undertaking a preliminary investigation in the Project Definition phase to determine if the existing regulatory regime is sufficiently comprehensive to cover CO_2 pipeline activities. If it is not, there may be a need to begin work at this stage with the appropriate agencies to put the regulations in place. In any case initial development of a comprehensive Permit Ledger listing all required regulatory approvals and timelines for obtaining them should happen early in the project development process.

9.2 Public consultation

Regulations exist to limit pipeline / human interactions. Generally they do not relate to CO_2 pipelines specifically.

Health issues related to exposure to high concentrations of CO_2 are well-known. Gaseous CO_2 is an asphyxiant in elevated quantities if a leak was to occur and a person was to be exposed to concentrated CO_2. Concentrations of 10% by volume in air or more can produce unconsciousness or death. Lower concentrations may cause:

- headache;
- sweating;
- rapid breathing;
- increased heartbeat;
- shortness of breath;
- dizziness;
- mental depression;
- visual disturbances and shaking.

Skin, eye, or mouth contact with dry ice or compressed CO_2 can cause tissue damage, burns or frostbite.

Technically such issues are handled through the physical design of the CO_2 pipeline in the same way they are dealt with for other gas pipelines. In Canada, CSA standard Z662 contains a section on CO_2 pipeline design, as does ASME B31.4 in the United States. See Chapter 8 for a discussion on how these issues are translated into capital cost estimates.

Irrespective of technical design considerations, from a public interest standpoint CO_2 is different from natural gas. Natural gas and its risks are better understood or accepted by the public, probably because of familiarity with and personal beneficial use of the product; e.g. for domestic heating. Moreover, small scale natural gas leaks are common in most urban areas and their (occasionally fatal) consequences are extensively reported in the press. On the other hand, CO_2 in pipeline quantities is not beneficially used on a household level and its effects in the case of a possible leak are less understood. Therefore it is natural for public opinion to focus on risks and unknowns rather than the more obvious positives (CO_2 is not explosive, not found in every neighbourhood).

In this situation planning for extensive and effective public consultation is essential and may include:

- Assessment of the possibility that public hearings may be required as part of the regulatory process;
- Early public engagement to avoid surprises on the part of either the public or the proponents.

9.3 Permit application

Specific steps and requirements for the permit application process vary from country to country. Table 25 presents highlights for different parts of the world.

Table 25 - Overview key elements of permitting for different parts of the world

Region	Source
North America	All pipelines require permits or permissions from regulatory authorities. In the United States, the Bureau of Land Management (BLM), a Department of the Interior agency, regulates the use of public or federal lands. Typically, the BLM issues a notice of scoping to interested parties or stakeholders followed by an Environmental Impact Statement (EIS) and in recent years an Environmental Assessment (EA). The United States is unique in that regulatory approvals must be sought from federal, state and local levels. Permitting can be an exhaustive and comprehensive exercise. As an example, permits for the Dakota Gasification CO_2 pipeline included the following on the United States side (AECOM, 2012): • North Dakota Public Service Commission Certificate of Corridor Compatibility and the Route Permit; • US Army Corps of Engineers Section 404 permits (Letter of Permission and Nationwide);

Region	Source
	- US Forest Service Special Use Permit (with EA documentation); - North Dakota State Water Commission Permit; - International Boundary Commission Permit; and - Presidential (US State Department) Permit. In addition, a permit application (Section 52) was submitted and approved by Canada's National Energy Board (NEB) and a Certificate of Public Convenience and Necessity was issued for the Canada segment of the route (Souris Valley Pipeline Ltd.). In Canada, the NEB regulates pipelines that cross national and/or provincial borders. Canadian intra-province permitting procedures are generally inclusive of CO_2 pipelines, either implicitly or explicitly.
Europe	In Europe permitting rules for CO_2 pipelines differ between countries. Typically, the following permits and steps are required: Onshore: - Water permit from the Ministry of Infrastructure and the Environment (federal); - Integration plan from the Ministry of Infrastructure and the Environment & Ministry of Economic Affairs, Agriculture and Innovation (federal). Offshore: - Water permit from the Ministry of Infrastructure and the Environment (federal).
Other parts of the World	In Victoria (Australia), onshore pipeline approvals fall under the Pipelines Act 1967, the Pipelines Regulations 2000 and Gas Safety Act 1997 (Element Energy, 2010). The developer is required to obtain: 1. A permit to own and use a pipeline; 2. A license to construct and operate a pipeline; 3. A construction and environmental safety case (approved by the Minerals and Petroleum Regulation Branch); 4. A safety case for operation and maintenance (approved by the Office of Gas Safety); 5. A consent to operate. In less developed countries it is imperative that a thorough legal analysis of the permitting system for pipelines and specifically CO_2 pipelines be undertaken, the earlier in the project the better. For example, a recent study undertaken by the Asian Development Bank on behalf of the Institute (TA-7575 (REG): Determining the Potential for Carbon Capture and Storage in Southeast Asia, 2012) covered the Philippines, Vietnam, Indonesia and Thailand and indicated wide differences in permitting requirements and ministries having jurisdiction, from relatively clear responsibilities to conflicting jurisdictions to no regulations at all for any kind of pipeline.

10 CO_2 pipeline FEED studies and Design

10.1 Scope and contents for CO_2 pipeline studies

FEED (Front End Engineering Design) studies are another step in moving any project from concept to reality. Generically they are carried out for several purposes, none of which distinguish CO_2 pipelines from any other project:

1. Increase the confidence in the cost estimates as an input to economic feasibility deliberations;
2. Through additional engineering study, confirm technical feasibility of the project;
3. Provide sufficiently detailed analysis to be used for initial public discussions;
4. Increase the level of detail available for discussions with potential feedstock suppliers and product purchasers.

These may be done internally or externally depending on staff availability and technical knowledge the staff possesses. They have the overall objective of bringing the capital and operating cost estimates to a confidence interval of +/- 30% or better. Some portion of detailed engineering is usually necessary to reach such a level of confidence in the cost estimate that is required for final project approval.

The contents of a FEED study for a CO_2 pipeline, while theoretically independent of both CO_2 sources and uses, is like any pipeline project highly dependent on the requirements of both suppliers and users of the material shipped. A typical study may contain information as summarised in Table 26. The information presented here is an amalgamation of information found in several FEED and feasibility studies used to research and elaborate this reference manual and are suggested as possible content to develop a study.

Table 26 - Feasibility study generic information

Item	Description
Scope	• Introduction • Objectives
Project description	• Site selection • Route • Terrain characteristics • Climatic conditions
Design	• Standards used • Design scenarios • Assumptions • Simulations • Special cases • Pipeline hydraulic profiles • Compression and pump design
Detailed technical information	• Material selection • CO_2 source • CO_2 destination • Compression requirements • CO_2 feed specifications, driven by pipeline technical considerations and by purchasers' needs, including purity, contaminant limitations, maximum water content and dehydration requirements • Mechanical considerations
Cost estimates	• Assumptions • Currency used • List of cost items • Vendor quotes for materials • Disclaimer about cost estimates
Economics	• Funding mechanisms • Funding sources • Indicators
Environmental issues	• CO_2 sequestration calculations (normally these would not be part of a pipeline project, but in the case of CO_2 they are essential to the entire CCS package and therefore to the pipeline portion) • Identification of Health and safety risks and proposed mitigations • Preliminary operating hazard analysis (HAZOP) • Brief environmental assessment
Conclusions	• Summary of the FEED documents • Recommendations for project implementation

10.2 Input and external information requirements

The FEED study contains an analysis of the CCS project from a technical perspective. In order to perform this analysis technical, commercial, regulatory and spatial information is necessary. Table 27 is a summary of key information requirements.

Table 27 - Key data input and outputs

Key input	Description	Output
Technical	Technical information is necessary to carry out detailed analysis of flow rates and pressures. Key data include: • Gas volume and composition (assumed primarily to be carbon dioxide and trace gases such as methane, H_2S, water vapour)(at this stage of design the physical properties of the CO_2 stream are sufficiently defined by the database in the process simulation model); driven primarily by the needs of the user but constrained by the requirements for safe and cost-effective pipeline transportation; • Nominal diameter and material of the pipeline.	• Flow rates; • Power requirements; • Design pressure and Pressure range during pipeline operations; • Pipeline simulations.
Commercial	Commercial information provides the yardstick against which the economics of the project is judged. Much depends on the proposed commercial arrangements; e.g. who owns the CO_2 in transit, who physically buys and sells the CO_2. Such matters are beyond the scope of this study.	• Economic analysis
Regulatory	Regulatory information defines the maximum permissible emissions. For example, this information is necessary to determine if environmental controls are necessary.	• Carbon offsets factored in as revenues • Environmental control
Spatial	Spatial information defines the route. This information is necessary to determine right-of-ways, actual length, elevation changes, methods of construction for challenging portions of the line (river crossings, etc.)	• Length and routing for pipeline; possible alternates, identification of key challenges in routing; • Material costs(also driven by safety, public perception and risk management factors).

Examples FEED studies for CO_2 pipeline projects

For several European CO_2 pipeline projects, FEED-studies are available online (see list below). As FEED-studies contain a lot of information on a wide range of subjects, these were a useful sources for this study. Key information from these FEED studies has contributed to the database that accompanied this Reference Manual:

- Jänschwalde
  http://www.globalccsinstitute.com/publications/feed-study-co2-transport-pipeline-ccs-demonstration-project-j%C3%A4nschwalde
- Kingsnorth
  http://webarchive.nationalarchives.gov.uk/20121217150422/http://decc.gov.uk/en/content/cms/emissions/ccs/ukccscomm_prog/feed/e_on_feed_/e_on_feed_.aspx
- Longannet
  http://webarchive.nationalarchives.gov.uk/20121217150422/http://decc.gov.uk/en/content/cms/emissions/ccs/ukccscomm_prog/feed/scottish_power/scottish_power.aspx
- ROAD
  http://www.globalccsinstitute.com/publications/road-ccs-project-non-confidential-feed-study-report

10.3 Summary topics specific to design of CO_2 pipelines

The following table presents a comparison of the effects of key differences in characteristics of CO_2 on pipeline design, contrasting these with natural gas pipelines. Please note that this table is intended to be a non-technical overview of similarities and differences. It is neither comprehensive nor does it contain all the technical implications for each characteristic.

Table 28 – Design characteristics CO_2 pipelines versus natural gas.

Characteristic	Natural Gas at typical pipeline conditions: (methane with small amounts of impurities; usually less than 2% inerts)	CO_2 at typical pipeline conditions (CO_2 with less than 5% impurities)
Flammability (Explosions)	Yes. Imperative to avoid explosive mixtures of natural gas and air in the pipeline at all times. Influences start-up procedures.	No. Confined mixtures of air and CO_2 pose no explosion issues.
Flammability (Fires)	Releases of natural gas can result in large fireballs.	Not combustible. No combustion issues with releases of CO_2, intentional or otherwise.
Corrosivity in the presence of water	Not a serious problem for corrosion as no compounds are formed. Common use of corrosion inhibitors.	CO_2 plus water = Carbonic Acid. Extremely corrosive, especially in the presence of water. Requires either measures to keep the gas

Characteristic	Natural Gas at typical pipeline conditions: (methane with small amounts of impurities; usually less than 2% inerts)	CO_2 at typical pipeline conditions (CO_2 with less than 5% impurities)
		extremely dry or stainless steel pipe and equipment. Influences commissioning and start-up procedures.
Depressuring characteristics (Joule Thompson effect)	Like any gas, natural gas cools as it depressures, but not unusually so in the range of pressures and temperatures usually experienced in natural gas pipeline systems.	CO_2 cools greatly as it depressures in pipeline conditions, creating extremely low temperatures that threaten to cause brittle failure of steel pipe. Influences start-up and shutdown procedures.
Depressuring characteristics (rate of depressurization)	A longitudinal rupture of a pipeline will be self – limiting, as the release of the gas through the initial failure quickly depressures the line to the point where the crack cannot propagate	A longitudinal rupture of a pipeline could propagate for long distances because the CO_2 depressures slowly. Pipeline must be designed with periodic crack arrestors (commonly, joints of pipe with greater wall thickness) to stop crack propagation.
Presence of more than one phase at pipeline conditions (Multiple phases cannot be tolerated by pumps or compressors.)	No multiphase issues (But see Hydrates, below). Natural gas is a gas at all expected pipeline conditions. The absence of issues with multi phases gives the natural gas pipeline designer a much wider range of acceptable design conditions to work with.	Yes. CO_2 can be a liquid or a gas at common pipeline conditions. Typical response is to operate the entire pipeline at supercritical pressures, which avoids the possibility of liquid CO_2 forming. The need to maintain CO_2 pipeline pressures above the critical point results in a much smaller range of acceptable design conditions, at pressures that are higher than for typical Natural Gas pipelines.
Asphyxiant; heavier than air	Yes. A cloud of pure natural gas could accumulate in low lying areas, will contain no oxygen and could asphyxiate people or animals. Emergency shutdown valves installed to limit size of potential releases in case of pipeline failure.	Yes. A cloud of pure CO_2 gas could accumulate in low lying areas, will contain no oxygen and could asphyxiate people or animals. Emergency shutdown valves installed to limit size of potential releases in case of pipeline failure. Intentional releases of CO_2 (routine venting for pipeline depressuring) may require that the CO_2 be heated by burning natural gas with it to decrease its density below that of air so it will loft and disperse.
Impurities (1)	Common impurities (H_2S, SO_2, O_2, N_2, CO) mix entirely as gases with natural gas and do not create operational problems.	Same common impurities. If the impurity content of the CO_2 is above 5% there is a likelihood that two phases (gas and liquid) will form; intolerable for rotating equipment.
Impurities (2)	Some common impurities (H_2S, SO_2, CO) are toxic and their presence requires increased pipeline design stringency	Same re. common impurities. As noted in Corrosivity, above, water content must be maintained at an extremely low level.
Hydrate Formation (solid material composed of gas and water)	Possible. Necessary to maintain low water contents or face addition of hydrate inhibiting chemicals.	Possible. Meeting the water content specification to avoid corrosion issues should also avoid hydrate formation.

10.4 Design standards

The design of CO_2 pipelines is governed by safety and design criteria standards. Generally one or more of the standards listed below are applied in the design process. Deviations if any must be justified to regulatory authorities.

The most commonly used standards in North America include Canada – CAN/CSA (Canadian Standards Association) Z662 and US – CFR (Code of Federal Regulations) 49 part 192 and 195, Natural Resource Code Chapter 117 and ASME B 31.4 pipeline design standards.

CAN/CSA Z662 (Canadian Standards Association, 2012) classifies CO_2 pipelines as high vapour pressure lines (HVP) and all design is governed by this classification including:

- spacing of valves;
- threading;
- depth of lay;
- pressure-control systems;
- pipe body notch toughness;
- type of pressure test medium among others.

The CFR 49 Part 195 is a set of regulations that covers 8 major areas divided into Subparts (US Government Printing Office, 2013) including:

- Subpart A—General;
- Subpart B—Annual, Accident, and Safety-Related Condition Reporting;
- Subpart C—Design Requirements;
- Subpart D—Construction;
- Subpart E—Pressure Testing;
- Subpart F—Operation and Maintenance;
- Subpart G—Qualification of Pipeline Personnel;
- Subpart H—Corrosion Control;
- Appendix A to Part 195—Delineation Between Federal and State Jurisdiction—Statement of Agency Policy and Interpretation;
- Appendix B to Part 195—Risk-Based Alternative to Pressure Testing Older Hazardous Liquid and Carbon Dioxide Pipelines;
- Appendix C to Part 195—Guidance for Implementation of an Integrity Management Program.

By comparison, in the United States CO_2 pipelines are regulated as “Hazardous Materials and CO_2”, giving them a more stringent inspection requirement than for crude oil, which is not included in the category. Overall, however, it is unclear as to whether such differences of distinction result in major differences in either design or operation of CO_2 pipelines from one country to the next.

A commonly used standard in Europe is the Recommended Practice DNV-RP-J202, Design and Operation of CO_2 Pipelines (Det Norske Veritas, 2010). Key topics addressed by this standard include:

- Specific properties of CO_2;
- Safety philosophy;
- Concept development and design premises;
- Materials and pipeline design;
- Construction;
- Operation;
- Re-qualification of existing pipelines to CO_2 pipelines.

Another commonly used standard is EN 14161: Petroleum and natural gas industries – Pipeline transportation systems. This International Standard includes requirements and recommendations for the design, materials, construction, testing, operation, maintenance and abandonment of pipeline systems used for transportation in the petroleum and natural gas industries. The standard applies for both onshore and offshore operation (ANSI, 2013).

Besides international and European standards, most European countries have their specific national standards:

- United Kingdom: Pipelines Safety Regulations 1996 (PSR);
- The Netherlands: NEN3650;
- Norway: NORSOK standards (e.g. L-001, L-002 and L-004).

10.5 Definition of key design parameters

Key design parameters are generally related to engineering aspects of pipelines and the designs will comply with (or even exceed) established design standards such as CAN/CSA Z622 or US CFR 49 part 195. Typical key design parameters include:

- pipeline length;
- assumed nominal diameter and pipeline wall thicknesses;
- routing and topography;
- expected throughput or flow rates;
- expected operating pressures;
- fluid properties such as gas composition, water content;
- ground temperature and thermal conductivity;
- coating or insulation.

These parameters are entered into proprietary or commercially available software such as Pro-II or similar to begin design simulations. Several iterations are needed to finalise the pipeline design. All parameters are expected to include safety factors; some prescribed by pipeline design standards and some introduced by the designers to ensure the finished pipeline perform up to its nominal design capacity.

11 Construction of CO_2 pipelines

11.1 Construction planning and timelines

While not particular to CO_2 pipelines and relevant to most pipeline projects, this section touches on some key topics in the construction phase. Planning and actual construction involve numerous steps from initial conceptualisation to final commissioning. The acquisition of necessary permits and securing of engineering, procurement and construction contractors in order to implement the project in a timely manner is a key step. Permitting and land acquisition for the right-of-way may be more time consuming than the actual construction of the pipeline.

The construction of a CO_2 pipeline involves several milestones or activities. While the discussion here focuses on onshore pipelines the principles are comparable for offshore pipelines. After the route has been selected, it is mapped and access roads for material delivery and work force access that need to be built are identified. Typically this will require clearing vegetation and constructing a road parallel to the actual pipeline right-of-way. The access road will consist of two main temporary lanes: a work lane and a travel or transit lane. The pipeline's right-of-way must be cleared and vegetation and topsoil removed and stored preferably on the side for backfilling and reclamation. At this time, grading the right-of-way will occur. None of this differs from the requirements for construction of any pipeline.

Once the clearing has been completed, a trench is excavated where the pipeline will be placed. The trench itself is excavated to a depth of minimum depth-of-lay plus pipeline diameter, which will vary depending on design considerations and throughput. Typically, the pipeline is buried under a layer of soil of minimum 1.2 meters. In the United States the Code of Federal Regulation (CFR) Section 195.248 prescribes a minimum 4 feet (1.2 metres) pipeline burial depth – without differentiation for CO_2 specifically. The trench should be shored properly to prevent the side slopes from failing. The bottom of the trench may require additional conditioning to accommodate the pipeline. The pipeline may also require bevelling and bending to suit the contours of the land and, finally, prepared for welding (Cenovus, N/A).

Pipelines may cross rivers or existing infrastructure. In such cases rather than trenching, drilling under the existing river crossing or infrastructure may be required. Pipeline wall thickness is greater at these locations to protect the pipeline from bearing loads and to reduce an already-small risk of rupture in areas of high consequence or difficulty of repair.

Once sections of the pipeline have been stringed (placed one end next to the other), the welding process begins. Sections are welded as per design recommendations and inspections are made to ensure that the pipeline sections have been properly welded. Figure 16 depicts a typical stringing and welding operation along a right-of-way. Welding inspections may be visual or using equipment such as x-rays to detect abnormalities or deficiencies. While the welding procedures may differ for CO_2 pipelines, the overall procedure is identical for all pipelines.

Figure 16 - Stringing and welding of pipeline (Shell, 2010)

Figure 17 - Placement of Cortez CO_2 pipeline section (Willbros, 2013)

Typically, the pipeline is delivered, stringed and assembled along the area adjacent to the trench and cranes lower the pipeline section into the trench. Pipeline delivery includes external coating and other protective measures to protect the pipeline. Figure 17 depicts the placement of a pipeline section for the Cortez CO_2 pipeline circa 1983.

The final step involves backfilling excavated material into the trench. Stored topsoil from initial stages of the project is used to re-vegetate and reclaim the right-of-way. Signage is placed and an inspection of the right-of-way is performed to assess inconformity or safety issues.

Figure 18 depicts a typical cross section of pipeline construction where the complete right-of-way is taken advantage. The whole right-of-way allows for the following:

- Storage of stripped material on both side of the right-of-way at the outermost sides;
- Storage of soil on the side of the trench opposite the transit lanes;
- Storage of pipeline sections on the other side of the trench next to the transit lanes;
- Transit lanes for work lane and travel vehicles.

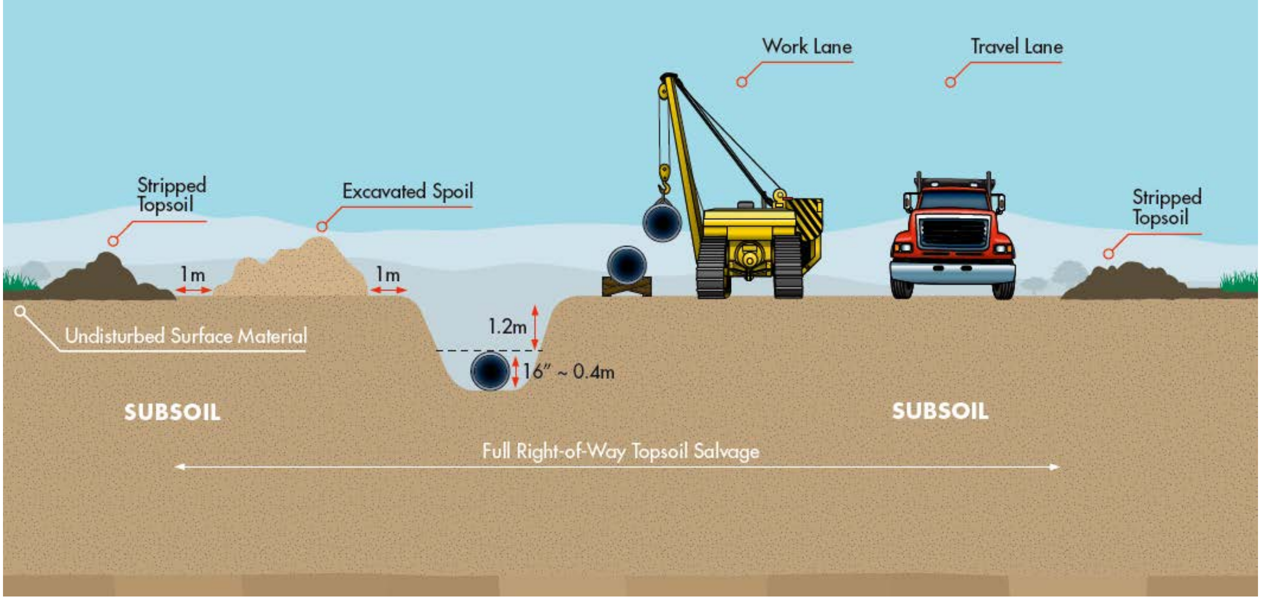

Figure 18 - Typical cross section of CO_2 right-of-way during pipeline construction (Shell, 2010)

11.2 Commissioning and testing

Once a pipeline has been built, regulations require testing pipeline integrity. Typically water is used to test the pipeline at pressures above the design Maximum Allowable Operating Pressure (MAOP) and is commonly referred to as hydrostatic testing. Other mediums include air. Table 29 summarises some of the commissioning and testing characteristics of CO_2 pipeline for the Weyburn CO_2 (Dakota Gasification Company, 2013) pipeline located in the United States/Canada and the Monell CO_2 pipeline (Buys and Associates Inc., 2003) located in Wyoming.

Table 29 - Hydrostatic testing pressures for selected CO_2 pipelines

Pipeline	Medium	Maximum allowable operating Pressure (MAOP)	Testing pressure (TP)	MAOP/TP
Weyburn- Souris Valley	Water	14” pipeline 2700 psig 12” pipeline 2964 psig	14” pipeline 3375 psig 12” pipeline 3705 psig	1.25
Monell	Water	6” pipeline 2500 psig	6” pipeline 3125 psig	1.25

The test pressure throughout the part of the system being tested must be done for a minimum of 4 continuous hours at a pressure equal to 125% or more of the maximum operating pressure (MOP) (US Government Printing Office, 2013). In the case of a pipeline that is not visually inspected for leakage during the test, for at least an additional 4 continuous hours at a pressure equal to 110 %, or more, of the maximum operating pressure.

Carbon dioxide pipelines that have been hydrostatically pressure tested are cleaned and air dried upon completion of testing to prevent corrosion that can otherwise occur on start-up of the system (Canadian Standards Association, 2012). For CO_2 pipelines, the presence of residual water following a hydro test could contribute to rapid pipeline corrosion and potential premature failure, so dry-out procedures must be carefully designed and followed. Several methods for effective drying of a pipeline are mentioned in literature, most of which would be applicable to CO_2 (McAllister, 2011):

- Very dry air;
- Methanol;
- Inert gas such as nitrogen;
- Internal sand blasting;
- Vacuum.

When the pipeline is first filled and on subsequent re-pressuring conditions must be carefully controlled to prevent expanding high pressure CO_2 from either forming a second (liquid or solid) phase or reaching temperatures that are below the allowable design limit, to avoid brittle fracture of the pipe. While these factors increase the complexity of CO_2 pipeline commissioning and start-up they are well understood and operating procedures exist to avoid related issues.

12 CO_2 Pipeline operation, inspection and maintenance

12.1 Operational requirements / constraints of CO_2 sources and users

Typically the CO_2 pipeline will be the most operationally reliable of the components of a CCS project, so the pipeline can usually accommodate the needs of both supplier and user. However, unlike the natural gas industry, the reciprocal is not the case. CO_2 pipelines and their operation have a unique place in the overall CCS scheme; quite different from that found in the natural gas production and utilisation industry. The cost of constructing and operating CO_2 capture equipment is very large, and the requirements of the user, particularly in an EOR operation, can directly and profoundly affect the unit cost of the CO_2 transported, as explained below.

Starting with the CO_2 sink, in this example an EOR operation, the user initially requires a large volume of CO_2 to get the EOR process started. Once the additional oil begins to flow, some CO_2 is produced with it. To maintain the same volume of injected CO_2, then, the user can recycle the produced CO_2 and reduce their purchase of CO_2 from the pipeline. While this may be satisfactory for the oil producer, it can be economically fatal for the pipeline and the CO_2 capturer, as sales volumes and related revenues diminish and uncaptured CO_2 emissions from the source plant increase and likely incur increased CO_2 emissions penalties. Drastically increased shipping tariffs by the pipeline owner will likewise be economically unacceptable to the producer and user of the CO_2.

Therefore, in a typical CCS project both the CO_2 producer and pipeline owner require consistent high volumes of CO_2 over the expected life of the project.

Absent other opportunities to sell CO_2, then, the EOR project should ideally be designed so that it continually expands to accommodate both a constant supply of CO_2 from the primary source production and all of the produced CO_2 recycle. This strong influence on the design of the CO_2 user's project by the pipeline and primary CO_2 source sets the overall system design apart from typical natural gas systems. These considerations make it essential that designers for all three components of the CCS project collaborate closely from the very beginning to ensure that the economic objectives of all three are met.

The situation in a CO_2 storage project tends to be much simpler, as the incentives of both the CO_2 producer and transporter are aligned towards full constant CO_2 shipments. Nevertheless, also here CO_2 supply may be intermittent for operational reasons at the source. For example, a power plant can decide to shut-off the capture unit when electricity prices are high. This will influence the operation of the pipeline. Overall, the net effect is that the needs of the CO_2 producer, transporter and user are often much more dependent on each other than for natural gas systems. This is particularly true with a single large CO_2 producer, dedicated pipeline and single user, a situation that is much more likely to occur with CO_2 than with natural gas.

12.2 Planning for pipeline operation

As a regulatory requirement, each operator must prepare and follow for each pipeline system a manual of written procedures for conducting normal operations and maintenance activities and handling abnormal operations and emergencies. For example, in the United States this manual should be reviewed at intervals not exceeding 15 months, but at least once each calendar year, and appropriate changes made as necessary to ensure that the manual is effective (US Government Printing Office, 2013). The manual is typically prepared before initial operations of a pipeline system commence, and appropriate parts are kept at locations where operations and maintenance activities are conducted. The regulatory body requires the operator to amend its plans and procedures as necessary to provide a reasonable level of safety. Detailed requirements may differ slightly in other jurisdictions but the overall objective remains the same.

The maintenance and normal operations manual includes procedures for the following to provide safety during maintenance and normal operations:

- Making construction records, maps and operating history available as necessary for safe operation and maintenance;
- Gathering of data needed for reporting accidents in a timely and effective manner;
- Operating, maintaining and repairing the pipeline system in accordance with requirements;
- Determining which pipeline facilities are located in areas that would require an immediate response by the operator to prevent hazards to the public if the facilities failed or malfunctioned;
- Analysing pipeline accidents to determine their causes;
- Minimising the potential for identified hazards and the possibility of recurrence of accidents;
- Starting up and shutting down any part of the pipeline system in a manner designed to assure operation;
- Minimising the likelihood of accidental ignition of vapours in areas near facilities;
- Establishing and maintaining liaison with fire, police and other appropriate public officials to learn the responsibility and resources of each government organisation that may respond to a hazardous liquid or carbon dioxide pipeline emergency and acquaint the officials with the operator's ability in responding to a hazardous liquid or carbon dioxide pipeline emergency and means of communication.

Specific operations and maintenance requirements are included in legislation and regulations, such as:

- United States: CFR 49 part 195 and -CSA Z662 section 10;
- United Kingdom: Health and Safety at Work etc. Act 1974 (sections 2 and 3), Pipelines Safety Regulations 1996 (PSR) (Part II, section 5);
- Norway: NORSOK O-DP-001 – Operational principles;
- The Netherlands: NTA8000 – Risk Management System.

Furthermore, section 12.4 of this Reference manual presents more details on the operation and maintenance requirement. Moreover, sections 12.5 and 12.6 present examples of the scope of operation and maintenance activities.

Note that in the United Kingdom and the Netherlands CO_2 is not regarded as a dangerous substance. However, in the Netherlands, CO_2 will be included in the BEVB (Directive on External Safety Pipelines) as per 2014. With this the pipeline operator is obligated to implement safety management system, in which also maintenance and calamities are included.

Procedures specific to CO_2 involve extra care to avoid introducing excess water to the pipeline and measures that avoid rapid depressurisation of the CO_2 and resulting extremely cold temperatures as the CO_2 enters and fills the line.

12.3 Consideration of key operational parameters

During the process of capture, transport and storage of CO_2, the CO_2 stream is monitored continuously on several parameters, among which:

- Moisture content;
- Composition of CO_2 stream;
- Compressor operation;
- Pipeline pressure;
- Temperature;

Pressure, temperature, water content and throughput are the key operational parameters to monitor. Pressure drops will indicate the presence or appearance of leaks. Typically, a SCADA (Supervisory Control And Data Acquisition) system is used to monitor and control the operation of the pipeline. When a deviation in one of the parameters is detected, the system will raise an alarm and if needed stop the operation. As with other gas pipelines very small leaks may be hard to detect. Use of an odorant in the CO_2 stream may be required to allow very small leaks to be more readily detected via physical checks of the line.

Limited data was available on the control systems that are used in CO_2 pipeline operations. As a positive exception, for the Weyburn project specific information was available, which is discussed in more detail in this section. In this project that is operated by the Dakota Gasification Company, the operators constantly monitors for leaks using a Leak Detection System or LDS (Dakota Gasification Company, 2009). The LDS receives data every 5 seconds and is displayed in a computer screen. The LDS can determine the size and location of a potential the leak based on proprietary software. If potential leaks are detected, the pipeline section where the leak is suspected is inspected and if necessary a shutdown of that section is performed using isolation valves (NEB, 1998). This ensures safe operating conditions. LDS and SCADA system are similar in that real-time data is acquired and displayed on a computer screen.

Also, pipelines may implement comprehensive inspection programs such as the one used by the Dakota Gasification Company's CO_2 pipeline that traverses North Dakota into Canada. They fall into two main categories: preventative maintenance and patrols (Dakota Gasification Company, 2013). Included are:

- Aerial patrols, 26 times per year;
- Cathodic protection survey, once each calendar year;
- Emergency systems check once per year;
- Internal inspection of the pipeline using an electronic tool (intelligent pig run), every five years or more frequently if necessary;
- Inspection and testing of overpressure safety devices, once each calendar year;
- Population density survey, once every two years;
- Public awareness and damage prevention program, once each calendar year;
- Cathodic protection rectifier maintenance, 6 times per calendar year;
- Valve maintenance and inspection, twice per calendar year;
- Right-of-way inspection, 26 times per calendar year.

12.4 Defining the inspection and maintenance program

In general, the ultimate aim of an Operating and Maintenance (O&M) program is to assure safety at all times. Additionally an O&M program should provide:

- Environmental protection;
- Economic efficiency and respect for the rights of those that may be affected.

A mass balance for product custody transfer is also performed using meters of various technologies at all pipeline inlet and outlet points so that contract obligations are met (McCollough & Stiles, 1987). The mass balance is also useful in detecting large leaks but is usually not sensitive enough to detect small leaks.

From a regulatory perspective the operation of a CO_2 pipeline requires an inspection and maintenance program to assure safe operations. For example, Subpart F—Operation and Maintenance of the CFR 49 Part 195 sets out a description of inspection and maintenance requirements (US Government Printing Office, 2013). Of importance is the need for the operator to have prepared and followed for each pipeline system a manual of written procedures for conducting normal operations and maintenance activities and handling abnormal operations and emergencies. This manual is to be reviewed at intervals not exceeding 15 months, but at least once each calendar year, and appropriate changes made as necessary to insure that the manual is effective. This manual is to be prepared before commencement of initial operations of the pipeline system, and appropriate parts are to be kept at locations where operations and maintenance activities are conducted.

In Canada, routine Operating and Maintenance (O&M) activities are evaluated by the National Energy Board (NEB) as part of the original application for the construction and operation of a pipeline so companies are not required to apply for additional approval to undertake most O&M activities (NEB, 2013). The National energy Act was amended in 2012 to provide further guidance on O&M activities. The goal of the Operations and Maintenance Activities on Pipelines Regulated Under the National Energy Board Act: Requirements and Guidance Notes (O&M Guidelines) is to provide all parties with greater clarity about how O&M activities on pipelines (including processing plants) under the National Energy Board Act (NEB Act) will be regulated.

For European countries, regulations on operation and maintenance are typically determined on the federal level. As an example, in the Netherlands, the “Inspectie Leefomgeving en Transport” (ILT) verifies the management system on an annual basis and check output randomly. The checks include interviews with key-persons and analysis of the relevant documents (Inspectie leefomgeving en transport, 2013).

12.5 Inspection activities for CO_2 Pipelines

Most of the CO_2 pipelines are buried underground, making inspection of the pipeline more difficult. One of the reasons for burying the pipeline is to minimise external influences. Still, it is possible that with building activities such as digging a pipeline is impacted. In most countries, building activities are prohibited within a certain range of the corridor (typically 5 meters from the pipeline). Still, every week the pipeline corridors are visually inspected for construction activities that may have taken place near the corridor. These so-called Right-of-Way inspections are performed visually by foot, car, or in some cases, helicopter (refer textbox on the following page).

The inside of the pipeline is inspected using so-called pig runs. A “pig” is a tool that can be used to clean the pipeline, measure wall thickness or detecting leakage and corrosion (see Figure 19). Most pipeline operators use pig runs to inspect the inside of their pipelines. Pig runs are costly, with estimated cost are of the order of magnitude of EUR 1 million per run for pipelines with a length in the range of 25 to 270 km (Read, 2013; Wevers, 2013). Typically, this operation is done once every two to five years with the interval determined by the findings of successive runs. The travel of a pig through a typical hydrocarbon pipeline is greatly eased by the lubricity of the fluid being transported. CO_2 possesses low lubricity, presenting challenges to the pig supplier and the CO_2 pipeline operator in preventing the pigs from getting stuck and/or damaging the pipeline or the pig itself.

***Case-studies Pipeline inspections*[13]**

The pipeline is externally inspected on a regular basis to prevent damage from outside. Depending on the length and the accessibility of the pipeline, different methods are being used for inspection (or proposed in case of pipelines that are not yet operational or that have been cancelled):

- Visual inspection by car and foot (OCAP and Barendrecht);
- Remotely Operated Vehicle patrols (Longannet);
- Aerial patrols, 26 times per year (Central Basin, Canyon Reef Carriers, Cortez, Sheep Mountain, Weyburn, Slaughter and Choctaw);
- For offshore pipelines, visual inspections are possible using submarines. As this is expensive, this will not be done at a regular basis. Same as for onshore pipelines, pipeline pigging will be done (typically once every 5-10 years) to inspect the pipeline from the inside (Read, 2013).

Figure 19 – An example of a (non-intelligent) pig in a pipeline

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[13] More information on these projects can be found in the database.

12.6 Maintenance activities for pipeline and equipment

Maintenance of the pipeline is complex as large parts will be buried under soil and in some of the projects, on the seafloor. As described in the previous sections, pipelines and pipeline corridors are visually inspected on a regular basis. Furthermore, once every 1 to 5 years a pig run will be carried out to inspect the inside of the pipeline. Based on the results of these inspections, maintenance will be performed.

Besides the pipeline, auxiliary equipment is also checked on a regular basis, including compressors, dehydration units, valves, the cathodic protection system, monitoring and emergency systems. The table below (Table 30) shows examples of equipment inspections and their frequency. As we had only little information available, we could only include two projects here:

Table 30 – Maintenance of equipment for 2 Kingsnorth and Weyburn projects where specific information was available.

Equipment	Frequency	Project
Compressor	Annual	Kingsnorth
Cathodic protection system	Annual	
Cathodic protection system	Annual	Weyburn
Emergency system	Annual	
Overpressure safety devices	Annual	
Rectifier maintenance	Bi-monthly	
Valve maintenance	Half yearly	

13 CO_2 Pipeline decommissioning and abandonment

Well-constructed and maintained pipelines have very long useful lives; considerably in excess of the individual projects that supply them or that they serve. Corrosion "hot spots" may be identified, dug up and replaced, as may valves, and other equipment, but the pipeline endures as an entity. Given careful attention to corrosion issues associated with water content, CO_2 pipelines can be expected to perform as well as or better than other pipelines. The usual reason for a pipeline to be decommissioned is that it no longer has a commercial use. As the CO_2 pipeline industry is relatively young (40 years) and increasing oil prices continue to drive new EOR projects there has been very little large scale decommissioning activity.

Pipeline decommissioning can be defined as the permanent deactivation of a pipeline in a manner prescribed by a regulatory body and includes any measures required to ensure that the pipeline is left in a permanently safe and secure condition (AER, 2011). This may also include the removal of related surface equipment no longer in use such as:

- pig traps;
- risers;
- block valves; and
- line heaters.

An exception is made if the equipment is located within the boundaries of a facility that will continue to have other licensed equipment operating after the pipeline abandonment.

When abandoning a pipeline, the licensee (operator) should

- notify parties along the entire pipeline right-of-way and those affected by setbacks prior to any abandonment procedures;
- ensure that proper abandonment procedures are in place complying with any regulatory requirements;
- submit a license amendment application of the abandonment within a specified time period of the pipeline abandonment.

It is of utmost importance to assure the safety of people and conditions when decommissioning.

A single decommissioned CO_2 pipeline was identified during the study only, with little specific information available regarding this step. However, it is safe to speculate that decommissioning and abandonment procedures for CO_2 pipelines would be substantially identical to those for a natural gas pipeline.

SECTION C

Overall findings and conclusions

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14 Key findings and conclusions

14.1 Existing CO_2 pipelines

Thousands of kilometres of CO_2 pipelines have been operating successfully for many years and in some cases multiple decades. This study collected lessons learned from a number of these existing pipelines (Figure 20). A large number of these transport CO_2 for injection in partially depleted oil fields for EOR in the United States. More recently, some CO_2 pipelines have been built to transport CO_2 for other purposes, such as Carbon Capture and Storage (CCS) and in some cases to be used in the food industry or to be used in greenhouses. Many more are in different stages of planning and these are typically associated with future CCS schemes across the globe, in particular Europe and North America.

With the exception of the United States most countries have little or no experience with CO_2 pipelines or CO_2-EOR operations. CCS project developers, agencies responsible for regulation and permitting of these CO_2 pipelines and the public are often not familiar with these pipelines. Access to the information and experienced gained with CO_2 pipeline projects elsewhere is likely to contribute to efficient and effective realisation of such projects. The purpose of the present study builds on this idea: to collect information on existing CO_2 pipeline infrastructure and to organise this in a comprehensive database. This Reference Manual document complements this database. It provides an overview of findings, and facilitates access to the database.

14.2 Available information

The work is based on publically available information for a selected set of 29 CO_2 pipeline projects, out of over 80 known CO_2 pipeline projects around the world. The information was collected based on reviews of a large number of documents and interviews with persons involved. This approach proved effective in building a comprehensive database that offers detailed information on over 100 topics for each project.

When compared to natural gas pipelines, the aggregate length of existing CO_2 pipeline is modest. Nonetheless, the total length, number and age of existing CO_2 pipelines are such that this offers a broad range of information to work with:

- Europe has approximately 2 million km of natural gas pipelines, versus 230 for CO_2;
- United States has some 550,000 km of natural gas pipelines, versus 6,000 km for CO_2.

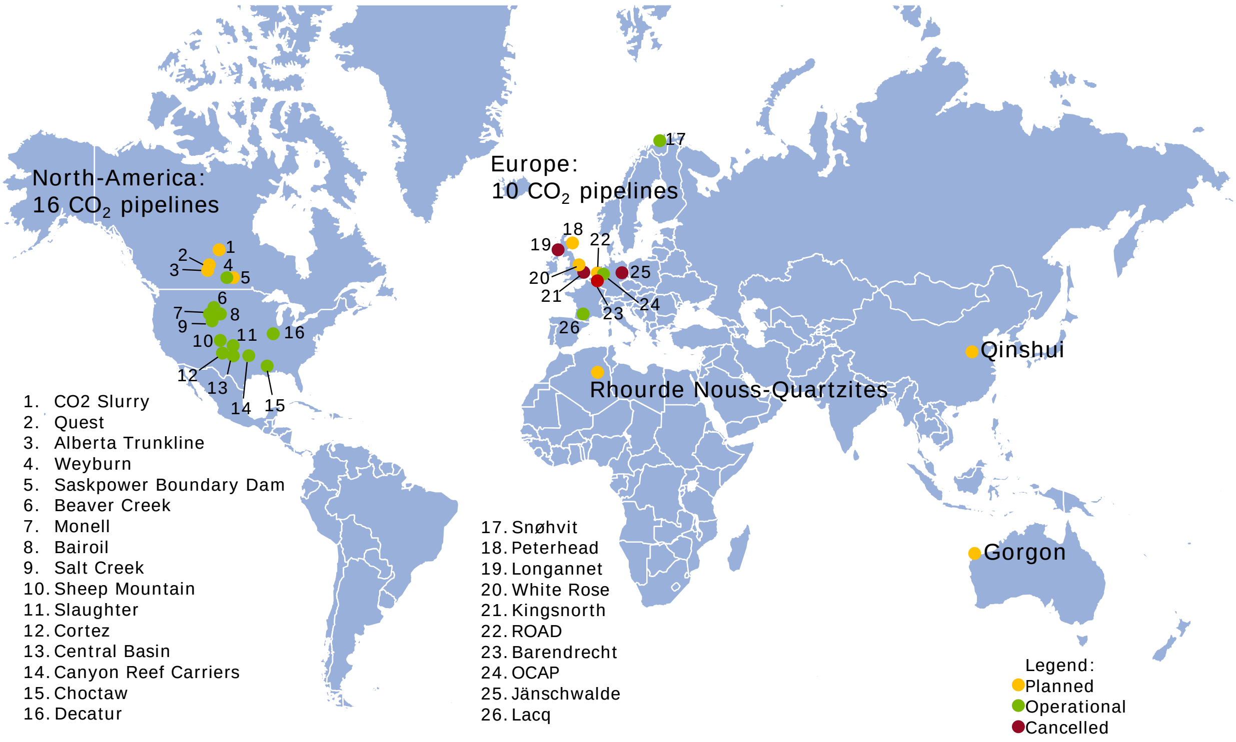

Figure 20 – Overview of CO_2 pipelines included in the study.

The following sources proved to be the most fertile for specific and in-depth information:

- Articles and papers on specific projects published in journals or at conferences, in particular for older CO_2 pipelines;
- FEED studies;
- Environmental Impact Assessment studies;
- Interviews with key persons involved in the planning, design, construction or operation.

However, there are clear limits to what information is publically available on some topics and for some projects. The most important reasons for this are:

- Information was considered confidential by the owner for commercial reasons. This played a role in particular with pipelines associated with commercial EOR schemes in the Americas;
- Auxiliary equipment (compressors, dehydration units) are usually tied to the operations at the terminal points of the pipelines, not to the pipeline itself, so information availability via the pipeline operator is not possible without extensive canvassing of third parties, most of whom are involved in competitive businesses and are reluctant to share information;

- Information on older projects was no longer available or could not be located. In part this was driven by the absence of digital copies of reports dating back to the 1970s and 1980s;
- Change of ownership with the current owners not having received all information from the time that the project was developed and built;
- Key people that had been involved in the realisation of a CO_2 pipeline were no longer working for the pipeline owners.

It proved useful to include some projects that have not yet been built or that will not be built, but for which in-depth information was available. In this way a broad variety of CO_2 pipeline projects could be covered, allowing insights in regional differences and differences that depend on the purpose of the CO_2 pipeline.

14.3 Drivers for CO_2 pipeline projects

EOR projects in the United States are commercial schemes where the aim is to increase revenues from incremental oil production. In many cases this can justify the substantial investment by private companies required for putting in place the required CO_2 transportation infrastructure. However, market conditions can change and there have been CO_2 pipeline projects for EOR that were abandoned in early stages of development due to the low oil prices at the time.

In some cases, additional revenue comes from generating carbon offsets under the United States' or Canadian carbon registering or offsetting schemes. This will come with specific requirements for registration, validation and verification of the CO_2 throughput.

In contrast, most CO_2 pipeline projects in European projects are focused on transporting CO_2 for injection and storage as a CO_2 emissions reduction option. The business case for such projects is substantially different from EOR projects. The CO_2 transportation and storage generates revenues under a CO_2 pricing scheme or financial support scheme only. In Europe this would be the Emissions Trading System (ETS).

14.4 Routing of CO_2 pipelines

The CO_2 pipelines studied connect a variety of sinks and sources. The most common sources are gas processing plants, coal-fired power stations and natural sources of CO_2. The latter source has been commonly used in the United States as early as the 1970s.

Common sinks are oil fields for EOR, but also depleted oil and gas fields are used. The benefit of these storage sites is that there is existing infrastructure in place that may be re-used for CO_2 transportation. In some of the European projects (OCAP, Barendrecht, Lacq, Peterhead CCS and Longannet) this has been seriously considered.

There are a number of examples where consortia or groups have joined forces to develop a larger scale CO_2 pipeline project. This is particularly relevant in cases where CO_2 sources and sinks are far apart and where there are multiple parties with parallel commercial interests. A number of the CO_2 pipelines in the United States run over substantial distances in the range of 200 to 800 km.

Where multiple CO_2 sources and sinks exist, a gathering, transmission and distribution networks may be developed. Several CO_2 pipeline hub systems have developed in the Southwest United States over time, where individual CO_2 sources are gathered and from which various CO_2 customers are supplied.

14.5 Design considerations

The following key parameters for CO_2 pipelines are the starting point for the pipeline design:

- CO_2 throughput capacity, presented and projected;
- Operating pressure and temperature. These govern the phase of the CO_2, where more than one phase in the same pipeline system is unacceptable. This is a key factor in the design of the pipeline and associated equipment;
- Purity of the CO_2 stream: this depends on the CO_2 source and the technology used to capture the CO_2 and ranges from >95% to >99% in the projects studied. For example, hydrogen plants produce a very pure CO_2 stream, while flue gases from coal-fired power plants may contain significant impurities. Water content is a particular concern as it can cause corrosion or freeze-outs in the pipeline. The usual response is to demand that CO_2 entering the pipeline system have a very low water content. In most cases the quality of the CO_2 stream is not regulated. However, when CO_2 is used for specific purposes, such as in greenhouses or for food production, strict purity requirements apply;
- Regulatory requirements and technical standards.

Beside these the pipeline design will consider:

- Detailed pipeline routing, vertical situation and burial, and crossings with existing infrastructure, spatial planning constraints and right-of-way arrangements. These elements are particularly relevant for ensuring safety of the pipeline and surroundings;
- Pipeline material, wall thickness and corrosion protection;
- Inclusion of devices as part of the pipeline to arrest longitudinal crack propagation.
- Installation and construction methods, including but not limited to requirements for welding, burial and directional drilling;
- Auxiliary equipment including compressors, dehydration and emergency shutdown valves;

- Inspection and maintenance requirements;
- Mode of operation, Supervisory Control and Data Acquisition (SCADA) system and monitoring systems for leak detection.

14.6 Regulatory regime

The design of CO_2 pipelines was new in the United States in the 1970s. At the time designs were based on meeting codes for natural gas pipelines in the absence of design codes or standards. Rulemaking specifically for CO_2 pipelines safety was introduced in 1989, not because of any deficiencies in the safety record, but rather the possibility of a high-consequence incident if a break in a CO_2 pipeline were to occur proposed. This led to a number of subparts being added to the existing regulations in CFR (Code of Federal Regulations) part 195.

The European Commission concluded in the CCS directive that the framework used for natural gas transportation pipelines would be adequate to regulate CO_2 transport (European Commission, 2008). There are broad similarities between the transport of CO_2 and natural gas, “albeit without the added risk of explosion posed by natural gas”. The details of the regulatory framework vary from country to country. In recent years the Recommended Practice on Design and Operation of CO_2 Pipelines (DNV-RP-J202) published by DNV in 2010 has been referred to as a key technical standard in Europe.

Such national legislation typically includes specific requirements on:

- Hazard identification and risk assessment;
- Inspection and maintenance plans;
- Surveillance of the pipeline route;
- Protection against third party interference;
- External emergency plans;
- Technical standards that should be adhered to;
- Safety measures, including pipeline integrity monitoring equipment, location specific burial depth and wall thickness, leak detection equipment, remotely operated safety valves.

14.7 Permitting

Permitting and approval processes play a key role in the realisation timeline for these projects. For example, the 808 km Cortez pipeline project took 8 years to complete, of which only 2 years were required for the construction works. Therefore, for a timely implementation of the project, it is essential that the relevant permits and approvals are pursued in an efficient way. Lessons learned from earlier CO_2 pipeline projects offer useful guidance in this respect.

Relevant permitting processes include spatial planning and / or right-of-way approvals. Requirements for safety distances with respect to existing infrastructure or populated areas are important considerations in this respect.

Another important step is the Environmental Impacts Assessment (EIA). There are only a few EIA studies that focus on CO_2 pipelines. In most cases the pipeline was considered only as a part of a bigger scheme for example CCS. Depending on the scale of the CO_2 pipeline project, an EIA procedure may be mandatory. In Europe, based on a European Commission Directive, this is typically the case for CO_2 pipelines with a diameter of more than 800 mm and a length of more than 40 km. For shorter and smaller CO_2 pipelines individual EU Member States can still decide whether an EIA is required. In some projects, the project developers have carried out an EIA study on a voluntary basis to substantiate the modest impacts of the pipeline and to contribute to public acceptance.

14.8 Safety statistics

Incidents with CO_2 pipelines are rare and seem to be less severe than those in natural gas systems when they do occur. The combined length and lifetime of CO_2 pipelines in the United States make this an interesting data set to evaluate. Over the 40 year history of these CO_2 pipelines there are no known reports of civilian injuries or casualties.

Records from the Office of Pipeline Safety (US Department of Transportation) indicate that in the United States for the time period 1972 – 2012 there have been no fatalities and 46 reported incidents involving CO_2 pipelines. These included:

- incidents were caused by relief valve failure;
- incidents associated with weld, gasket or valve packing failure;
- incidents due to corrosion;
- incident due to outside forces damaging the pipeline.

Some small scale incidents with CO_2 pipelines have been reported in Europe as well, but again no personal injuries or casualties. In contrast to the United States, there is no incident reporting or analysis system in Europe from which safety trends and statistics could be evaluated (COWI, 2011). Industry itself gathers statistics on a voluntarily basis.

14.9 Public concern

Public concern has had a prohibitive effect on some CCS projects in Europe. A part of the public sees CCS activities as an unhealthy perpetuation of fossil fuel dependence, or is against plans to store CO_2

near or underneath their communities. During interviews with several operators, it became clear that CO_2 pipelines by themselves tend not be the main attractor of public concern. However, given the close functional relationship such causes may well get mingled in the public mind. For CO_2 pipeline developers, it is important to understand what key potential drivers of the public concern are, so that these can be addressed in a focussed way.

While planning, permitting and public communication on CO_2 pipelines is quite similar to what is needed for a high-pressure natural gas transmission pipelines, some key distinguishing features are:

1. Regulatory agencies and members of the public who are not familiar with CO_2 pipelines are inclined to perceive them differently. Unlike natural gas infrastructure they do not deliver a product that is directly beneficial to a household level and in many places represent first-of-a-kind projects;
2. A single high-profile incident involving a large number of fatalities from concentrated CO_2 emissions (Lake Nyos, Cameroon) while not in any way related to pipelines, has created a perception of public risk from concentrated CO_2 releases from pipelines and other parts of CCS projects;
3. CO_2 pipelines are not separated in the public mind from the perceived risks associated with geological storage of CO_2.

As a result of these differences, typically more comprehensive effort needs to be invested in public awareness, education and consultation as well as working with regulatory authorities. Effective communication strategies and availability of transparent and high quality information are key elements in effectively addressing any such concerns.

14.10 Costs

Detailed cost information proved difficult to acquire for many of the CO_2 pipeline projects studied. This information is treated confidentially for commercial reasons. Also, a number of pipelines have been designed and built by an initial owner who subsequently sold the pipeline to other interested parties, without disclosing the original cost.

In the absence of actual data, pipeline capital cost can be estimated from credible sources. A key source of information the National Energy Technology Laboratory 2013 study entitled Carbon Dioxide Transport and Storage Costs in NETL Studies. The key factor determining the cost is the geography and geology of the terrain traversed by the pipeline, followed by length and capacity of the pipeline. Such an approach should be used as an indicator of possible costs for a project but never as an accurate estimate.

14.11 Trends and developments: Future CO_2 Pipelines

In many parts of the world, any CO_2 pipeline would be a first of a kind. With the increasing number of CO_2 pipelines currently being planned or constructed this is likely to change. In this respect, the recent history of the existing CO_2 infrastructure in the United States offers an interesting perspective on the future for other parts of the world. Arguably, both the technology and regulatory regime associated with CO_2 pipelines for EOR operations in the United States have matured substantially since the first CO_2 pipelines were constructed there. A comparable development may be expected as more and more CO_2 pipelines are constructed elsewhere.

Signs of such developments include the introduction of dedicated technical standards for CO_2 pipelines usually as part of existing pipeline standards for other types of pipeline. . These include:

- Dedicated subparts added to the existing regulations in CFR (Code of Federal Regulations) part 195 in the United States in 1989;
- Parts of CSA Z662 in Canada;
- Publication of the Recommended Practice on Design and Operation of CO_2 Pipelines (DNV-RP-J202) published by DNV in Europe in 2010;
- ISO/TC 265 Carbon dioxide capture, transportation, and geological storage. This standard is currently under development and will include many aspects of CCS, among which transportation (ISO/TC 265/WG 2). The standard will be based on existing standards (ISO TC 67, CEN TC 234) and will define additional requirements or recommendations for CO_2 transportation by pipelines.

The development of technology for pipeline design, construction, inspection and maintenance continues at a range of research institutes and universities. There are several research programmes focusing on CCS and the associated pipeline infrastructure or specific topics such as corrosion and materials. Besides these, various private businesses are actively involved in the development of pipeline technology. Several large companies such as Kinder Morgan (North-America) or consortia of pipeline companies (European Pipeline Research Group and Pipeline Research Council International) have research programs to develop additional knowledge on pipelines and pipeline issues.

However, a critical difference between the past United States/Canada experience and present and future European experience is the very large difference in population density between western United States/Canada and western Europe. Additionally the areas of North America containing CO_2 pipelines are subject to extensive long standing existing oil and gas operations so the concept of multiple pipelines is somewhat more accepted.

Based on the findings of this study it can be concluded that at least in the near future CO_2 pipelines and their operating parameters may be expected to be very similar to those being designed today. Research can be expected to produce improvements in corrosion resistance, increased ability of intelligent pigs to detect flaws in operating systems, and more cost effective methods of arresting longitudinal crack propagation.

As described in section 14.9 CO_2 pipelines are not immune to negative publicity, related directly to the pipeline itself or associated projects. Therefore, despite increasingly sophisticated technology and operating procedures, it is likely that the chief area where major improvements will be necessary is in the area of public opinion.

14.12 Guidance for realisation of CO_2 pipeline projects

There are only a small number of respects in which CO_2 pipeline projects are different from those for natural gas pipelines. The project cycle for realising, operating and maintaining and decommissioning of CO_2 pipelines can therefore largely be built on the established practices for such other gas pipelines.

Key issues specific to CO_2 pipelines have been elaborated in this Reference Manual. At a high level, these are reiterated in the following three points:

1. Unfamiliarity of the public and regulatory bodies with CO_2 pipelines in many places, where such projects would be first of kind;
2. CO_2 pipelines are not separated in the public mind from the perceived risks associated with geological storage of CO_2. As a consequence greater effort has to be invested in in public awareness, education and consultation as well as working with regulatory authorities;
3. Regulatory framework and design standards that are either not as well developed or less mature than these are for natural gas pipelines.

The experience gained and track record accumulated with existing CO_2 pipelines offers a wealth of information that may serve useful guidance for owners / developers and regulatory bodies dealing with new CO_2 pipeline projects in jurisdictions where these are new.

The present study has considered a broad range of these existing CO_2 pipelines with a wide variety of characteristics and peculiarities. Readers looking for guidance for any specific new CO_2 pipeline project will be able to find relevant examples of projects with comparable features in the database.

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Appendices

Appendix A List of CO_2 Pipelines

Pipeline Projects	Region	Status
CO_2 Pipelines discussed in this study		
CO_2 Slurry	Canada	Planned
Quest	Canada	Planned
Alberta Carbon Trunk Line	Canada	Planned
Weyburn	Canada	Operational
Saskpower Boundary Dam	Canada	Planned
Beaver Creek	US	Operational
Monell	US	Operational
Bairoil	US	Operational
Salt Creek	US	Operational
Sheep Mountain	US	Operational
Slaughter	US	Operational
Cortez	US	Operational
Central Basin	US	Operational
Canyon Reef Carriers	US	Operational
Choctaw (NEJD)	US	Operational
Decatur	US	Operational
Snøhvit	Norway	Operational
Peterhead	UK	Planned
Longannet	UK	Cancelled
White Rose	UK	Planned
Kingsnorth	UK	Cancelled
ROAD	Netherlands	Planned
Barendrecht	Netherlands	Cancelled
OCAP	Netherlands	Operational
Jänschwalde	Germany	Cancelled
Lacq	France	Operational
Rhourde Nouss-Quartzites	Algeria	Planned
Qinshui	China	Planned
Gorgon	Australia	Planned

Pipeline Projects	Region	Status
Other CO_2 Pipelines		
In Salah	Algeria	Operational (on hold)
Alberta CO_2 transportation	Canada	Study
Sasquatch CO_2 Pipeline	Canada	Operational
Green Hydrogen	Netherlands	Planned
K12B	Netherlands	Operational
Mongstadt	Norway	Test centre
Kasto	Norway	Planned
Bati Raman	Turkey	Operational
Mussafah-Taweelah	UAE	Planned
Adair	US	Operational
Anton Irish	US	Operational
Borger TX to Camrick, OK	US	Operational
Bravo	US	Operational
Centerline	US	Operational
Chaparral	US	Operational
Coffeyville–Burbank	US	Operational
Comanche Creek	US	Operational (inactive)
Cordona Lake	US	Operational
Dakota Gasification	US	Operational
Delta	US	Operational
Dollarhide	US	Operational
El Mar	US	Operational
Enid-Purdy (Central OK)	US	Operational
Este I to Welch, TX	US	Operational
Este II to Salt Creek Field	US	Operational
Ford	US	Operational
Free State	US	Operational
Green Line I	US	Operational
Greencore pipeline	US	Operational
Joffre Viking	US	Operational
Llaro	US	Operational
Lost Soldier/Werrz	US	Operational
Mabee Lateral	US	Operational
McElmo Creek	US	Operational
Means	US	Operational
Mountaineer CCSII Project	US	Operational
North Cowden	US	Operational
North Ward Estes	US	Operational
Pecos County	US	Operational
Pikes Peak	US	Operational
Plant Barry to Citronelle	US	Operational
Powder River Basin CO_2 PL	US	Operational
Raven Ridge	US	Operational
Rosebud	US	Operational
Sheep Mountain North	US	Operational
Shute Creek	US	Operational
Sonat	US	Operational
TransPetco	US	Operational
Val Verde	US	Operational
Wellman	US	Operational
White Frost	US	Operational
WTexas	US	Operational
Wyoming CO_2	US	Operational

Appendix B Checklist used for data collection

Pipeline infrastructure
Physical characteristics
Pipeline routing, including onshore / offshore
Map of pipeline route
Starting point coordinates
End point coordinates
Length of pipeline (km)
Length of pipeline
Crossings, artificial buildings
Depth of lay (meters)
Depth of lay (under soil or seabed)
Pipeline material composition
Diameter of pipeline - *external (in mm)*
Diameter of pipeline - *internal (in mm)*
Wall thickness - *(in mm)*
Remarks at pipeline
Corrosion protection / inhibition
Other protective coating
Moisture control
Crossings and interfaces with other infrastructure
Reuse of pipeline
Pipeline routing, including onshore / offshore
Auxiliary equipment
Compressor - *numbers in operation*
Compressor - *description (types, etc.)*
Compressor - *pressure (bar)*
Compressor - *cost (in mln EUR)*
Compressor - *operation (in hours per year)*
Compressor - *operating history*
Compressor – capacity *Flow (in ton/hr)*
Compressor – capacity *Energy consumption (in MW)*
Dehydration units - numbers in operation
Dehydration units - description (types, etc.)
Dehydration units - *cost (in mln EUR)*
Dehydration units - *operation (in hours)*
Dehydration units - *operating history*
Dehydration units – capacity *Flow (in ton/h)*
Dehydration units – inlet *Flow (in ton/h)*
Dehydration units – outlet *Flow (in ton/h)*
Dehydration units – capacity *Energy consumption (in MW)*
Costs
Design Costs (*in mln EUR)*
Design Costs - *Remarks*
Construction cost (in mln *EUR*)
Construction cost - *Remarks*
Compressor - *cost (in mln EUR)*

Operation & Maintenance	Risk & Safety
Operational characteristics	Safety procedures
Characteristics of CO_2 transported - Volume (designed) *in Mton/y*	Safety criteria in design
Characteristics of CO_2 transported - Volume (annual) *in Mton/y*	Safety corridors and distance to other infrastructure / zones
Characteristics of CO_2 transported - Source of CO_2	Types of valves
Characteristics of CO_2 transported - Purity of CO_2	Valves spacing
Destination of CO_2	**Safety requirements**
Process control system	Safety assessment - Material
Phase of transported CO_2	Safety assessment - Equipment
Maximum operating pressure (design) - *in bar(a)*	Safety assessment - Corridors pipeline
Operating pressure - *in bar(a)*	Reporting minor leakage
Operational pressure - *Remarks*	**Safety statistics - CO_2 pipelines**
Operational flexibility - Flow (volume) *in kg/hr*	Accidents
Operational temperature (at compression) - *in degrees Celsius*	Fatalities (CO_2)
Operational temperature (at injection) - *in degrees Celsius*	**Safety statistics - Natural gas pipelines**
Operational temperature - *Remarks*	Accidents (Natural Gas)
Flow assurance	Fatalities (Natural Gas)
Operational safety: steps to avoid rupture	
Monitoring	
Pipeline inspections (frequency and elements)	
Pipeline monitoring processes	
Costs	
Operation cost	
Maintenance cost	
Monitoring cost	

Regulatory regime	Public concern
Realisation process	**Public communication**
Spatial planning process	Website, flyers, phone line, tv-programme
Environmental Impact Assessment process	Public meetings
Strategic Environmental Impact assessment process	Safety publications
Testing and commissioning required	Health effects
Permits/concessions - Building	Guidance for public
Permits/concessions - transport CO_2	**Decision process**
Permits/concessions - Land-use	Environmental Impact Assessment
Timeline (development, permitting, realisation)	**Research**
Start operation	Interview locals
Restrictions (e.g. as result of spatial planning)	ICQ
Restrictions - Location of pipeline	
Restrictions - Land-use	
Restrictions - transport of CO_2	

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