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Abstract

Sources of CO_2 within the research area as well as potential sinks are well known and described here. Different scenarios for the evolvement of capture technology are explained. A rather conservative scenario assumes that by 2020 a capture rate of 1 Mt/a might be reached within the test case area, 3.6 Mt/a in 2025, 14 Mt/a in 2030, 17 Mt/a in 2035 and 23 Mt/a in 2045 and 2050.

As explained in this report, in Germany all of the 50,000 km of pipelines for natural gas transport are in place and in operation for this one commodity. This infrastructure is expanding, very profitable and will not allow chances for CO_2 reuse by 2015, most likely by 2020.

There are a number of technological issues that undergo improvement at the moment. Especially the occurrence of corrosion at transport networks as well as the noise level during a blow-down are at the focus of research these days. The pipeline hydraulic design and the cost structure for the construction of a transport network are dealt with in this report.

The procedures for land use planning with respect to CO_2 transport are not defined, including the aspects of right of way. Clear regulations for competent authorities as well as for the public and for the developing CCS business need to be defined and deployed. In Germany, this applies for the national as well as the state level. So far, a legal CCS framework is missing in Germany and The Netherlands.

Regional test case for the development of CO$_2$ transport infrastructure:

Rhine/Ruhr area (D) – Hamburg (D) – North Sea (D, DK, NL)

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Internal project report

Date of issue: 14.07.2010

Contributing project partners to WP4.2:
RWE, VRD, SLB, E.ON Eng. UK, CO2-Net, CO2-Global, Nacap, AV, TNO

It should be noted in general that names of storage sites and IGCC- or PCC-power plant locations as well as harbour or hub locations, pipeline sizes and distances mentioned in this report are indicative only. No conclusion shall be drawn from these names and locations, whatsoever.

CO_2-Sources, sinks, and general strategic considerations are part of SP2 and SP3. Hence, this WP 4.2 also grounds on the baselines defined within SP2 and SP3.

Project summary

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

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

Project partners

Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek- TNO	Netherlands
Stichting Energieonderzoek Centrum Nederland	Netherlands
Etudes et Productions Schlumberger	France
Vattenfall Research & Development AB	Sweden
NV Nederlandse Gasunie	Netherlands
Linde Gas Benelux BV	Netherlands
Siemens AG	Germany
RWE DEA AG	Germany
E.ON Benelux NV	Netherlands, Belgium, Luxemburg
PGE Polska Gruppa Energetyczna SA	Poland
CEZ AS	Czech Republic
Shell Downstream Services International BV	Netherlands, United Kingdom
CO2-Net BV	Netherlands
CO2-Global AS	Norway
Nacap Benelux BV	Netherlands
Gassco AS	Norway
Anthony Velder CO_2 Shipping BV	Netherlands
E.ON Engineering Ltd	United Kingdom
Stedin BV	Netherlands

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

1 CO$_2$ sources for this test case

In this study, data from the database developed in the EU FP6 GeoCapacity project was used. (GeoCapacity, 2009). For projecting the CO$_2$ emission for 2020, 2030 and 2050, a study prepared for the European Commission Directorate-General for Energy and Transport was used (EC, 2008a), where emissions scenarios for all EU member countries are presented. The scenarios are based on several policy assumptions and calculated by the integrated energy-economic-environment PRIMES model.

The area of the lower Rhineland and the industrial territory of the Ruhr comprise the major sources of CO$_2$ emissions within Germany. In this region, around 145 Mt/a are emitted by major power plants and steel mills. In an internal study by the Wuppertal-Institute (15.05.2009) these CO$_2$ sources are summarized to five major clusters (Figure 1). These are the cluster east with around 5 Mt/a (power plants Veltheim and Petershagen), the cluster centre with 45 Mt/a (comprising power plants from Hamm to Essen in the Ruhr area), the cluster northwest comprising 31 Mt/a (cities Oberhausen, Duisburg, Düsseldorf), the cluster south-west with 48 Mt/a (comprising the main lignite power plants Frimmersdorf, Niederaußem, Neurath and Goldenbergwerk near Hürth) and finally the power plant Weisweiler with 16 Mt/a (in the Aachen area, Rhineland).
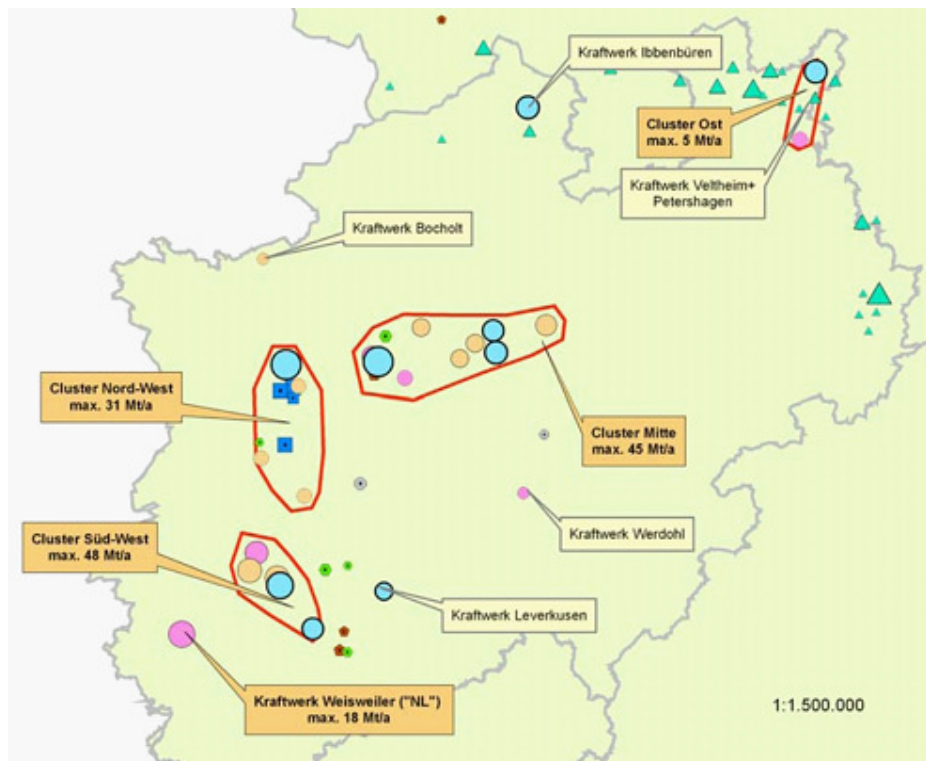

Figure 1: Major single CO$_2$ sources in the state of North Rhine-Westphalia, Germany. Source: Wuppertal-Institute, internal study (15.05.2009).

Emissions from the Hamburg/Bremen region is collected from the CO2Europipe deliverable D2.2.1 (2010) – *Development of a large-scale CO_2 transport Infrastructure in Europe: matching captures volumes and storage availability*.

In D2.2.1, it is estimated that only CO_2 point sources larger than 250 kt/yr will use CCS. As an approximation of the total point source emissions from industry the sector emissions were considered from the iron & steel, non-ferrous metals, chemicals, non-metallic minerals, paper industry and the energy sector. Figure 2 shows the resulting geographic distribution of the source clusters in North West Europe.
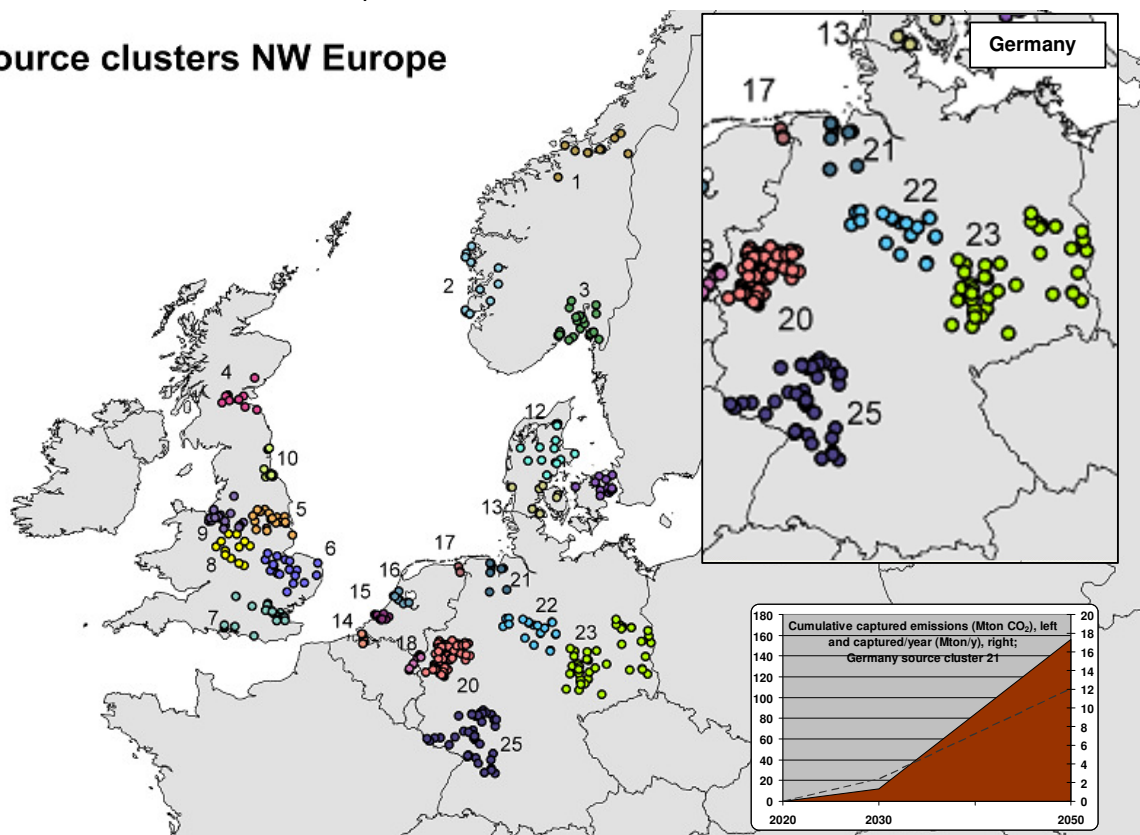

Figure 2: CO_2 source clusters in North West Europe from D2.2.1 (2010).

According to D.2.2.1, the total amount of the emissions included in cluster number 21, near Hamburg, was 12.432 Mt per year (figures from 2005). It should be mentioned that only point sources larger that 100 kt are included.

Once the CCS business will leave the pilot and demo phases and will reach commercial status, CO_2 for a transport network from the Rhine/Ruhr area will certainly come from one or some of these emission clusters, especially from these four: cluster centre, cluster north-west, cluster south-west and cluster number 21 (Figure 1 and Figure 2).

Table 1 shows the emission projection for cluster 21 over 2020, 2030 and 2050.

		2020	2030	2050
Cumulative captured emissions	[CO_2 Mt]	0	11,8	155,9
Captured emissions per year	[CO_2 Mt/yr]	0	2,4	12

Table 1: *Emission projections for 2020, 2030 and 2050 for cluster 21.*

The development of capture activities is assumed here in three different scenarios. They differ in speed of deployment. Scenario 1 is an "early bird" scenario with the first capture in 2015 and the first industry-scale project in 2020. It starts with minor captured quantities of around 50 kt/a and reaches about 3.5 Mt/a from cluster centre, cluster north-west and cluster south-west in 2020. From there, captured volumes would quickly step up to 68 Mt/a in 2025, 80 Mt/a in 2030, 86 Mt/a in 2035 and remain on a stable high plateau of around 92 Mt/a in 2045 and 2050 (Figure 3). A rather moderate view is represented by scenario 2. There, capture starts in 2017, reaching almost 1 Mt/a in 2020, rising to 40 Mt/a in 2025, 55 Mt/a in 2030, 58 Mt/a in 2035 and a plateau of 63 Mt/a in 2045 and 2050. A very conservative and rather CCS-sceptic way is incorporated in scenario 3. Following this path, around 1 Mt/a would be reached in 2020, 3.6 Mt/a in 2025, 14 Mt/a in 2030, 17 Mt/a in 2035 and 23 Mt/a in 2045 and 2050 (Figure 3). These quantities could be increased by 3 to 7 Mt/a coming from sources in the Hamburg area.
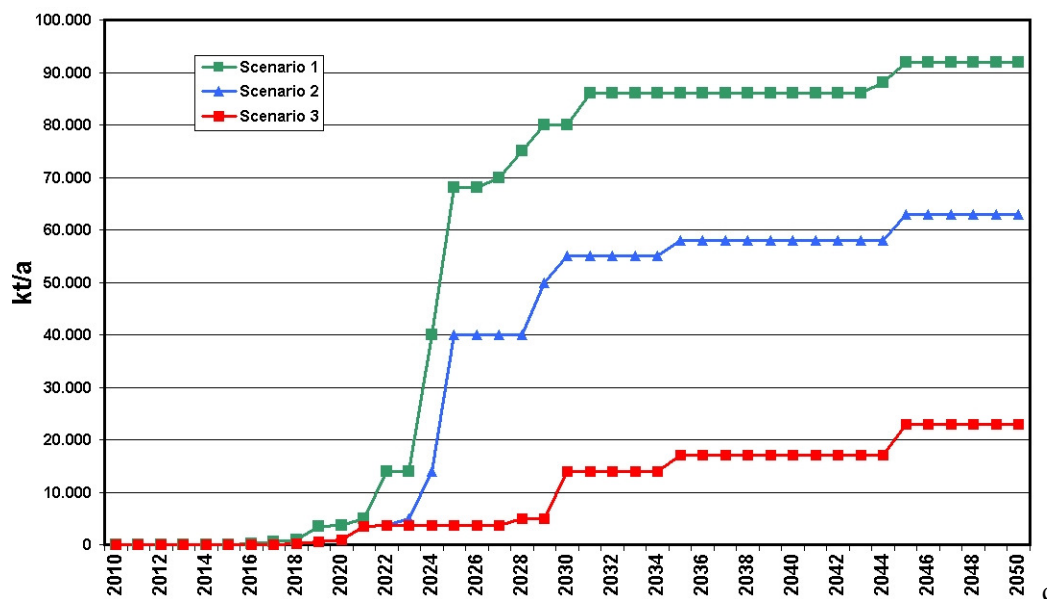

Figure 3: Three scenarios of CO_2 capture deployment in the state of North Rhine-Westphalia, Germany. Source: Wuppertal-Institute, internal study (15.05.2009); RWE (internal study).

Whatever of these scenarios might be close to future reality, in every case substantial quantities of CO_2 ready for transport will come from the Rhine/Ruhr area and will demand the construction of an accommodated transport infrastructure.

2   CO$_2$ sinks for this test case

According to WP2.2 (deliverable 2.2.1: appendix A, pages 50-54) realistic CO$_2$ sinks which guarantee permanent containment are old depleted gasfields (EGR, DGR), old depleted oil-fields (EOR, DOR) and saline aquifers (DSF). For WP4.2, from a regional and economic point of view, only the sinks closest to the Rhine/Ruhr area and Hamburg have hopefully moderate to good chances of realization. Concerning all possible CO$_2$ sinks, WP2.2 groups the sinks in clusters. For gasfields, the only spots of interest for WP4.2 are these six clusters: NO_UK_4, DK, Southern North Sea, NL_offshore, NL and DE (Table 2).

Sink cluster	Cumulative capacity [Mt]	Injectivity [Mt/a]
	2050	2050
NO_UK_4	479	20
DK	424	17
Southern North Sea	1963	89
NL_offshore	800	32
NL	1943	85
DE	2262	93
Sum	**7871**	**336**

Table 2: List of gasfields which are of potential interest as CO$_2$ sink for WP4.2. Data from WP2.2 (deliverable 2.2.1).

For oilfields, the only spots of interest for WP4.2 are these four clusters: NO_UK_4, NO_UK_DK, DK and DE (Table 3).

Sink cluster	Cumulative capacity [Mt]	Injectivity [Mt/a]
	2050	2050
NO_UK_4	187	11
NO_UK_DK	126	8
DK	246	11
DE	56	4
Sum	**615**	**34**

Table 3:   List of oilfields which are of potential interest as CO$_2$ sink for WP4.2. Data from WP2.2 (deliverable 2.2.1).

Finally, for saline aquifers, the only spots of interest for WP4.2 are these six clusters: NO, UK, NL, DE, DE_1 and DK (Table 4).

Sink cluster	Cumulative capacity [Mt]	Injectivity [Mt/a]
	2050	**2050**
NO	26507	678
UK	14304	440
NL	438	4
DE	6361	190
DE_1	20003	507
DK	16672	466
Sum	**84285**	**2285**

*Table **4**: List of saline aquifers which are of potential interest as CO_2 sink for WP4.2. Data from WP2.2 (deliverable 2.2.1).*

3   Technical framework of CO_2 transport

This chapter outlines the most suitable transport fluid composition, recommendations for choice of technical material, pipeline layout, optimum hydraulic design and transport capacity calculations.

3.1 Pipeline layout

Experiences with pipeline transport of natural gas in Europe and CO_2 transport in the USA as well as transport modelling lead to the following layout recommendations:

Facilities:	CO_2 compression to 200 barg at the power station. The simulation of compression was performed by RWE Dea AG, Hamburg. Costs were estimated but not included in economic evaluation of scenarios and pipeline sizes.
	Construction of two (2) CO_2 injection well site areas.
	Office & control building.
	CO_2 Injection Pumps at Storage Site.
	CO_2 leakage monitoring at storage site.
Pipelines: of	Carbon steel API 5L Grade X65 material with 3Layer PP coating. The layout pipeline was peer reviewed by Intetech Ltd., UK.
	Same preliminary pipeline route for all scenarios. Deviation for scenarios with transport shorter than 300km: Here, only one major river crossing (with sewer pipe) is included in the calculations.
Infrastructure:	10km of high voltage power supply line, connected to local grid.
	5km road constructions for access to storage facilities.
Wells:	Well injection capacity 0.6 Mio t/a for each well.
	Abandonment of wells 5 years after injection has ceased.
Monitoring:	2D and 3D Seismic Surveys: Permanently installed grid of geophones covering the whole storage area. CO_2 gas detectors permanently installed at strategic locations.

Transport of CO_2 over a long distance was calculated in many studies, taking into account costs, operational reliability and risk potential (see literature, e.g. „Transport of CO_2“, coordinated by lead authors Richard Doctor - United States and Andrew Palmer - United Kingdom). The following chapter comprises information about various possibilities of transporting CO_2.

For the Rhine/Ruhr test case, a pipeline with no booster station all along its way is designed. Due to high operational costs (100 €/MWh for electricity supply from grid) and resulting additional CO_2 emissions for generating these power, an installation of midline booster stations should only be considered in future for a de-bottlenecking or short term pipeline capacity increase.

3.2   Transport options

Logistically the transport, situated behind the CO_2 capture facilities and delivering a link to storage-sites, can be performed in different systems. The selection of the transport system basically depends on three parameters:

capacity,

distance between source and sink,

storage site (on/offshore).

The transport infrastructure for CO_2 should be able to carry big quantities annually and to guarantee a continuous mass flow. Figure 4 shows an overview of different transport options.
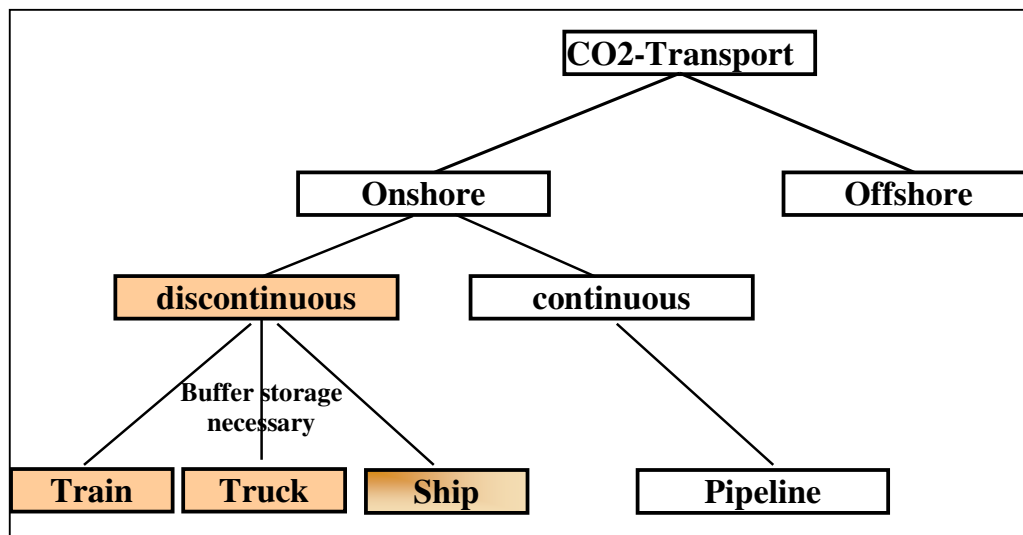

Figure 4: Continuous and discontinuous transport options.

Transport via pipeline is a continuous transport (Figure 4). The transport via ships, trucks and rail represents discontinuous options. The combination of both transport types is generally possible. However, additional technical means are necessary for intermediate storage. The intermediate storage is possible in steel tanks or underground storage formations.

3.3   Pipelines for CO_2 transportation

The transport by pipelines for CO_2 masses of more than 1 Mt/a is the most economic alternative. There is a lot of experience in construction and operation of off- and onshore pipelines. The biggest CO_2 volumes are transported by pipelines at present (EOR/EGR industry) in USA, Canada and Turkey. The pipeline network for CO_2 in North America is already more than 3200 km long. The pipelines run through deserts and densely populated areas. The oldest US pipeline was built in 1972. Every time, the design of the pipelines must be optimized between the following factors:

Diameter,

Wall thickness,

Pressure variations (e.g. due to topography of pipeline route),

Flow rates,

Operation period.

Further parameters for pipeline operations are general pressure, temperature and the quality of the CO_2. A booster station maybe required (with distances more than 300 km). All the parameters have effects on the choice of material. In the USA, ordinary carbon steel is the material of choice for CO_2 pipelines. The high investment costs require sufficient dimensioning of pipelines. Long utilization periods of decades and the continuity of mass flow support to choose the pipeline as best way for CO_2 transport. The break even point will be reached earlier than with all the other transport possibilities (see Figure 5 below).
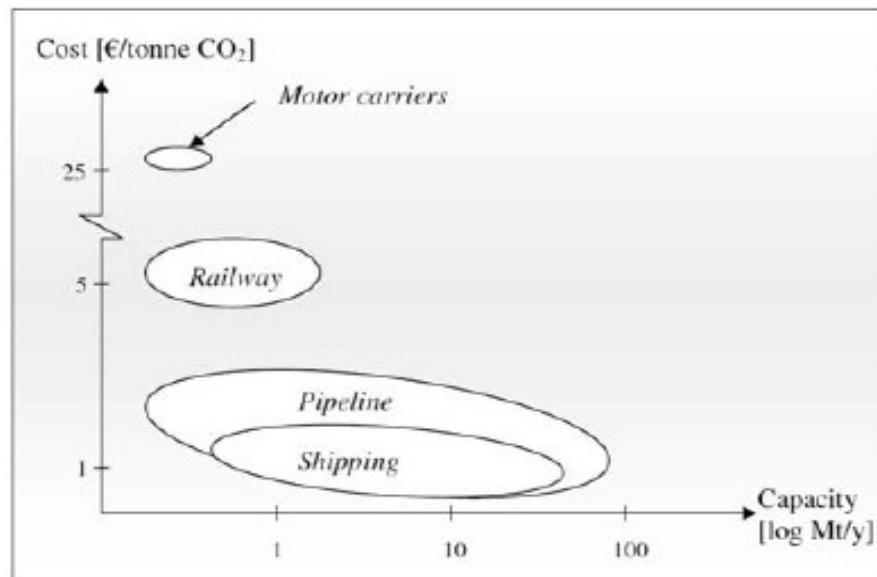

Figure 5: Costs and capacities for different CO_2 transport alternatives (distance 250 km).

The planned capacity for transport defines the choice of means of transportation. When transporting CO_2 by truck, one truck (with a gross vehicle weight of 40 t) has a capacity of CO_2 transport of nearly 25 t. The transportation of CO_2 occurs at pressures of 20 bar and a temperature of –20 °C. Assuming the RWE IGCC CCS demo project in Hürth (Rhineland), the quantity of CO_2 sums up to 2.6 Mio. t/a. This would afford 285 trucks per day. Additionally, investments into interim CO_2 storage and the infrastructure of sufficient transfer points would be needed. These effects would drive costs into absolutely non-economic and high levels (see Figure 5).

A detailed comparison between railway and road shows that the capacity is significantly higher by train (1,300 – 3,000 t/d). However, the transport by train requires the construction of additional infrastructure like a new railway station with more than four platforms next to the capture plant to handle the CO_2. Hence, the transport by rail and road is suitable for small plants and shorter operational periods only. On the other hand, this means that for demo pro-

jects with less than 1 Mt/a (which accounts for many of the recent proposals) railway or road might be the most suitable way of transportation.

3.4 CO_2 Fluid Data

For the Rhine/Ruhr case, the CO_2 will be transported in dense or liquid phase, either in a pipeline, ship or train. It is important not to have any free water in the CO_2, at any time.

For transportation the CO_2 must have a certain composition in order to prevent corrosion inside the transport mean. CO_2 pipeline operators have established minimum specifications for composition. Baselines for CO_2 quality specification are defined. A CO_2 pipeline through populated areas might have a lower specified maximum H_2S content.

The technical quality specifications for transported CO_2 have been defined in CO2EuroPipe, SP3.

3.5 Considerations regarding corrosion

In the presence of CO_2 and H_2O the low-corrosive acid H_2CO_3 may be generated, attacking the containment of the transport means. Having free water in the CO_2, according to internal investigations, may cause a corrosion rate of several millimetres per year. Usually there will be surface corrosion affecting large areas, occasionally there will be pitting corrosion.

There are various kinds / types of corrosion which may occur during the transportation of CO_2 if there is free water in the CO_2.

Pitting:
Corrosion will occur in small pitting points. At such points the corrosion rate can be by orders of magnitude higher than in the vicinity of such a point.
Pitting is more dangerous than uniform corrosion since in one point even holes might be generated at relatively high speed.
The reasons may be variations of the metal (alloy) composition, locally concentrated.

Crevice Corrosion:
Crevice corrosion in interfaces, such as nuts and threads.
Influence by bacteria (metabolic reduction of sulphate into H_2S).

Erosion-Corrosion or Impingement:
High-speed flow in pipes and turbulences may lead to wear of protective coats and thus accelerate corrosion.

Mechanically damaged spots of a protective coat also lead to increased corrosion, often also in the form of pitting corrosion.

Cavitation:

Pressure oscillations may cause phase changes (gas bubbles in liquids) and may force any robust containment to finally burst. The forces acting in this process are very strong.

Cavitation may occur when the pressure suddenly drops in transport means below the bubble point of the transported liquid.

Cavitation damages can be often found in pumps or parts of a ship (propeller).

Intergranular Corrosion:

Corrosion on metal, driven by the metallurgical structure (also granular disintegration).

Dry carbon dioxide does not corrode the carbon-manganese steels generally used for pipelines, as long as the relative humidity is less than 60% (see, for example, Rogers and Mayhew, 1980). This conclusion continuously applies in the presence of N_2, NO_x and SO_x contaminants.

The corrosion rate of carbon steel in dry CO_2 is low. For AISI 1080, values around 0.01 mm/a have been measured, at 90–120 bar and 160°C–180°C, during lab experiments of 200 days. Short term tests confirm this. In a test conducted at 3ºC and 22°C at 140 bar CO_2 (with H_2S content of 800 to 1000 ppm), the corrosion rate for X-60 carbon steel was measured at less than 0.5 μm/a (0.0005 mm/a). Field experience in the USA indicates very few problems with transportation of high-pressure dry CO_2 in carbon steel pipelines. During 12 years of operation, the corrosion rate in a pipeline amounted to 0.25-2.5 μm/a (0.00025 to 0.0025 mm/a).

The limit of water solubility in high-pressure CO_2 (500 bar) is as high as 5,000 ppm at 75°C and 2,000 ppm at 30°C. Methane lowers the solubility limit, and traces of H_2S, O_2 and N_2 may have the same effect. Corrosion rates are much higher if free water is present. Additionally, in such cases hydrates might form.

Seiersten (2001) measured a corrosion rate of 0.7 mm/a in 150 to 300 hours exposure at 40°C. The water was equilibrated with CO_2 at 95 bar. Corrosion rates increased with decreasing pressures. She found little difference between carbon-manganese steel (American Petroleum Institute grade X65) and 0.5 chromium corrosion-resistant alloy. These measured high corrosion rates demonstrate that it is not safe (on a long term) to transport wet CO_2 in low-alloy carbon steel pipelines.

If the CO_2 cannot be dried, it may be necessary to build the pipeline from a corrosion-resistant alloy ('stainless steel'). This is an established technology. However, the costs of steel has greatly increased recently (ca. factor 10). Hence, stainless steel may not be economical.

Once the CO_2 has been dried and meets the transportation criteria, the CO_2 is monitored and transported on its way to the final storage site.

3.6   Mechanical Design

For the pipes, bends and fittings low-alloy carbon steels, such as the X65 or X70 acc. to API 5L, will be used with special requirements, for example, to the composition of alloy elements and to the mechanical strength in certain temperature ranges.

For the Rhine/Ruhr case, preliminary mechanical design has been performed for pressure containment only. Results have been used for hydraulic/pressure drop calculations and pipeline cost estimates. Final wall thickness and grade of material selected needs to be specified during detailed layout. This can only be performed after determination of the exact pipeline route, route survey and after the completion of calculations considering operational, environmental and constructional loads. All these factors influence and determine the required wall thickness and material grade. The factors are listed here:

Pipeline Strength and Fatigue

Allowable strength, design factors, hydro-test strength,

Loads, sustained, transient, thermal, occasional, pressure, vacuum, bending, spanning, pressure surge, vibrations, reaction forces.

Stress analysis, thermal analysis, dynamic and fatigue analysis,

Overburden loads, anchor design, construction loads.

Pipeline Route and Shape

Weight, D/t Ratio, topology and pressure,

Wall thickness, tees, branches,

Hot and cold bending, forged fittings,

Spanning, twisting, moments and forces,

Resisting collapse, buckling, vacuum,

Flexibility analysis,

Component shapes,

The required pipeline wall thickness for pressure containment has been calculated with a spreadsheet program which is based on calculation methods specified in reference standards below, taken into consideration, e.g. pipeline delivery specifications like pipe mill wall thickness tolerances, corrosion allowance, minimum yield strengths.

Reference standards:

DIN: EN 14161:2003 Petroleum and Natural Gas Industries – Pipeline Transportation Systems.

ISO 3183-3   Petroleum and Natural Gas Industries Steel Pipe for Pipelines – Technical Delivery Conditions.

PD 8010-2:2004 Subsea pipelines (British Standard for offshore pipelines).

Material Weight and Potential Weight Reduction

Pipeline material weight estimates were done for 300 and 500 km lengths with design factors for 0.72 and 0.77 of SMYS. Material costs for long distance pipelines are one of the major CAPEX factors amounting to 35 to 50% of the total costs of project. Significant savings in material and construction costs can be achieved, if the design proves that the pipe wall thickness can be reduced. Means to reduce the wall thickness are:

Selecting steel of higher strengths like X70 or X80. However, the final choice will be a compromise between material and construction costs and schedule. Important to consider in terms of timing are the welding ability of pipe material under construction, the site conditions and delivery times. Globally, there are only a handful of pipe mills left who can deliver high strengths grade pipes in the quality and quantity required.

Increasing the maximum allowable SMYS, e.g. using 0.77 instead of 0.72 as defined by the European standard EN 14161, is one option of optimizing costs (Figure 6). This implies that certifying authorities in Germany can be convinced and also that the "light" design is supported by rigorous design calculation, a tight quality control during the pipe manufacturing process and pipeline construction as well as using advanced operation controls and inspection techniques.
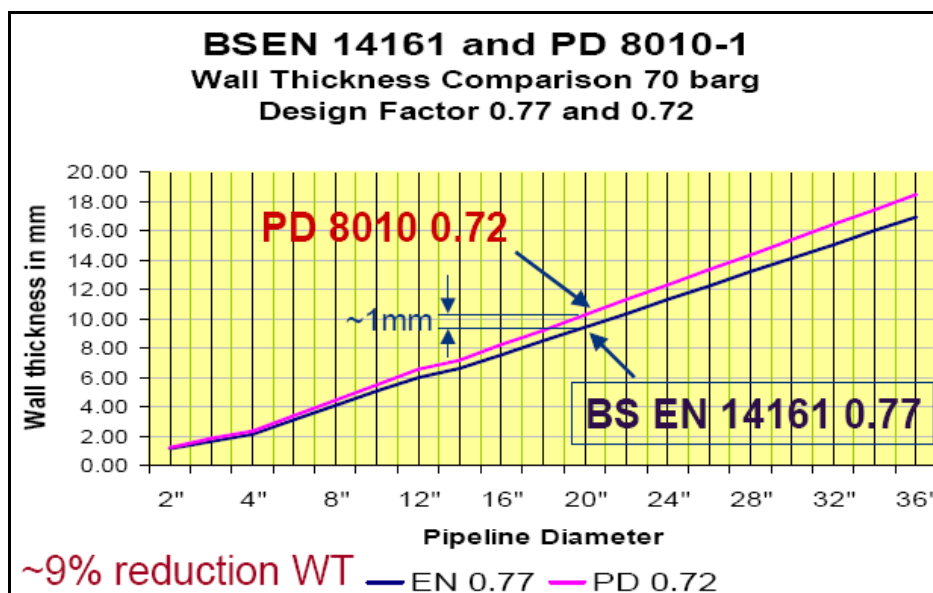

Figure 6: Material design of pipelines. Adapted from JP Kenny and J McKinnon's presentation at PIPESPEC2006: "Opportunities and Challenges". Conference in Amsterdam, Netherlands, 7th March 2006.

For the Rhine/Ruhr test case, a pipeline with no booster station all along its way is designed. Due to high operational costs (100 €/MWh for electricity supply from grid) and resulting additional CO_2 emissions for generating these power, an installation of midline booster stations should only be considered in future for a de-bottlenecking or short term pipeline capacity increase.

3.7 Pipeline Hydraulic Design

Pipeline transport of CO_2 is not new. More than 3,200 km of pipe have been built and are operated in the (western) USA to carry large volumes, up to 50 Mio t/a. Examples are the transport of CO_2 from natural sources/reservoirs in Colorado to enhanced oil recovery projects in Texas.

Design principles of CO_2 pipelines are similar to high capacity gas or oil transmission pipelines. Onshore pipelines for oil and gas transport are routinely operated at pressures between 60 to 90 bars, with intermediate booster stations spaced 80 to150 km. This depends largely on the terrain topography. Offshore transmission pipelines are operated at much higher pressures, generally without intermediate booster stations. For example, the first section of the new 1,200 km long 42"/44" Diameter Ormen Lange submarine gas export pipeline from Nyhamna (Norway Coast) via Sleipner Platform to the Langeled Terminal (UK Eastern Coast) is designed for an operating pressure of 250bar. Short inter-field pipelines and sub-sea flow lines are operated at pressures up to 500 bar.

From published studies and data, e.g. IPCC 2005 (Special Report on CCS, Chapter 4) or the Kinder Morgan report (about Weyburn) it can be summarized that most of the CO_2 pipelines operate in the range of 150 to 230 bar. There, CO_2 is in its dense phase.

Today, normal operating pressure ranges of gas transmission pipelines in Germany range between 60 and 90 bar, with few exceptions of up to 100 bar. Some consider an operating pressure of 200 bar to be a big step forward,. But as mentioned before, this is the standard for offshore pipelines and not a real technical challenge. However, approving authorities, certification bodies and the public need to be convinced that pipeline transport of large volumes of CO_2 at 200 bar and above is a technically, commercially and environmentally friendly and very viable option compared to any other transport means. CO_2 transport with 200 bar does not pose an increased hazard to the public and environment.

The graph in Figure 7 shows the isothermal CO_2 densities over the recommended operating pressure range for constant fluid temperatures of 0 ºC to 50 ºC, being the likely fluid temperature range of the pipeline considered for the Rhine/Ruhr case. The coloured overlay (light yellow) in Figure 7 is the area of planned pipeline operational regime. Figure 7 shows that under all assumed and predicted operating condition the CO_2 fluid will stay above the critical point of CO_2 and no phase changes will occur in the pipeline.
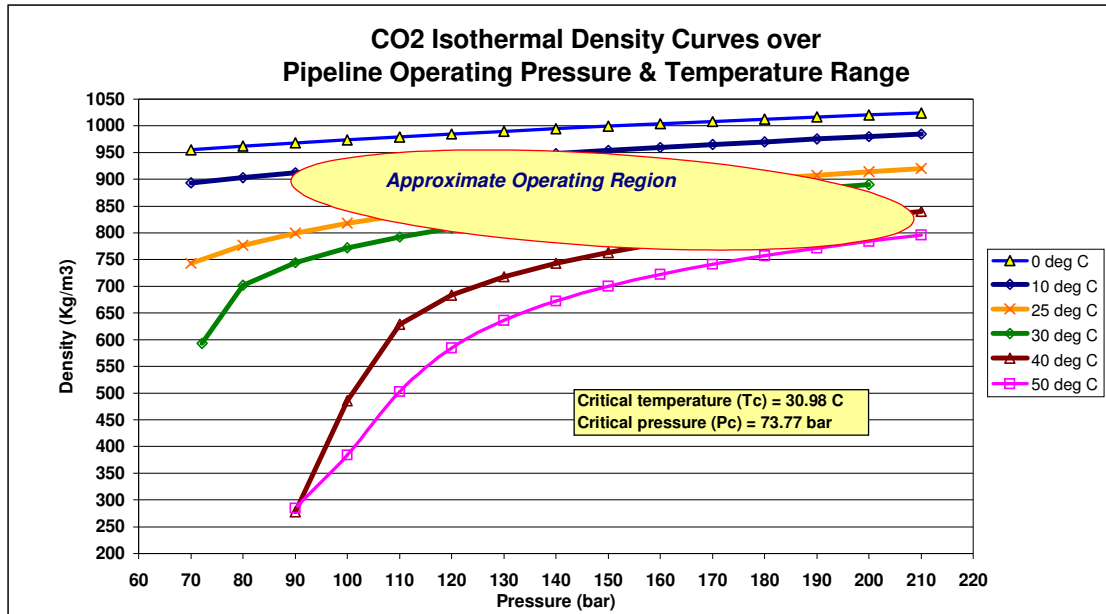
Figure 7: Material design of pipelines. Adapted from JP Kenny and J McKinnon's presentation at PIPESPEC2006: "Opportunities and Challenges". Conference in Amsterdam, Netherlands, 7th March 2006.

Booster Station Considerations

Capital investment and operating costs of pipelines generally increase when intermediate compressor stations are required to compensate for pressure losses along the pipeline. Normally, gas pipeline compressor stations are installed for matching seasonal demand changes.

The natural gas network system with its inherently large spare capacity allows switching to alternative supply routes within minutes in case of compressor station outage. In contrast to this, a failure of a compressor/booster station in a single CO_2 pipeline would suddenly reduce the throughput. This would have a direct knock-on effect on the operation of the IGCC-CCS power plant in Hürth. Omitting compressor stations reduces the complexity of the CO_2 transport system and improves the availability of the transport system.

For natural gas pipelines, the fuel gas required to power the compressor is taken from the stream of the medium transported. For CO_2 pipelines, booster pumps or compressor stations would require an external energy supply, probably either fuel gas or electricity. As these station will be remote from the IGCC-CCS power plant, energy costs will be presumably expensive and above the prevailing market level, which will add upon OPEX further. Required energy for boosting and its equivalent CO_2 emissions would have to be accounted in the overall life cycle balance of the CCS project.
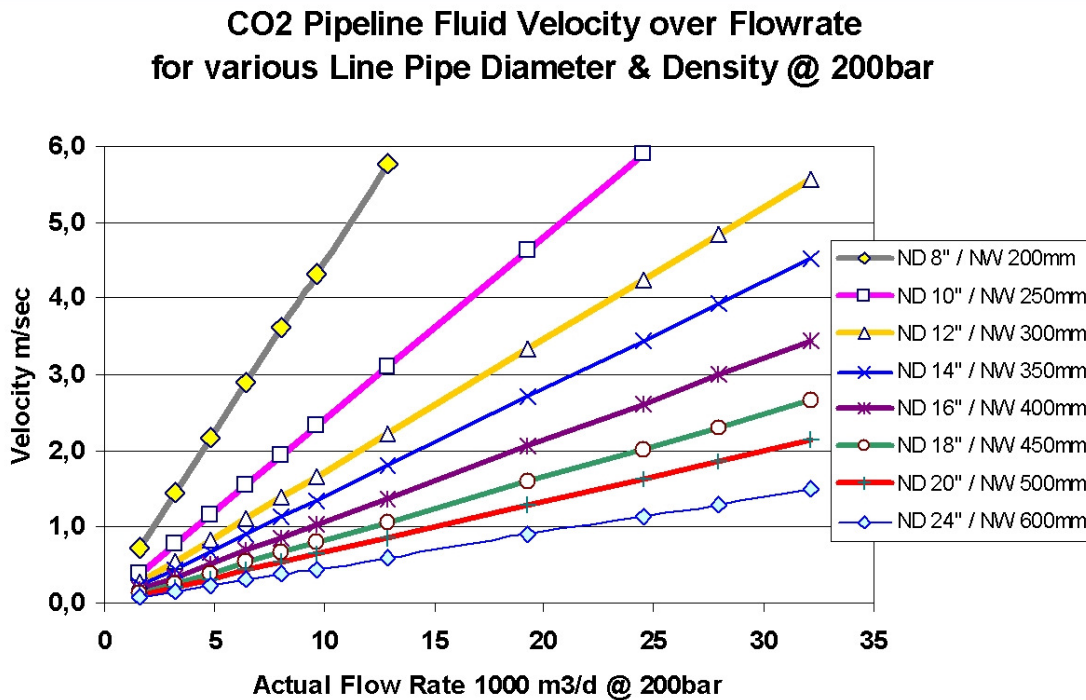
CO2 Pipeline Fluid Velocity over Flowrate
for various Line Pipe Diameter & Density @ 200bar

Figure 8   Graph of CO_2 fluid velocity in the pipeline over flow rate. Source: RWE.

Fluid Velocity Calculation

Reported transport velocities vary from 1 to 5 m/sec. Friction losses increase with the square of fluid velocities. Therefore, pipeline diameters should be optimized in the design stage with the aim not to exceed 2 m/sec of velocity for dense fluids.

Increasing the pipeline diameter will reduce the fluid flow velocity, hence resulting in lower frictional losses. Intermediate compressor stations can be avoided as hydraulic calculations for 300 and 500 km long pipelines have shown. However, the final selection of pipeline diameter will be a compromise between investment, operating costs and the long-term business strategy and CO_2 policy of the operating company/consortium.

In Figure 8, pipeline velocities over CO_2 flow rates are plotted for various pipeline diameters for a constant fluid density and a laminar flow (Re < 2300), corresponding to a pressure of 200 barg.

Figure 9 shows the effect of CO_2 density change on fluid velocities for operating pressure of 200bar and 73.75 barg at a constant fluid temperature of 10 ºC for various flow rates and a pipeline Ø of 14''.

**14" CO2 Pipeline - Effect of Density Change
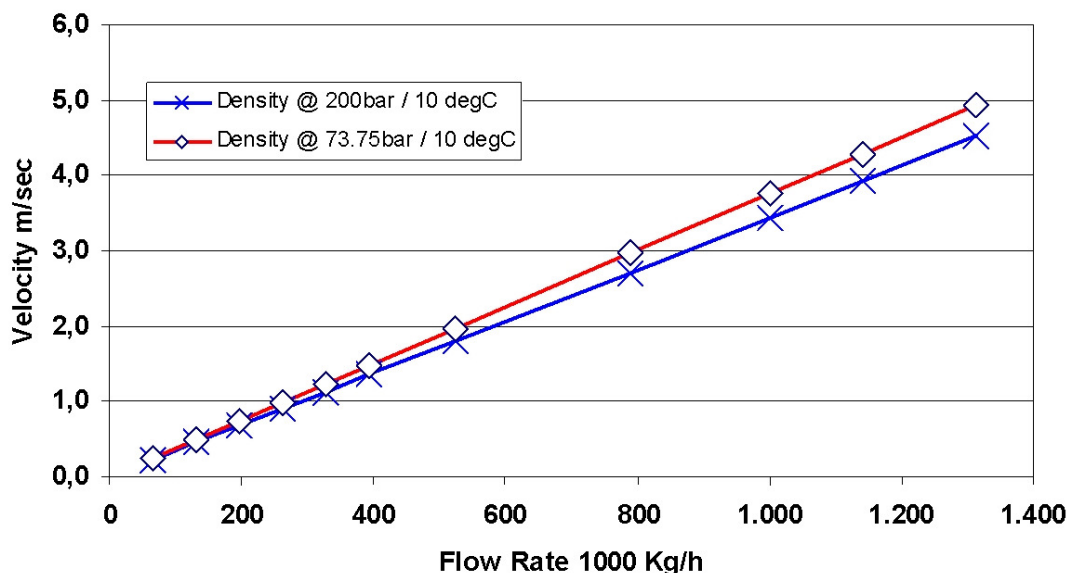on Fluid Velocity for various Flowrates**

Figure 9: Effects of density changes on fluid velocity. Source: RWE.

3.8 Costs of hydraulic design

Capital and operating costs of pipelines must be considered during the process of hydraulic design. These costs can be categorized in three major groups:

Construction costs

Material/equipment costs (pipe, pipe coating, cathodic protection, telecom & control equipment). Eventually intermediate booster stations (equipment & materials).

Booster station infrastructure (energy supply, fuel gas or power lines).

Installation & commissioning costs (equipment and labour).

Operation costs

Energy costs for head station (power for CO_2 compression at CO_2 source).

Energy costs for booster stations.

Pipeline inspection and monitoring cost.

Maintenance cost for compressor station.

Other costs

Design & project management.

Regulatory fees and taxes.

Insurances costs.

Right-of-way costs.

Contingencies.

During the final hydraulic design, it will be necessary to optimize pipeline investment and operating costs with regard to pipeline diameter and pressure loss. For this CO2EuroPipe study, hydraulic calculations were performed for fictive straight pipelines lengths of 300 and 500 km. Elevation differences and changes in pipe direction were not considered.

3.9   Calculations of pipeline capacity

In Figure 10, the results of numerous calculations are summarized for different pipeline sizes and a length of 300 km. Pipeline maximum capacity values are for a constant inlet pressure of 200barg and constant outlet pressure of 90barg at 5 ºC ambient temperature. The fluid will be in the dense (supercritical) phase, except during start-up (filling of the line). No phase changes will occur under normal operating conditions. Due to adiabatic expansion and heat transfer to surrounding soil, the fluid temperature for each pipeline diameter and throughput rate is calculated for each line segment. Summary curves are shown in Figure 10.

Simulation Summary   Case File: CO2-AO1.xls

Pipeline Lengths 300 Km

Pipeline Size	Mass flow			Volume Flow	
	kg/h	Mio ton/a @ 365 days	Mio ton/a @ 7500 h	Act.m3/h @ 201 bar; 50 ºC	Std vap @ 0 C m3/h
10" / NW 250	180.500	1,58	1,35	260	91.910
12" / NW 300	273.600	2,40	2,05	394	139.300
14" / NW 350	354.200	3,10	2,66	510	180.400
16" / NW 400	499.500	4,38	3,75	719	254.400
18" / NW 450	687.800	6,03	5,16	991	350.300
20" / NW 500	899.000	7,88	6,74	1.295	457.900

Figure 10: Calculations of pipeline capacities. Source: RWE.

A potential use of the CO_2 pipeline as natural gas line has been discussed. This could offer following commercial and legal/approval strategic benefits:

Accelerating the approval process if the pipeline would be built within current legal framework and initially used as gas transport (and storage) line with the option of later change to a CO_2 pipeline when regulatory framework and approval processes are available for CO_2 transport and storage.

Legal uncertainties and commercial risks would be reduced if the pipeline could be approved as a multi-product line.

Pipeline construction could be bundled with other planned pipeline projects that are in competition for the same main pipeline route.

4   CO$_2$ transport network

4.1   Technology challenges on the way to reuse

A number of gaps in knowledge represent obstacles on the way to reuse existing pipeline in-frastructure.

CO$_2$ corrosion at existing pipes has to be tested in greater depth to prevent risks, due to the fact that not all impacts of corrosion are known. Uncertainties exist regarding cross effects of CO$_2$ and of impurities in the CO$_2$ stream and effects of these impurities on storage formations at selected sites. The knowledge regarding the Equation of State for different combinations of impurities has to be improved. Furthermore pipeline-monitoring with, for example, pigging could especially be a risk for soft materials (rollers, discs) because exact pipeline routing or internals like unpiggable valves are unknown.

Sudden pressure releases may challenge existing seals (but not new pipelines, as they will be equipped with metal gaskets). Will they break when an explosive decompression of CO$_2$ takes place? Also, some soft materials like rubber will partly dissolve in dense phase CO$_2$. When existing pipelines shall be reused for CO$_2$, the possibility to switch to metal gaskets should be examined.

To minimise risks when reusing existing infrastructure, the simulation tools need improvement by additional experimental data. For instance, the pipeline flow behaviour during transient conditions (e.g. start-up, shut-in, blow-down) should be more carefully studied. This is also valid for the dispersion of CO$_2$ during leakages and especially blow-down.

The noise level during a blow-down is a well-known problem. Due to the fact that existing pipelines may be routed closer to populated area as new pipelines (which will be democrati-cally planned with all facets of modern land use planning) it might be difficult to build sufficient sound absorbers. Sustainable land use planning of new CO$_2$ pipelines can exclude this prob-lem.

4.2   Legal uncertainties

So far, a legal CCS framework is missing in Germany and The Netherlands. Hence, up to now it is not possible to clearly identify the legal pitfalls that might occur when reusing pipe-lines. Will the authorities ask for monitoring and inspection of these pipes in a way different from pipelines which in future will be natively built for CO$_2$ transport? What will be the legal situation for CO$_2$ being transported in a mingled infrastructure of old (reused) and new (CO$_2$-) pipelines, with CO$_2$ coming from different sources and being transported to a variety of sinks?

Today it seems that these legal uncertainties may prevent investment decisions. To minimize legal threats, it seems to be best to purely concentrate on newly built CO$_2$ transport network, which hopefully will materialized in a more precisely defined legal environment.

The procedures for land use planning with respect to CO$_2$ transport are not defined, including the aspects of right of way. Clear regulations for competent authorities as well as for the pub-

lic and for the developing CCS business need to be defined and deployed. In Germany, this applies for the national as well as the state level.

The CO_2 transport through different German states by pipeline (up to now) is planned to be regulated similar to the regulations of natural gas transport. There, one regional authority is granted the right to coordinate the permitting procedure in the name of all other affected authorities.

4.3   Transport within Germany

In Germany, more than 50,000 km of pipelines for natural gas are in place and in operation. A detailed map of the relevant research area for WP4.2 is illustrated in Figure 11. Over long distances, these pipelines are operated at pressures between 50 and 90 bars. As this is a difficult pressure regime for CO_2 (phase changes) and corrosion is a delicate issue (see chapter 3), the existing pipelines are not applicable for a reusability for CO_2 transport. Up to 2015, none of the existing pipelines will be available for CO_2. Furthermore, due to regulations in German law, the purpose for a pipeline (transport of a certain commodity) is fixed in the approval. Hence, the competent authority would have to start a new permitting process and then approve the reuse of an existing pipe for the new purpose of transporting CO_2.

The infrastructure for natural gas transport is even expanding in the coming years. Hence, from an economic point of view there is no reason to apply cuts to the infrastructure of the profitable transport of natural gas and to replace part of this infrastructure by a non economic business, the transport of CO_2.

Flowlines and existing infrastructure within oil and gas fields

Intrafield flowlines could be operated with CO_2 after the oil/gas fields will be depleted (after 2015). These flowlines normally have a design pressure above 100 bar and represent the existing infrastructure of the fields. Due to strict German rules of pipeline maintenance, there is a lot of information about the trim of these flowlines available. However, these flowlines could only bridge a short distance between major CO_2 sources and sinks.

4.4   Transport cross-border

According to WP2.2 (deliverable D2.2.1: chapter 6.2, page 35) cross-border transport is likely to reach 112 Mt/a by 2030 and 319 Mt/a by 2050, assuming the reference scenario. From a more progressive point of view, in the offshore-only scenario, cross-border will reach 3Mt/a already in 2020. This might climb up to 249 Mt/a in 2030 and to 861 Mt/a in 2050.

Figure 11: Networks of gas supply in Germany. Source: VGE, Verlag Glückauf Essen (2003).

The details of cross-border transport for this WP4.2 will be developed and explained in deliverable D4.2.2, to be finalized in 2011. This will include a barging concept cross-border with capacity data of inland channels, available barges and maybe cost data plus information about potential CO_2 hubs (location, capacity, ownership) along the NL-D-DK coast.

5   Summary

Sources of CO_2 within the research area as well as potential sinks are well known and described here. Different scenarios for the evolvement of capture technology are explained. A rather conservative scenario assumes that by 2020 a capture rate of 1 Mt/a might be reached within the test case area, 3.6 Mt/a in 2025, 14 Mt/a in 2030, 17 Mt/a in 2035 and 23 Mt/a in 2045 and 2050.

As explained in this report, in Germany all of the 50,000 km of pipelines for natural gas transport are in place and in operation for this one commodity. This infrastructure is expanding, very profitable and will not allow chances for CO_2 reuse by 2015, most likely by 2020.

There are a number of technological issues that undergo improvement at the moment. Especially the occurrence of corrosion at transport networks as well as the noise level during a blow-down are at the focus of research these days. The pipeline hydraulic design and the cost structure for the construction of a transport network are dealt with in this report.

The procedures for land use planning with respect to CO_2 transport are not defined, including the aspects of right of way. Clear regulations for competent authorities as well as for the public and for the developing CCS business need to be defined and deployed. In Germany, this applies for the national as well as the state level. So far, a legal CCS framework is missing in Germany and The Netherlands.