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Abstract

Sources of CO_2 within Northwestern Germany as well as potential sinks are well known and described here. Different scenarios for the evolvement of capture activities 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, 2.5 Mt/a in 2025, 10 Mt/a in 2032, and 20 Mt/a in 2040 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 2025. However, the pipeline hydraulic design and the cost structure for the construction of a CO_2 transport network are dealt with in this report.

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

For the period 2020 – 2050, this report presents an outlook on the transport infrastructure for CO_2 in northwest Germany. The infrastructure is based on the most up to date databases and on current corporate and national CCS plans as well as on storage feasibility studies. Company plans of CCS developments were used as a basis in matching the gradually growing captured masses with storage capacity that gradually becomes available. The aim of this report is to identify likely transport corridors and to estimate the order of magnitude of transported masses in a future CCS infrastructure.

EXECUTIVE SUMMARY

In SP2 and SP3 within CO2Europipe a basic knowledge about CO_2 transport has been established. Generic information is of fundamental value, but the case studies (like this WP4.2) may be used to illustrate particular aspects and to give examples of how specific system assumptions result in a certain geographic routing, technical solutions and cost estimates. These assumptions narrow down the generality of the results of this study. This is valid for instance with respect to transport alternatives and volumes. These boundaries, however, allow to elucidate the CO_2 transport options within northwestern Germany in a much more precise way than from a bird eye perspective. Partly, results from previous studies performed by some participating companies have been included. Mainly, this study is based on work done within CO2Europipe.

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 activities 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, 2.5 Mt/a in 2025, 10 Mt/a in 2032, and 20 Mt/a in 2040 and 2050.

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, most likely even after 2025. However, the pipeline hydraulic design and 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 and cross-border transport. Clear regulations for competent authorities as well as for the public and for the developing CCS business need to be defined and deployed. So far (July 2011), a legal CCS framework is missing in Germany and The Netherlands. The draft of the German CCS law allows cross-border CO_2 transport. Also, expropriation (e.g. compulsory acquisition of ground) will be possible.

For the period 2020 – 2050, this report presents an outlook on the transport infrastructure for CO_2 in northwest Germany. The infrastructure is based on the most up to date databases and on current corporate and national CCS plans as well as on storage feasibility studies. Company plans of CCS developments were used as a basis in matching the gradually growing captured masses with storage capacity that gradually becomes available. The geographical distribution and timing of emission points (capture locations) and available storage capacity largely dictates the shape of the transport network. The aim of this project is to identify likely transport corridors and to estimate the order of magnitude of transported masses in a future CCS infrastructure. This future infrastructure is not designed in detail. CO_2 point sources and storage locations have been grouped together into clusters, connecting capture clusters with storage clusters.

Within Germany and the Netherlands, there is a large potential for CO_2 pipelines and inland CO_2 barging to both German and Dutch seaports. This is driven e.g. by the fact that ample troughput capacity exists on the considered waterways. Inland shipping is capable to circumvent the complexities and lengthy permit application procedures for pipeline transportation. A preferred scenario is to transport CO_2 from the Rhineland and Ruhr area down the Rhine to Rotterdam/Maasvlakte – as this route allows for the largest convoy size and subsequent highest volume transfers.

(Politically motivated) prohibition against onshore CO_2 storage will reduce the amount of CO_2 stored per year by approx. 20%. Thus, an optimal, low-cost connection of CO_2 sources and sinks that is in line with CO_2 emission reduction targets is only possible if no political hurdles (especially if technically unjustified) are placed in the paths of CCS projects.

The IEA has established that CCS is the 2nd cheapest option to reduce CO_2 emissions. Timely and cost-effective transport infrastructure for CO_2 (on- and offshore) is essential for large scale deployment of CCS in Germany. Thereby, CCS can contribute very significantly to the CO_2 reduction goals of Germany and the EU while maintaining the profitable growth and export of the German industrial heart land as the motor of the national economy and Europe at large. We urge the leaders in Europe to communicate these goals clearly and establish rules and legislation that facilitate timely deployment of a large CO_2 transport infrastructure.

PROJECT SUMMARY

The CO2Europipe project contributes to defining the framework for 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 preconditions using a number of realistic scenarios. These 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, summarized in [D1.1.1]:
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.

This report D4.2.2 focusses on the German specific situation for a potential future CO_2 transport network. Most reasonable routes for pipe and ship transport within Northwestern Germany are worked on here. This report is embedded in recommendations given by other parts of the project CO2Europipe to enable the development of a large-scale European CO_2 transport 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 New Build and Engineering	United Kingdom
Stedin BV	Netherlands

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Making CO_2 transport feasible: the German case

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

TABLE OF CONTENTS

Page

TABLE OF FIGURES

Page

final WP4.2 project report

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Main authors: chapters 1 to 4, 10, 11: RWE; chapter 5: AV; chapter 6: CO2-Net; chapters 7 to 9: 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 [D2.1.1, D2.2.1, D2.3.1, D3.1.1, D3.1.2, D3.2.1, D3.3.1].

1 Summary

Sources of CO_2 within Northwestern Germany 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, 2.5 Mt/a in 2025, 10 Mt/a in 2032, and 20 Mt/a in 2040 and 2050. These numbers imply the construction of a barge and pipe infrastructure. If pipeline transport should be the focus, these numbers call for the construction of around 600 km pipeline by 2025, ca. 2000 km by 2032 and about 4000 km by 2040.

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 2020, most likely by 2025.

There are a number of technological issues that are undergoing improvement at the moment. Especially the occurrence of corrosion in transport networks as well as noise levels 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 CO_2 transport network are dealt with in this report.

The procedures for land use planning with respect to CO_2 transport are currently 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 (July 2011), a legal CCS framework is missing in Germany and The Netherlands. Existing natural gas laws will not be applied. The draft of the German CCS law plans to allow cross-border CO_2 transport. Also, expropriation (e.g. compulsory acquisition of ground) for CCS purposes will be possible.

Conclusions

1. CO_2 storage capacity is not a limiting factor in the development of large scale CCS infrastructure, also within the test case area of WP4.2.

2. Available storage capacity is, however, not evenly distributed over the area considered, with the larger part located in the North Sea.

3. Transport infrastructure construction efforts will be considerable, but lowest when onshore storage and cross-border transport are possible.

4. International cooperation and alignment of infrastructure developments and cross-border transport is required for an efficient CCS transport network in Europe.

2 Introduction and Methodology

CO2Europipe aims at important contribution towards large-scale Europe-wide infrastructure for transport and injection of CO_2 from the capture plants. The project identifies and disseminates the technical, organisational, financial, political and societal barriers to large scale CO_2 infrastructure development. Advice is given on how they can be overcome. The project delivers a road map of European CO_2 transport infrastructure.

The project aims at:

1. information about how CCS can become viable (e.g. carbon price)
2. strategies to make CCS work
3. confirmation that CCS is an international issue, with need for EU oversight.

This workpackage WP4.2 scales these topics down to the regional context of one test case. For the period 2020 – 2050, this final report within WP4.2 presents an outlook on the transport infrastructure for CO_2 in northwest Germany. For simplification, the term “northwest Germany” is used here as analogue term for the WP4.2 research area “Rhine/Ruhr – Hamburg – NorthSea”. The infrastructure is based on the most up to date databases and on current corporate and national CCS plans as well as on storage feasibility studies. Company plans of CCS developments were used as a basis in matching the gradually growing captured masses with storage capacity that gradually becomes available. The geographical distribution and timing of capture locations and available storage capacity largely dictates the shape of the transport network. The aim of this project is to identify likely transport corridors and to estimate the order of magnitude of transported masses in a future CCS infrastructure. This future infrastructure is not designed in detail. CO_2 point sources and storage locations have been grouped together into clusters, connecting capture clusters with storage clusters.

At the moment, opinions regarding CCS are differing in politics and the public. The region of WP4.2 is the Western German Rhineland and Ruhr area, which is a major European source for CO_2 emissions. If the society as a whole would really like to considerably reduce CO_2 emissions, this area has to be linked (mainly by pipeline) with major CO_2 storage areas in Northern Germany and in the Southern North Sea. In Northwestern Germany, there are some more big point sources of CO_2 emissions, especially around the cities of Bremen, Wilhelmshaven and Hamburg. This is why WP4.2 is named the Rhine/Ruhr-Hamburg-NorthSea case. An additional transport option, which is also considered here, is the transport (by ship or pipe) down the Rhine to the planned CO_2 hub near Rotterdam (see D4.1.1).

WP4.2 is subdivided into subtasks. These are:

a) CO_2 sources and sinks for this test case
b) Technical aspects of CO_2 transport in NW Germany
c) Financing mechanism of CO_2 transport in NW Germany
d) Risk assessment of CO_2 transport in NW Germany

WP4.2 uses the project-internal work within SP2 and SP3 as valuable input for defining the framework of this test case (D2.2.1, D2.3.1). Additionally, the regional transport links with WP4.1 (Rotterdam case, D4.1.1) and WP4.3 (Norway case, D4.3.1, D4.3.2) are considered. These links as well as an increased focus on gas are regarded as vital if a European CO_2 transport network (including cross-border transport) should reach true realization.

The approach (methodology) is to analyse the base facts first. Firstly, precise maps of the major (>250 kt/a) CO_2 sources and sinks in the test case area have to be deduced from public information (D2.2.1). Secondly, mainly technical details like pipeline layout, routing, booster stations and purity of CO_2 have to be engineered. Part of the basics is also the societal and political background. Here we have to state that within the CO2Europipe project period (2009-2011) the political CCS sky was clouding. Because of public and therefore political concern, projects on CO_2 transport were scaled down. As part of the methodology, financing mechanisms of CO_2 transport were developed, keeping the given background conditions in mind. Finally, the technical risks of CO_2 transport were elucidated to conclude on advice for lowering HSE risks along planned transport routes within WP4.2.

To date, the German federal government drafts a national CCS law, which is planned to pass the two chambers of German parliament (Bundestag and Bundesrat) by 23.09.2011. So far (draft July 2011, e.g. §4) the CCS law does provide regulations for cross-border transport, but not for offshore storage. Some attorneys and barristers interpret this as a legal ban on e.g. offshore storage. The aim of WP4.2 was and is to describe the background (technically, economically, politically, and legally) needed to initiate a CO_2 transport network from the Rhine/Ruhr area towards the North Sea. However, WP4.2 also comments on the likelihood that such a network will become reality. As explained, to date some existing boundary conditions hinder rather than foster its realization.

3 CO_2 sources and sinks for the NW German 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 2008), 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. These data were linked with a study verifying the CCS project plans in terms of likelihood of realization (RWE 2010).

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 a study by the Wuppertal-Institute (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 north-west* 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).

(Mt/a = Million metric tons per year)

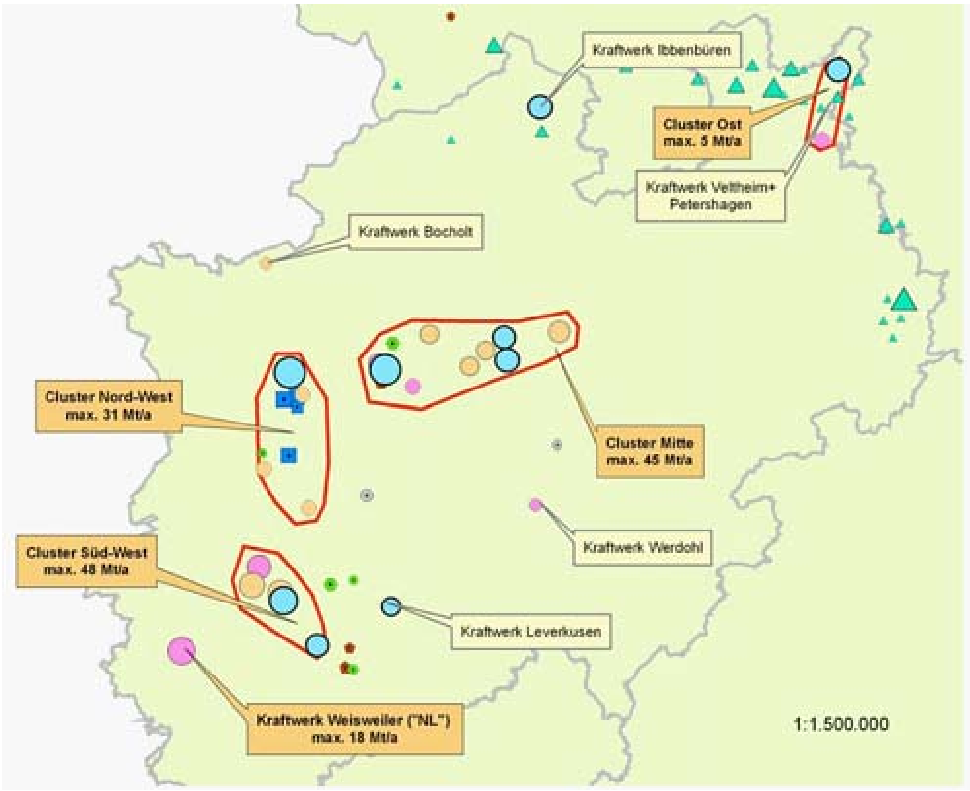

Figure 1: Major single CO_2 sources in the state of NRW, Germany. Source: W-I (2009). NRW = German state of North Rhine-Westphalia.

Emissions from the Hamburg/Bremen region are 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 (2010), 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 and 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.

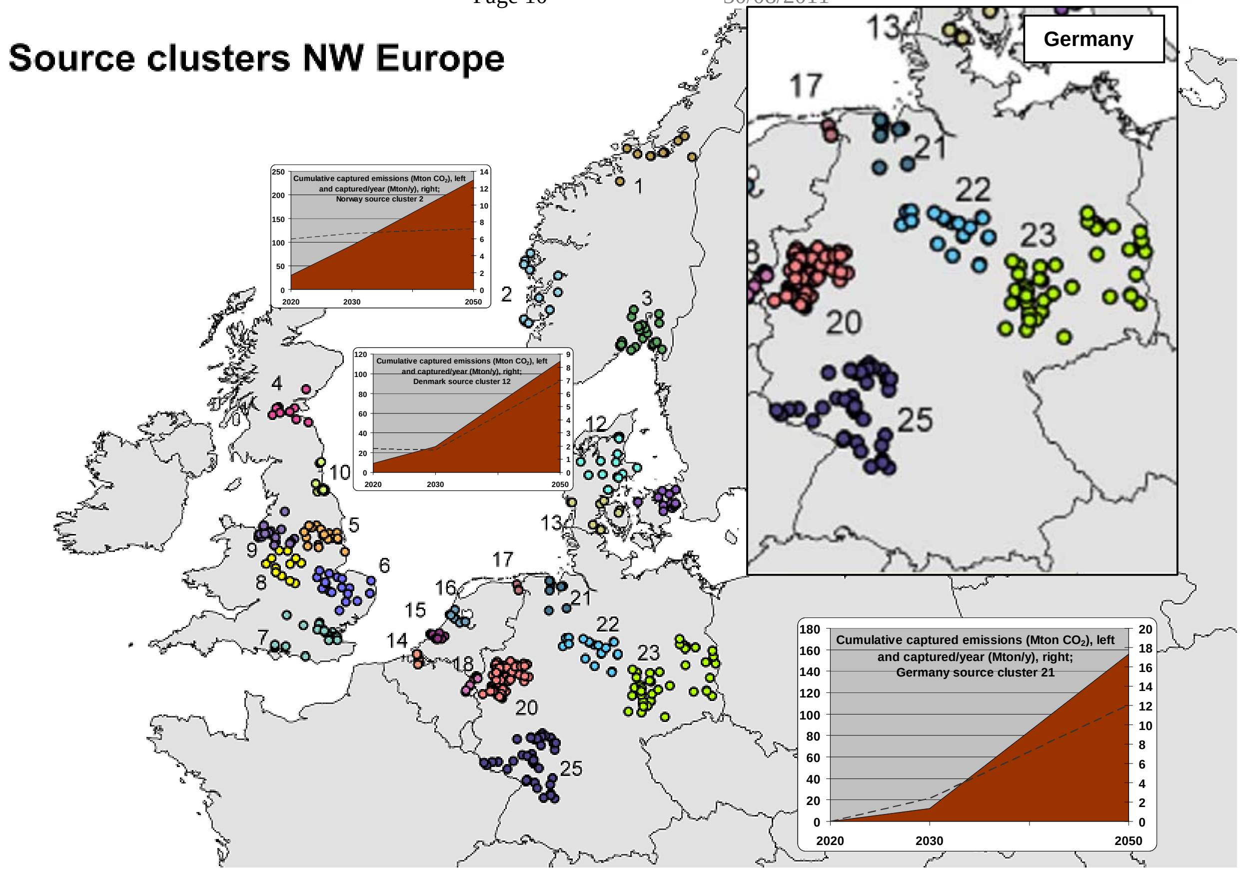

Figure 2: CO_2 source clusters in North West Europe; from D2.2.1 (2010).

According to D.2.2.1 (2010), the total amount of the emissions included in cluster number 21, near Hamburg, was 12.432 Mt per year (figures from 2005).

Once the CCS business leaves the pilot and demo phases and reaches 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 (Hamburg/Bremen region) over 2020, 2030 and 2050.

		2020	2030	2050
Cumulative captured emissions	[CO2 Mt]	0	11,8	155,9
Captured emissions per year	[CO2 Mt/yr]	0	2,4	12

Table 1: Emission projections for 2020, 2030 and 2050 for cluster 21 (shown in figure 2).

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 industry-scale project in 2020. It starts with minor captured quantities of around 2.5 kt/a and reaches about 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 reaches 0.5 Mt/a in 2018, 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 conservative outlook is incorporated in **Scenario 3**. Following this path, around 2.5 Mt/a would be reached in 2025, 10 Mt/a in 2032, and 20 Mt/a in 2040 and 2050 (Figure 3). These numbers imply the construction of a barge and pipe infrastructure. If pipeline transport should be the focus, these numbers call for the construction of around 600 km pipeline by 2025, ca. 2000 km by 2032 and about 4000 km by 2040. Finally, **Scenario 4** is rather CCS-sceptic, keeping low public acceptance in mind. Here, CO_2 capture from WP4.2 does never exceed 5 Mt/a. These quantities could be increased by 3 to 7 Mt/a coming from sources in the Hamburg area.

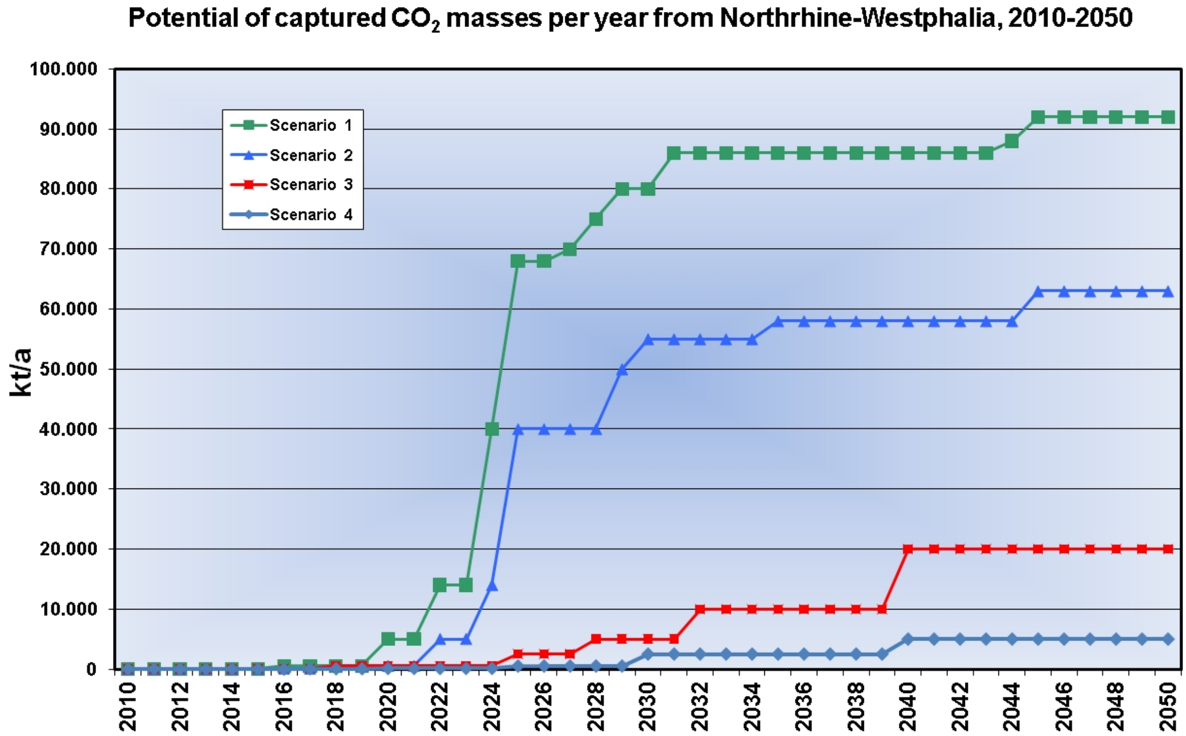

Figure 3: Four scenarios of CO_2 capture deployment in NRW, Germany. Sources: W-I (2009); RWE (2010).
NRW = German state of North Rhine-Westphalia.

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

Just from comparing CO_2 source size numbers with those of CO_2 sinks, one could deduce that there is more than sufficient storage capacity for the CO_2 from WP4.2 up to the year 2050 and beyond. According to WP2.2 (D 2.2.1, 2010, appendix A, pages 50-54) realistic CO_2 sinks which guarantee permanent containment are old depleted gasfields (EGR, DGR), old depleted oilfields (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 D 2.2.1 (2010). (Mt/a = Million metric tons per year)

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

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 D 2.2.1 (2010).

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 D 2.2.1 (2010).

Looking at the Hamburg/Bremen area and the natural gas network already in place, a short comparison of pipeline corridors and pipeline dimensions related to a needed new infrastructure for CO_2 in this specific region is made.

Figure 4: Existing natural gas pipeline network in the Hamburg/Bremen region. Source: VGE (2003).

Referring to report D2.2.1, Figure D.1, storage clusters (aquifers and gas fields) onshore that are suitable for CO_2 exist to the north/northeast and south/southwest of Hamburg. Figure 4 shows that it has been possible to find pipeline corridors for large pipelines especially southwest of Hamburg and westwards thereof, for the natural gas network (of course depending on the locations of natural gas fields and the areas of highest gas demand). But, it should be kept in mind that adding another infrastructure for CO_2 could still be a challenge, because of population density and (by July 2011) non-established regulations for CO_2 pipelines in Germany. Geography in the region is such, that if a CO_2 source is located in or at the Hamburg urban area, and the CO_2 is planned to be transported from there, it would be easier to find a pipeline route southwest from Hamburg than northeast, depending on the varying population density in the region and topographic characteristics of the urban area. Also safety aspects are important here (see chapter 7 on risk assessment). On the west coast, where CO_2 hubs for export by pipeline or ship offshore might be planned and installed, some nature protection areas (esp. “Norddeutsches Wattenmeer”) occur in the vicinity – and have to be considered.

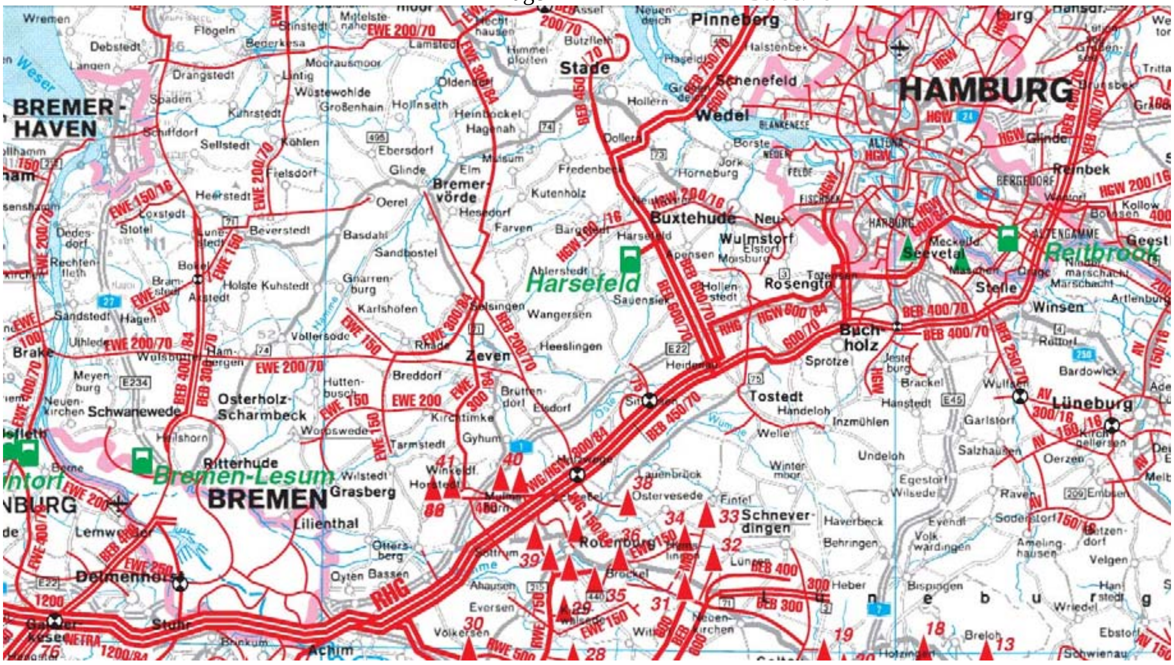

Figure 5: Excerpt (zoom-in) of Figure 4. Dimensions are given for each natural gas pipeline. Example: 450/70 means a diameter (DN) 450 mm and pressure (PN) 70 bar. Source: VGE (2003).

Referring to report D4.2.1, Figure 10, the pipeline dimensions needed for the expected CO_2 amounts in the CO2Europipe scenarios will be large, up to 500 mm diameter (or even more). These required CO_2 pipeline dimensions would be comparable to the dimensions of the natural gas pipelines in the Hamburg/Bremen region, as can be seen in Figure 5. However, operational pressures for dense phase CO_2 in pipes will be higher (typically >100 bar) than for the existing pipelines (see chapter 4).

So to conclude, **there is a wealth of storage capacity in place**. From the WP4.2 area, CO_2 could be transported to Northern Germany (on- and offshore) and additionally offshore to the North Sea sectors of Germany, Denmark, the Netherlands, the UK and Norway. Saline aquifers, depleted gas-fields and depleted oilfields offer a theoretical storage capacity of more than 90,000 Mt. Assuming a mass of captured CO_2 of around 20 Mt/a by 2040 (see Figure 3: capture scenario 3), **less than 0.3‰ of gross storage capacity would be called upon every year.**

CO_2 emissions within the EU-27 – if current CO_2 emission reduction targets are taken seriously – will significantly decrease. Plants participating in EU-ETS will have a disproportionately high share in this reduction as they permit relatively inexpensive emission reduction measures to be implemented. According to Blesl & Kober (2010) in 2030, 195 to 255 mill. t/a of the emission reductions achieved in the EU-27 will be attributed to the use of CCS. By 2050, this amount is to increase to between 605 and 795 mill. t/a. Based on the same calculations, between 65 and 80% of these CO_2 quantities will be captured in Germany, the UK, the Netherlands, Denmark and Poland and stored in these countries plus Norway. According to Blesl & Kober (2010), Germany (and thus essentially the region considered in WP4.2) will have a share of 45% in the stored quantities of the EU-27 in 2030.

Even if the absolute numbers of the captured quantities are certain to differ from the above in reality, it becomes apparent that the region considered within CO2Europipe is bound to house the centre-piece of the European CCS infrastructure one day.

What is vital to the connection of CO_2 sources and CO_2 sinks is the permission to transport CO_2 across borders and to store it both on- and offshore. According to Blesl & Kober (2010), a (political) prohibition against onshore storage (as it exists in the UK, the Netherlands and Denmark and is being discussed in Germany) will lead to a doubling of cross-border CO_2 transport after 2030 compared with a scenario of free access to on- and offshore storage facilities. This applies if the ambitious climate protection targets are maintained at the same time.

However, Blesl & Kober (2010) also draw the conclusion that a (politically motivated) **prohibition against onshore CO_2 storage will reduce the amount of CO_2 stored per year by approx. 20%.** Thus, an optimal, low-cost connection of CO_2 sources and sinks that is in line with climate protection targets is only possible if no political hurdles that are technically unjustified are placed in the paths of CCS projects.

4 NW German case specific technical aspects of CO_2 transport

CO_2 transport is considered to be the lowest cost element of CCS. This is true as long as compression costs are allocated with capture. However, transport may be the element that needs most planning and guidance during its development. Recently, several outlooks on the transport infrastructures required for CCS have been published and possible networks were published for various regions (e.g. BERR 2007; DTI 2007; Haszeldine et al 2009). Most studies conclude that infrastructure development is feasible in principle, but that significant hurdles exist at the regulatory level, rather than technical level. The focus in this study is on north-western Germany.

Logistically the transport, situated after the CO_2 capture facilities and delivering a link to storage-sites, can be performed in different systems. The choice for a 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 6 shows an overview of different transport options.

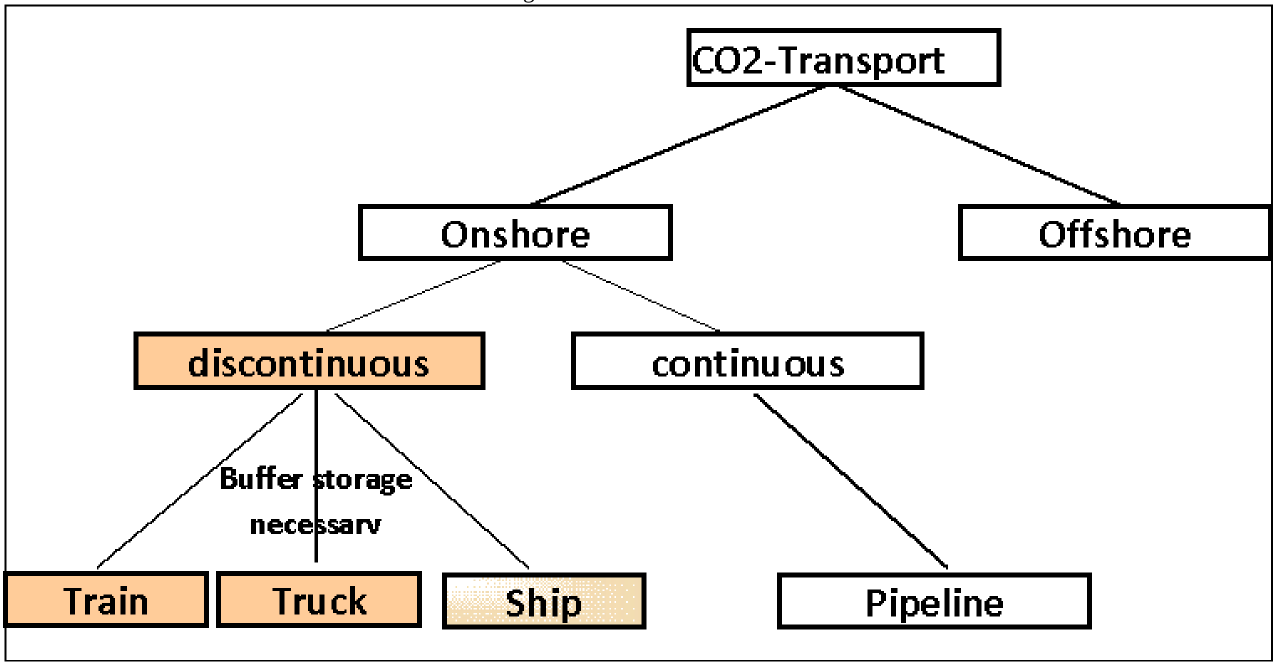

Figure 6: Continuous and discontinuous transport option.

Transport via pipeline is continuous transport (Figure 6). The transport via ships, trucks and rail represents discontinuous options. The combination of both transport types is generally possible. However, in such cases additional intermediate storage is required, which is possible in steel tanks or underground storage formations.

The transport by pipelines for CO_2 masses of more than 1 Mt/a is the most economic alternative. Worldwide a lot of experience in construction and operation of off- and onshore pipelines exists. The biggest CO_2 volumes (esp. for EOR/EGR) are transported by pipelines in USA, Canada and Turkey. The pipeline network for CO_2 in North America is already more than 3500 km long. The pipelines run through deserts but also densely populated areas. The oldest US CO_2 pipeline was built in 1972.

Design of pipelines implies optimization between the following factors:

- Diameter,
- Wall thickness,
- Pressure variations (e.g. due to topography of pipeline route),
- Flow rates,
- Operation period.

Additionally, parameters like pressure, temperature and the quality of the CO_2 have to be considered. A booster station maybe required (at distances above 300 km). All these parameters influence the choice of material. In the USA, carbon steel is the material of choice for CO_2 pipelines. Long utilization periods of decades and the option of 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 D4.2.1).

Corrosion

Corrosion is a physical and chemical process deteriorating the quality of pipe material. Hence, corrosion causes a deep impact on the safety of pipeline operations. To provide long term resistance to corrosion, a variety of corrosion resistant alloys (CRAs) is used. Depending on the specific environments which are encountered in CO_2 capture, transport and storage, different CRAs are employed. Key environmental parameters influencing the corrosion properties of CRAs are:

- Temperature
- Partial pressure of CO_2
- Partial pressure of H_2O
- Partial pressure of H_2S
- Chloride ion concentration
- Environment pH (partial pressure of H^+)
- Presence of other (esp. acidic) contaminants, like free oxygen

These parameters have an influence on:

- The stability of a passive film on CRAs surface (initiation of pitting)
- Ease/complication of repassivation of initiated pits
- Rates of dissolution of metal from pits
- Development of brittle cracks

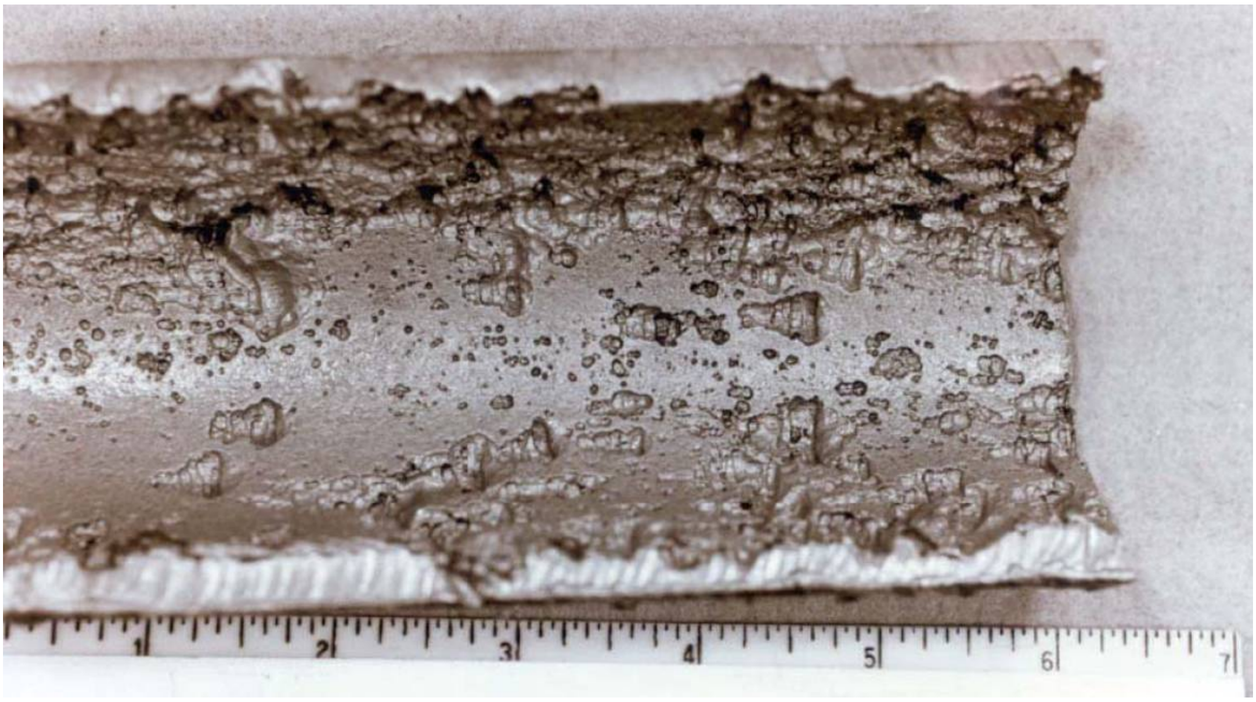

Figure 7: Typical morphology of CO_2 corrosion in downhole tubing at a US site (RWE 2009).

The choice for a specific CRA depends on the given environment and the expected operating conditions. Within this frame, the safest and most cost-effective CRA option is to be chosen.

Pure dry CO_2 is essentially non-corrosive. However, if dry supercritical CO_2 receives water and reaches water saturation, the velocity of corrosion processes increase by about three orders of magnitude (i.e., by around factor 1000). Russick et al (1996) and Seiersten (2001, see table 5) investigated corrosion rates in detail. Water could also accumulate in low-point regions of the pipeline along the route which could cause local corrosion. The impact of impurities in the CO_2 stream is still subject to research with respect to corrosion and physical behaviour, e.g. changes in the phase diagram (ZEP 2011).

Material	**Conditions**	**Corrosion rate (mm/year)**
Carbon Steel AISI 1080	Dry supercritical CO_2 90-120 bar CO_2, 160-180°C during 200 days	0.01 mm/year
X-60 carbon steel	3 and 22°C at 140 bar CO_2, 800 -1000 ppm H_2O and 600-800 ppm H_2S	0.5 µm/year
Carbon steel	Export gas pipelines (typically dried to dewpoint 10degC below minimum operating temperature)	0.25-2.5 µm/year
Carbon steel	Wet CO_2, pH 3.5, 50 bar	13 mm/year
Carbon steel	Wet CO_2 10 to 52 bar at 40°C	LPR (Linear Polarisation Resistance) results 14-23 mm/year Weight loss results 1-7 mm/year
Carbon steel API 5L x65 (Kongshaug)	CO_2 saturated 1% NaCl solution, 10-80 bar CO_2, 50°C	4-7 mm/year
Carbon steel (Hesjevik et al)	CO_2 saturated 1% NaCl solution, 35 bar, 24°C 128 hours	3.2 mm/year

Table 5: Corrosion rates of carbon steel in CO_2 environments (RWE 2009, drawn from Seiersten 2001). Units: mm = millimeters, µm = micrometers.

However, effects of certain additives are also well known, which decrease the corrosion rate. Kongshaug & Seiersten (2004) show that monoethylene glycol (MEG) can have this effect. As a conclusion, to prevent or reduce corrosion in a CO_2 transport network, the transported medium in any case has to be water-undersaturated. Additionally, adding components like MEG should be considered and decided upon case-by-case.

For the Rhine/Ruhr case, preliminary mechanical design has been performed. Results have been used for hydraulic/pressure drop calculations. Final wall thickness and grade of material selected needs to be specified during detailed design. 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 – parallel to compliance with common practice safety. All these factors influence and determine the required wall thickness and material grade.

For the Rhine/Ruhr test case, a pipeline with no booster station all along its way is designed. Due to higher operational costs (80 – 100 €/MWh for electricity supply from grid) and resulting additional CO_2 emissions for generating this power, an installation of midline booster stations should only be considered for a de-bottlenecking or short term pipeline capacity increase. The Rhine/Ruhr test case shows that only high pressure compression at the power plant capture site is required for CO_2 transport – thereby reducing energy costs, CO_2 emissions and the need for extra booster equipment along the pipeline trajectory.

Pipeline transport of CO_2 is not new. More than 4,200 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. Most of the CO_2 pipelines exiting today transport CO_2 from natural reservoirs whereas the predicted volumes of CO_2 in Europe, referred to in this report, would be captured CO_2 from industrial sources and power production. The chemical composition of the CO_2 stream will vary depending on the source and therefore also the technical requirements for the pipeline.

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. 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 Ormen Lange submarine gas export pipeline (42"/44" Diameter) from Nyhamna (Norway Coast) via Sleipner Platform to the Langeled Terminal (UK Eastern Coast) is designed for an operating pressure of 250bar. Short interfield pipelines and sub-sea flow lines are operated at pressures up to 500 bar. Most of the CO_2 pipelines worldwide are operated in the range of 150 to 230 bar (IPCC 2005). There, CO_2 is in its dense phase.

Capital investment and operating costs of pipelines generally increase when intermediate compressor stations are required to compensate for pressure losses along the pipeline. Normally, (natural gas) pipeline compressor stations are installed for matching seasonal demand changes, only. Omitting compressor stations reduces the complexity of the CO_2 transport system and improves the availability of the network.

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 pipeline layout will be a compromise between investment, operating costs, the long-term business strategy, and CO_2 policy of the operating company/consortium.

5 Ship transport of CO_2 on inland waterways in NW Germany

5.1 Introduction

Transport of CO_2 in quantities of kilotonnes/load and more can be realized by pipeline or ship. Ship transport would be an alternative for projects with a few 100 kt CO_2/a or in an early phase of a big-scale CCS project, during pipeline construction. Additionally, small scale projects with a remotely located storage site can have use of ship transport, rather than constructing pipelines. Ship transport of CO_2 is favourable for sources that are located close to the coast or to a waterway, for easy access to ship loading facilities. Hence, ship transport is most interesting when a port is available and a CO_2 hub can be built there.

Due to its flexibility, ship transport is also an option for sources that produce low or fluctuating volumes of captured CO_2. Storage sites that are amenable to supply by ship include depleted gas and oil fields that are either small or located far from a CO_2 trunk line. Ship transport can also be used during the start-up of CCS in a cluster of sinks, during the construction of a pipeline network.

Work package 4.2 provides a view on cross border transportation between The Rhine/Ruhr area to the Netherlands and Hamburg. CO_2 piping trough densely populated areas imply lengthy and complex permitting procedures in both German and Dutch territories. Hence, here the inland waterway CO_2 transportation capacity in North Western Europe is assessed. In order to do so this document is to provide a high level overview of different barging scenarios for (liquefied) CO_2 from large inland emitter sources within Germany to Dutch and German seaports. From these seaports the CO_2 can be shipped to offshore sinks by ship and/or pipeline.

CO_2 transportation is not a novelty, but only a few inland CO_2 barges exist today. No data relating to the shipment of this cargo is available. The scenario selection for this analysis was based on the following criteria:

1. **Expected inland sources' CO_2 capturing rate:** Capture rates of the sources must be sufficient to support the CO_2 transportation project. Herewith, sufficient is defined as economically feasible, e.g. a barge filling rate of at least 80% is assumed. Capturing volumes that increase over time will favour a barging concept due to its flexibility that can accommodate changing demand. Existing information regarding 2030 CO_2 capturing rates from WP2.2 is used.

2. **Distance from source to a large inland waterway:** Sources must be at or near a major waterway to enable (cost) efficient CO_2 barging – no additional piping is needed to transport captured CO_2 from emitter site to the inland water way loading port/terminal. It is assumed that sufficient plot space is available to accommodate liquefaction and intermediate storage facilities.

3. **Distance from the source to a suitable seaport:** A seaport is considered suitable if it can be reached via inland waterways without having to cover excessive distances above 400 km. It is also deemed realistic that existing CO_2 trades from the considered seaport to offshore sinks will enhance the feasibility of inland CO_2 shipping. This is due to the fact that CO_2 handling facilities (intermediate storage, liquefaction, loading terminal) are already in place parallel to offshore exit flows of the CO_2 – being by piping or by ship.

4. **Waterway capacity:** The overall transport capacity of the inland waterway under consideration must be sufficient to accommodate the barge transportation of CO_2. With the limitations on barge convoy dimensions imposed by the Conférence Européenne des Ministres de Transport (CEMT 1992, http://www.internationaltransportforum.org) and the assumption that capacity growth is safeguarded (BVB 2009) it was concluded that the selected waterways can cope with the increased number of barge convoys that CO_2 volumes would command although exact determination of the throughput capacity of the Rhine was impossible to make due to the lack of data.

5. **Allowable convoy size:** The maximum allowable convoy size (combination of linked barges and push boat – i.e. length, breadth, height, draft) between a source and a seaport was chosen as large as regulatory possible to enhance overall transportation capacity. In Table 6 an overview of allowed convoy sizes is given as a function of the different categories the inland waterways are sub-divided in. These categories formed the basis for the scenario selection.

In order to harmonise waterway dimensions in Western-Europe, inland shipping in Europe is divided into CEMT classes. The term 'CEMT class' refers to the Conférence Européenne des Ministres de Transport, which established these classes (CEMT 1992). According to the system, each class has maximum sizes for vessels and push-tug combinations. The classification helps to determine where particular vessels are allowed to travel based on bridge heights and lock sizes, draught, waterway width and so forth. Nowadays, however, the figures in Table 6 no longer fully represent the current

West-European fleet as a result of scaling-up and the widespread extension and expansion of ships. Nevertheless, CEMT classification still serves as a reliable basis of many of the official documents related to inland shipping and is applied here.

Type of inland waterways		Classes of navigable waterways	Motor vessels and barges – Type of vessel: General characteristics					Pushed convoys – Type of convoy: General characteristics					Minimum height under bridges 2/	Graphical symbols on maps
			Designation	Maximum length	Maximum beam	Draught 7/	Tonnage		Length	Beam	Draught 7/	Tonnage		
				L(m)	B(m)	d(m)	T(t)		L(m)	B(m)	d(m)	T(t)	H(m)	
1		2	3	4	5	6	7	8	9	10	11	12	13	14
OF REGIONAL IMPORTANCE	To West of Elbe	I	Barge	38.5	5.05	1.80-2.20	250-400						4.0	
		II	Kampine-Barge	50-55	6.6	2.50	400-650						4.0-5.0	
		III	Gustav Koenigs	67-80	8.2	2.50	650-1,000						4.0-5.0	
	To East of Elbe	I	Gross Finow	41	4.7	1.40	180						3.0	
		II	BM-500	57	7.5-9.0	1.60	500-630						3.0	
		III	6/	67-70	8.2-9.0	1.60-2.00	470-700		118-132	8.2-9.0	1.60-2.00	1,000-1,200	4.0	
OF INTERNATIONAL IMPORTANCE		IV	Johann Welker	80-85	9.5	2.50	1,000-1,500		85	9.5 5/	2.50-2.80	1,250-1,450	5.25 or 7.00 4/	
		Va	Large Rhine vessels	95-110	11.4	2.50-2.80	1,500-3,000		95-110 1/	11.4	2.50-4.50	1,600-3,000	5.25 or 7.00 or 9.10 4/	
		Vb							172-185 1/	11.4	2.50-4.50	3,200-6,000		
		VIa							95-110 1/	22.8	2.50-4.50	3,200-6,000	7.00 or 9.10 4/	
		VIb	3/	140	15.0	3.90			185-195 1/	22.8	2.50-4.50	6,400-12,000	7.00 or 9.10 4/	
		VIc							270-280 1/ 195-200 1/	22.8 33.0-34.2 1/	2.50-4.50 2.50-4.50	9,600-18,000 9,600-18,000	9.10 4/	
		VII						8/	285	33.0-34.2 1/	2.50-4.50	14,500-27,000	9.10 4/	

Table 6: Classification of European Inland Waterways (CEMT 1992).

5.2 CO_2 barging transport scenarios

Taking the above listed criteria into consideration and using the estimated CO_2 capture data compiled in WP 2.2, four sources and three seaports were selected. The source location centres in Germany are Düsseldorf, Hannover, Rosslau and Mannheim and are predicted to capture in 2030, 35 Mt/a, 4 Mt/a, 18 Mt/a anf 8 Mt/a of CO_2 respectively (see WP2.2). An overview is given below in Table 7; the CO2Europipe cluster coding from WP2.2 (D2.2.1, see there) is respected.

The destination ports are selected in line with the current likely CO_2 hub locations and their accessibility from the hinterland via inland waterways. The seaports chosen are Rotterdam, Wilhelmshaven, Brunsbüttel and Ijmuiden.

Source areas	Cluster code (Europipe)	Center location	Cluster prod in 2030 [mmtpa]
Ruhr Area	20	Dusseldorf	35
	22	Hannover	4
	23	Rosslau	18
	25	Mannheim	8

Destination areas
Rotterdam
Willemshaven
Brunsbuttel
IJmuiden

Table 7: Selected sources and seaports used for creating scenarios (Source CO2Europipe, D2.2.1)

With these source clusters and destination ports, six different CO_2 barging transport scenarios were generated (see Figure 8 and Table 8 below).

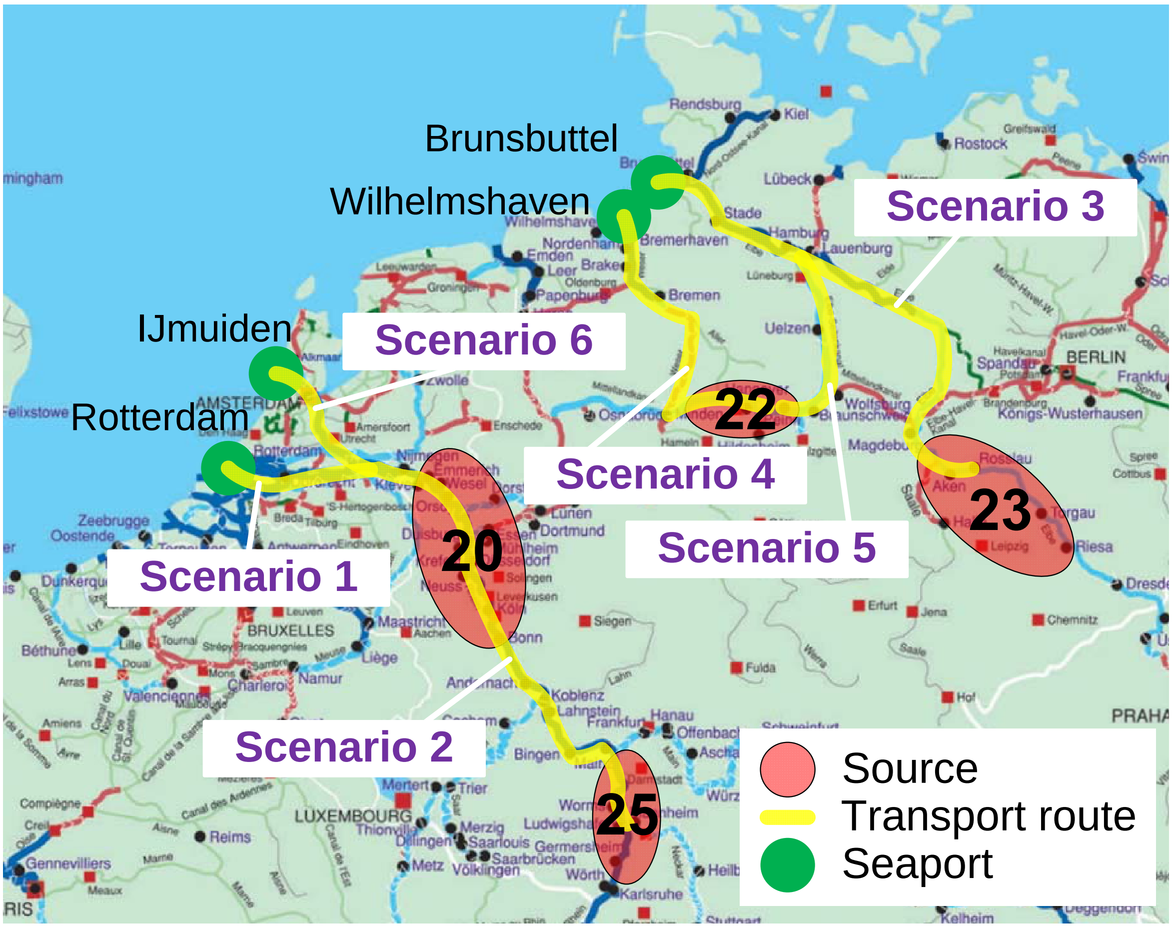

Figure 8: Selected CO_2 barging transport scenarios on the map.

Transport scenarios						
Scenario	Source location	Destination location	Distance [nm]	Lowest CEMT class on route	Nr of barges per convoy	Load cap convoy max [t/con]
1	Dusseldorf (20)	Rotterdam	140	VI c	6	18000
2	Mannheim (25)	Rotterdam	311	VI b	4	12000
3	Rosslau (23)	Brunsbuttel	220	V a	1	3000
4	Hannover (22)	Willemshaven	140	IV	1	1450
5	Hannover (22)	Brunsbuttel	159	V b	2	3200
6	Dusseldorf (20)	IJmuiden	135	VI a	2	6000

Table 8: Different CO_2 barging transport scenarios. The CEMT class determines the maximum number of barges in a convoy and convoy capacity. nm = nautic miles

The scenarios in Table 8 are given with their respective shipping distances, corresponding categories for those specific waterways (thus taking into account dimensional limitations) as well as the subsequent number of barges per convoy and the CO_2 loading capacity. The first scenario from the Ruhr Area (Düsseldorf) offers the highest loading capacity per convoy. This coincides well with the assumption that the Ruhr area will be one of the main CCS focal points of Western Europe together with Rotterdam.

5.3 Ship transport capacities

In order to determine the annual transportation capacity of a barge convoy (with its carrying capacity as listed in Table 8) for the selected scenarios, the assumptions in Table 9 are used.

General assumptions:	
Speed [knots]	8
Loading rate [t/hr]	600
Disch rate [t/hr]	800
Voyage rel. spare [d/rt]	1
Availability [d/yr]	238

Table 9: General assumptions for transport calculations. (d/rt = days needed per round tour)

The numbers in Table 9 were deduced taking into account the following:

- **Barge design:** Currently no dedicated CO_2 barges exist. Current capacity assumptions will only consider cargo density and tank weight as seen with dedicated CO_2 ships. Properties like barge speed, loading rates, etc. are assumptions as well. More detailed engineering is required for more precise numbers – parallel to further research.

- **Regulations concerning CO_2 transport by barge:** Currently, CO_2 transport by barges through Europe does not occur on the scale given/contemplated in the different CO2Europipe scenarios. As such no clear regulations have been described regarding the (cross border) transportation of CO_2, though initial EU directives point in the direction of not deeming captured CO_2 as a waste product. Preferably, EU and member state legislative authorities will adhere to thus eliminating stringent legislation that applies to cross border waste transportation. It is therefore assumed that **no** regulatory limitations are set, especially given that CO_2 already has a so called ADN number meaning that the inland water way regulatory body has acknowledged CO_2 as a cargo. [1]

- **Availability:** Due to fluctuating water depths over the year (due to seasonal meteorological influences), high or low water may cause draft restrictions and as such decreased transportation capacity or even unavailability of the waterway. For the scenarios chosen 33% unavailability due to fluctuating water depths is assumed. Further historical research concerning fluctuating water depths and barge properties is required for more precise numbers.

With the maximum carrying capacity of one convoy (dictated by the category of the considered waterway) and the given assumptions determining the roundtrip duration, the annual capacity per barge convoy is calculated. Looking at the needed transportation capacity (based on projected 2030 CO_2 captured emissions) the number of barge convoys needed is then calculated and deduced. The results are given below in Table 10.

Scenario	**1**	**2**	**3**	**4**	**5**	**6**
Source location	Dusseldorf (20)	Mannheim (25)	Rosslau (23)	Hannover (22)	Hannover (22)	Dusseldorf (20)
Destination location	Rotterdam	Rotterdam	Brunsbuttel	Willemshaven	Brunsbuttel	IJmuiden
Distance [nm]	140	311	220	140	159	180
Lowest UN/ECE class on route	VI c	VI b	V a	IV	V b	VI a
Number of barges per convoy	6	4	1	1	2	2
Load cap convoy max [t/convoy]	18000	12000	3000	1450	3200	6000
Transport capacity [mmtpa/convoy]	**0.79**	**0.43**	**0.17**	**0.11**	**0.21**	**0.39**
2030 CO2 volume [mmtpa]	**35**	**8**	**18**	**4**	**4**	**35**
Number of convoys needed	**45**	**19**	**108**	**36**	**19**	**90**

Table 10: Transport capacity calculations for different CO_2 transport scenarios nm = nautic miles

For scenarios 1 to 6, the number of convoys needed to ship the CO_2 from the different sources to the considered seaports varies from 19 to 108 convoys. Although representing a significant increase in barge fleet numbers, the time line taken (i.e. now up to 2030) should be sufficiently far away in the future to accommodate for this fleet growth.

Scenario 1 and 6 will cause the highest volume increase. In 2008, German inland waterways carried over 252 million tons of goods. A map is shown in Figure 10. An additional 35 million tons of CO_2 would represent an increase of approximately 14 %. This appears to be achievable, allowing for these CO_2 flows to find its path towards the seaports and offshore storage locations. Nevertheless, the CO_2 seaport terminal infrastructure and capacity will need to be extensive. Assuming a gradual ramp up of CO_2 volumes this should not represent a hurdle.

[1] ADN = European Provisions Concerning the International Carriage of Dangerous Goods by Inland Waterway. See also: http://www.safefreight.co.uk/legislation.htm

5.4 Conclusions on ship transport

With the available information on ship transport, high level estimations of transport capacities for the selected transport scenarios have been made in this report D4.2.2. Though the results generated are based on well considered assumptions, further research must be performed taking into account historically fluctuating water depths of the German and Dutch waterways considered here.

Within Germany and the Netherlands, there is a large potential for inland CO_2 barging to both German and Dutch seaports. This is driven by the fact that ample troughput capacity exists on the considered waterways and that inland shipping circumvents the complexities and lengthy permit application procedures for pipeline transportation.

Here the most feasible scenario is to transport CO_2 from the Rhineland and Ruhr area down the Rhine to Rotterdam/Maasvlakte (Scenario 1 in Table 10) – as this route allows for the largest convoy size and subsequent highest volume transfers.

To date we can only speculate what the effects of climate change could be on ship transport down the Rhine and other rivers. If water depths and water availability are expected to be in decline in future years this could negatively effect the transport capacities of the ship option. But it could also well have no effect.

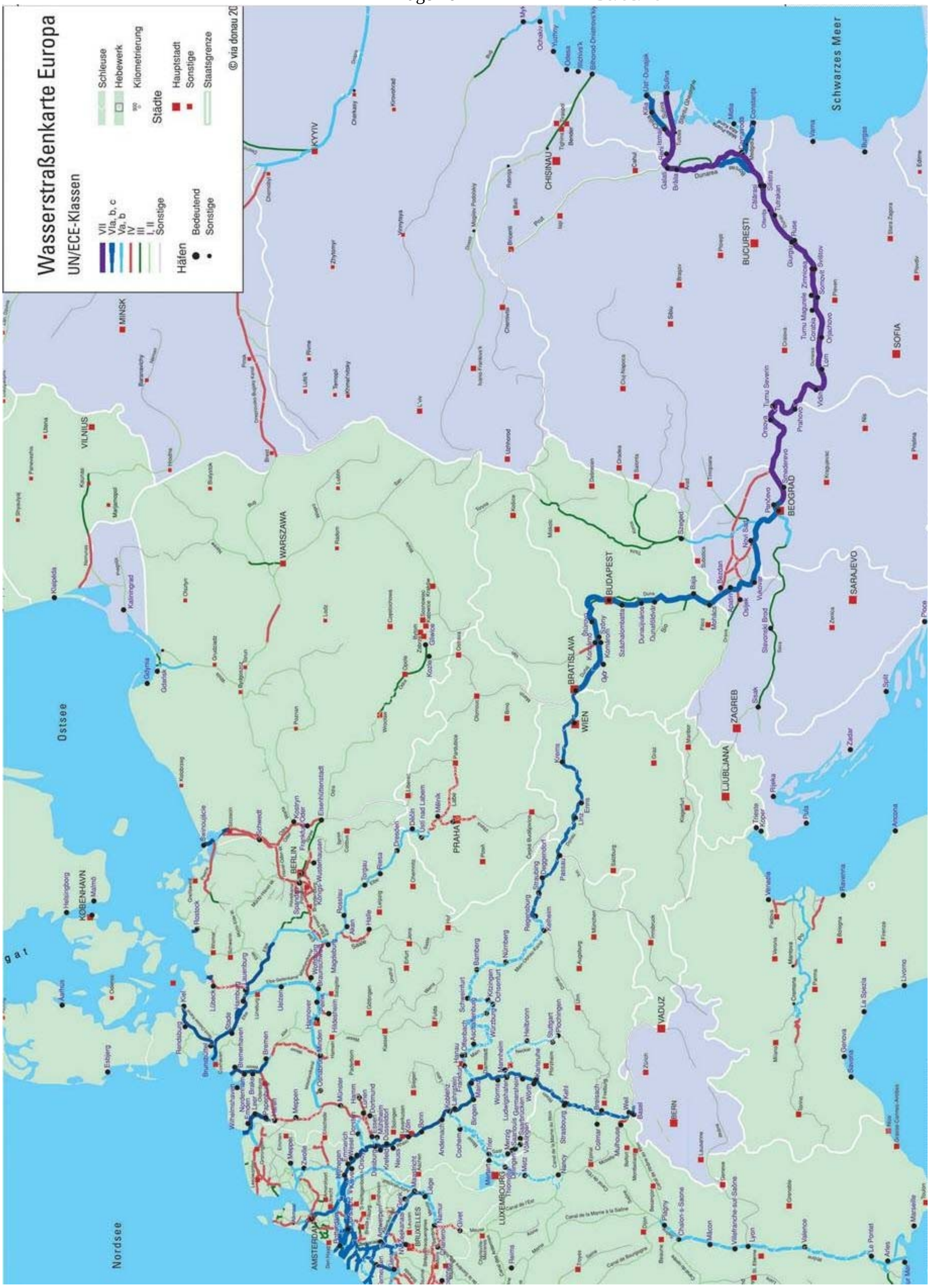

Figure 9: European Inland Waterways Categories
(Source: www.inlandnavigation.org/documents/Facts%20Figures/Network/Map_Waterways_Europe.jpg)

6 Financing mechanisms of CO_2 transport in the German context

6.1 Introduction

The industrial clusters in the German Ruhr region are vital to the local communities, the German economy as a whole and its export capacity. The required power for many of the industrial processes (chemicals and metal processing) in this region is to a large extent based on locally produced power by coal fired power plants. Lignite is locally mined in large quantities for power production, but is not an internationally traded commodity unlike hard coal due to its lower caloric content that renders long distance transport uneconomical. Lignite fired powerplants are therefore bound to the lignite mining region in order to maintain the revenue stream from the lignite to power value chain. To maintain and grow the industrial based economy in Germany and thereby securing employment while realizing high CO_2 reduction ambitions CCS is vital. The BLUE map scenario developed by the IEA (2008a,b) and endorsed by the G8 in Gleneagles in 2005 shows that CCS is the 2nd largest contributor (with energy efficiency being first) to the ambition of 80 % CO_2 emission reduction by 2050. Its global CO_2 reduction potential is calculated at 9.4 Gton CO_2/year in 2050. Without CCS the marginal carbon cost abatement would rise from US$175 to US$300 per ton of CO_2. This cost reduction can be seen as the CCS value and equates $US 500 billion per year for the EU in 2050 based on 2008 dollars and excludes the value of EOR and revenue generated in other parts of the fossil fuel value chain. Clearly, Germany's part of this value would be substantial.

Given this economic rationale at macro level; the question remains how to finance the investments in large scale CCS which currently do not have economic drivers at business level. This question will be addressed with a focus on financing CO_2 transport per pipeline from the industrial clusters to offshore sinks in the North Sea as well as to CO_2-hubs in Rotterdam (explained in D 4.1.1) and North-German harbors from Emden to Hamburg.

6.2 Business model

There are two simple models that can be used to finance pipeline investments and that have a large consequence for financing;

1) vertical integration of CCS in a power company
2) standalone transport company using a common carrier model

In the case of vertical integration the power company invests in capture, compression, pipelines, ships, storage facilities and all other equipment to make CCS possible. The other alternative is to set up a separate company that only transports CO_2 as a service for emitters and storage parties. Naturally, there are also hybrid combinations possible where a company supplies commodities per pipeline on an exclusive basis like Air Liquide. Some companies have no common carrier approach (thus no access to 3rd parties). Vertical integration is preferred under the following circumstances:

1) emitter company has all the expertise and competences inhouse for CO_2 pipe or ship transport
2) emitter company has access to sufficient capital at low cost for the pipeline or ship investment
3) allocated capital for pipeline does not negatively compete with more profitable destinations

4) No foreseen regulation that forces open access to pipeline at unfavourable conditions (that might undermine the initial business case)
5) CO_2 flow from one emitter company is dominant compared to total CO_2 flow to be transported from cluster to sink locations

Clearly, the first two arguments are applicable to large integrated power companies like RWE. Financing might be done from the company balance sheet at relatively low cost. The 3rd argument will be discussed in the subchapter 6.3 "benchmarking returns and financing". The 4th and 5th are very likely not valid in an area with several large CO_2 emitters which implies that this option will not capitalize on the economy of scale that a large pipeline offers for high CO_2 volumes. Also the lengthy and complex permitting process in densely populated areas will favour one large diameter pipeline instead of multiple smaller pipelines.

A standalone transport company might benefit from both, economy for scale and one permitting process by collecting all major CO_2 flows for one pipeline trajectory. In order to attract project financing at acceptable cost, for this transport company a portfolio of long term transport contracts is required - from financially solid emitters. The interests from emitters and transport companies might be aligned by creating a consortium with the major emitters as shareholder. The federal government (or several regional governments) might also act as shareholder to align the CCS business interest with the political CCS interests and facilitate the permitting process. From a financial point of view a government entity is not essential as shareholder as long as there are government guarantees to protect the loans against political risk. However, the presence of the German government as a shareholder will likely lead to lower interest rates on loans for the transport company. Gas- and power transport are to a large extent regulated businesses. The EU tends to enforce EU wide regulation as e.g. unbundling. It seems likely that CO_2 transport will be treated in the same manner. The transport company will comply with unbundling regulation if the entity is legally separated from the power production and trading business.

Cross-border transport project consortia for power (BritNed project; see BritNed 2011, TenneT 2011) and for gas (BBL 2011) demonstrate that commercial management is feasible and that certain exemptions from regulated returns have been approved. These examples show that also regulated businesses in gas and power transport can set up commercial ventures and they might act as example of an investment approach with CO_2 transport.

6.3 Benchmarking returns and financing

In order to attract capital for financing pipeline investments one should have benchmarks on capital returns in similar businesses. High pressure gas pipeline transport and high voltage power transport offer a good analogue to high pressure CO_2 pipeline transport in terms of EPC (engineering, procurement and construction), technology, permitting, contractual structures, and contract partners (large energy and industrial companies). There are however two main differences:

1) Short term contracts (spot market) become increasingly important in current gas and power business. This is not (yet) likely to happen in the emerging CCS business.

2) Except for CO_2-EOR there is not yet a commercial driver for large scale CCS with current and expected future low EU-ETS prices. This implies CO_2 transport is associated with political and economic risks that are absent with gas and power.

In the following Table 11 a number of transport companies is listed with crucial financial parameters.

Company	Country	ROI (%)	ROE (%)	profit margin (%)	dividend (%)
				net (after tax)	yield
Enagas SA	Spain	7,10%	19,27%	24,92%	3,40%
National Grid PLC	UK	4,60%	30,70%	11,49%	5,30%
Snam Retegas SpA	Italy	6,32%	15,88%	29,49%	5,40%
Ren Redes Energeticas Nacionas SGPS	Portugal	7,53%	19,73%	27,31%	6,91%
Gasunie NV	The Netherlands		8,60%	27,00%	NA
Red Electrica de Espana SA	Spain	6,19%	23,07%	25,07%	3,37%
TenneT	The Netherlands		7,60%		NA
All data are 5 year averages from 2005 until 2010, except for Gasunie and Tennet (data from 2010)					
ROI = return on investment; ROE = return on equity					

Table 11: Financial data of transport companies in gas and power, derived from www.reuters.com.

Five year averages are shown to get a mix of the company performance before and during the financial crisis as well as in the early and later phase of liberalization and regulation. Gasunie and TenneT are 100 % government owned and therefore not listed at a stock exchange. Some parameters as dividend yield are thus lacking. All other companies are listed at a stock exchange; they show a high ROE (return on equity) as well as a high nett proft margin and pay good dividend to shareholders. A potential CO_2 transport company with these financial data could easily attract capital from shareholders and lenders to invest in its infrastructure. The Return On Equity numbers show that these investments can succesfully compete with many other energy related projects on ROE. A potential concern is the low ROI (return on investment); this shows that a high leverage (debt to equity ratio) is essential to reach the high ROE. It can be concluded that these transport companies are only able to realize a high return on equity by financing a large part of their investment needs with low interest loans. Banks and lenders specialised in financing infrastructure (e.g. the European Investment Bank, EIB) will only give these loans to a potential CO_2 transport company if the political risk is covered by government guarantees as mentioned in chapter 6.2.

In addition, the collateral for the loans need to be of high quality; thus long term contracts with companies with a high credit rating parallel to solid asset based collaterals. The high credit rating will usually be the case for energy companies. It is worth mentioning that onshore pipelines between big industry clusters are considered safer to finance as the alternative value is higher. When CO_2 transport is no longer required these onshore pipelines might still be used for transport of natural gas, oil or other gases or liquids. The likelihood for an offshore pipeline to be used for other purposes is considered much smaller. On the other hand the project risk for an onshore pipeline is higher due to potential hurdles in the permitting and public engagement process. Shipping CO_2 in that sense has an alternative trade option, namely to transport LPG, offering a certain investment risk mitigant.

6.4 Margin on natural gas versus CO_2 transport

The use of natural gas transport companies as a financial benchmark for future CO_2 transport companies requires that the transport tariff should be a certain percentage of the value of the transported commodity which should for CO_2 not be much higher than for natural gas. D4.1.1 compares the OPEX energy costs for transport of natural gas versus CO_2 across a similar offshore pipeline (thus similar CAPEX) and concludes that the transport energy OPEX for the same mass flow of CO_2 at the same output pressure is 10 times lower than for natural gas. Also, energy OPEX costs are dominant in the transport tariff as they constitue more than 60 % of transport costs. A gas price of 23 EUR/MWh equates to a price of 406 EUR/ton natural gas. This is a high value compared to the current EU-ETS price of 16 to 24 EUR/ton CO_2 – even if EU-ETS prices increase strongly. Therefore, the potential profit margin on CO_2 transport is limited compared to natural gas transport even though the OPEX energy is lower for CO_2 transport.

6.5 Conclusions

It can be concluded that the project and commercial contract development in European gas- and power transport companies could be a suitable template for a potential CO_2 pipeline transport company that would be tasked with transporting large CO_2 flows from the main industrial clusters in Germany to either The Netherlands (Rotterdam CO_2-hub) or to the North German harbors (Emden to Hamburg) and from there to offshore sinks in the North sea. This CO_2 transport company could have a similar structure as consortia for cross-border transport of high pressure gas (BBL 2011) or high voltage power (BritNed 2011). The financial key ratios of various stock exchange listed European gas and power transport companies offer therefore a reasonable benchmark for the future profitability and return on equity for CO_2 pipeline investments. Consequentially, it is expected that enough capital, both in the form of debt and equity, can be raised given the attractive returns that can be reached (above 15 % ROE and net profit margins between 20 and 30 %). However, a crucial difference is the political risk that is associated with CO_2 transport and that warrants government guarantees in order to attract capital.

7 Technical risk assessment of CO_2 transport in NW Germany

7.1 Introduction

This part of work package 4.2 aims for a technical risk assessment of a high pressure CO_2 pipeline, using one of the CO2Europipe transport cases: from the Ruhr area to Emden in Germany.

Although risk assessments are performed on regular bases for many other substances transported by pipeline in bulk amounts (e.g. natural gas, chlorine, ammonia or LPG), performing a similar risk assessment for CO_2 still is quite a complicated matter. CO_2 behaves differently from the other commonly known pipeline transported substances. These unique characteristics introduce uncertainties for risk and effect calculations.

Before performing a risk assessment, a literature survey has been performed to identify the points of attention that are specific for CO_2 modelling.

In the USA and Canada long distance transport pipelines for CO_2 are already in use. The operating pressures vary between 100 and 200 bars. Only some of these pipelines are located in densely populated areas. The CO_2 is mostly used for Enhanced Oil Recovery (EOR). In Norway (Statoil) a 200 bar off-shore pipeline is in use since 1996. In the Netherlands CO_2 is also transported, however, at much lower pressures and at a much smaller scale: 10-22 bar (OCAP pipeline, Zoetermeer).

For large CCS (Carbon Capture and Storage) projects the most likely option for CO_2 transport is transport as a dense liquid as this is the most economical way. In addition, the CO_2 will be transported at pressures above its critical point ($p_{critical}$ = 72.9 bar) to prevent two-phase flow under normal operating conditions.

However, in case of an accidental release the amount of CO_2 released from the pipeline is larger in case of liquid or dense phase transport than in case of vapour transport. In order to be able to assess these risks, proper validated models for the outflow and dispersion of CO_2 are needed. These models are still in their development stage.

7.2 Risk analysis data on CO2 pipelines – literature review

7.2.1 Introduction

This chapter reviews the literature on risk assessments of CO_2. The following system characteristics affect risk of loss of containment (EnBW et al 2008):

- Pipeline design and construction (materials choice and characteristics, number of intersections, connection of intersections, number of valves per unit length)
- Pipeline location (above ground or buried/covered, geology and terrain features, urban areas, protected nature environment)
- Pipeline use (operational circumstances, throughput)
- Pipeline maintenance (monitoring technologies, mean time to failure).

First the elements of a risk assessment are shortly described. Next it is reported which of these elements are presented in the various literature sources.

7.2.2 System description

In the scope of this literature survey the risks of a release of CO_2 that is transported by pipelines, is reviewed. For modelling the outflow of material from a pipeline, data is necessary on the pipeline system such as the diameter of the pipeline, the length of isolatable sections and the presence of soil coverage.

Buried as well as above ground pipelines are considered in several references. Pipelines are connected through flanges and welds and may contain valves. These are part of the pipeline system, pumps are excluded. In most literature references it is mentioned that risk analyses at this stage for CO_2 adopt a generic system because a final system design is not yet available. It is expected that CO_2 will be transported as dense liquid at pressures up to 200 bars. The diameter of pipelines operated at pressures of 100 up to 200 bars (300 bars off-shore) varies from respectively 406 mm (16 inch) up to 914 mm (36 inch).

7.2.3 Failure scenario's for pipelines

Possible Loss Of Containment events (LOC's) of pipe line systems are (full bore) rupture, leakage, fissure, hole and split. The definition of rupture is not univocal. Definitions of rupture are for instance:

- a leakage bigger than half of the diameter of the pipelines (CRR 1999)
- a crack of 75 mm or longer and 10% of the minimal width (Lyons 2002)

The LOC's most commonly modelled in risk analysis are rupture and leakage. Pinhole leakages are generally not modelled because their contribution to risk is minimal. According to RIVM (2009) in the event of a rupture outflow occurs on both sides of the rupture; the location of the rupture determines the flow rate. A leakage has an effective diameter of 10% of the nominal diameter, with a maximum of 50 mm (RIVM 2009). For underground pipelines leakage is modelled as outflow from a 20 mm hole. According to the PURPLE BOOK (2010) the material of the pipeline, the presence of lining and the design pressure are of no influence on the scenarios and failure frequencies.

7.2.4 Failure frequency

The failure frequencies are reported in Table 14. For the use of general failure data of pipelines and fittings, the properties of CO_2 in the supercritical state as well as the influence of impurities in combination with water should be reminded. The solvating ability of supercritical CO_2 demands that the design/construction of e.g. gaskets, seals and internal linings is compatible with the use of the pipeline for CO_2 transport according to EGIG (Hill & Catmur 1995). In general it should be considered if due to different failure mechanisms, existing pipelines have to be re-qualified for transmission of CO_2. The risk portfolio of CO_2 pipelines is very similar to pipes transporting other goods, with external interference showing the highest failure rate of 0.28 (per 1000 km*year; see Hill & Catmur 1995).

Koornneef et al. (2010) argues whether failure rates for natural gas pipelines can be used for CO_2 pipelines. Rates that have been used in other QRAs and in the study Koornneef et al. (2010) are between $0.7*10^{-4}$ and $6.1*10^{-4}$ km^{-1} $year^{-1}$. As a result the distance to the $1*10^{-6}$ risk contour may vary between 48 and 204 meters.

7.2.5 Crater formation

A full bore rupture of a pipeline can occur during digging activities of a buried pipeline. During such an accident, the crack may propagate until the pipeline material arrests a fracture or a so called 'crack arrestor' is reached (e.g. a weld, reinforcement). In the event a gas pipeline bursts open very rapidly, the escaping gas expands instantaneously and will possibly result in a pressure wave in the environment. In this case the physical explosion will possibly result in a bigger crater and the dimensions of the crater (length, width and depth) determine whether the outflow will lose its momentum. McGillivray & Wilday (2009) refer to a study whereby the angle of the crater is determined in order to calculate the conditional probability of a jet dispersion. According to them, larger hazard ranges are produced by smaller crater angles. If horizontal jets in the crater collide with each other in the event of a two sided outflow, the outflow may lose its momentum completely (Molag & Raben 2006). However there is a clash of opinions in Molag (2010) and RIVM (2007) about the loss of momentum as well as about the mixing with air in the event of colliding horizontal jets in a crater. According to Molag (2010) statements should be based on outflow experiments under high pressure.

7.2.6 Physical processes during the outflow of pressurized gasses

The outflow process of a general, pressurised gas can be described in this way. After rupture of the pipe, the processes inside the pipe determine the outflow (choke) pressure, flow rate, and vapour mass fraction of the flow. Just outside the pipe there is an expansion region where the pressure drops to ambient and the fluid flashes, resulting in a two-phase, turbulent jet of vapour and droplets. Due to the high velocity, ambient air will be entrained into the free jet. During the flashing solid particles are formed and, depending on their size, the particles will either rain out and form a solid bank on the ground, or remain airborne and eventually vaporise. Due to the mixing with the ambient air the momentum of the jet decreases and the cloud is further dispersed by the surrounding air movements. In a separate process the solid bank will evaporate and also be dispersed.

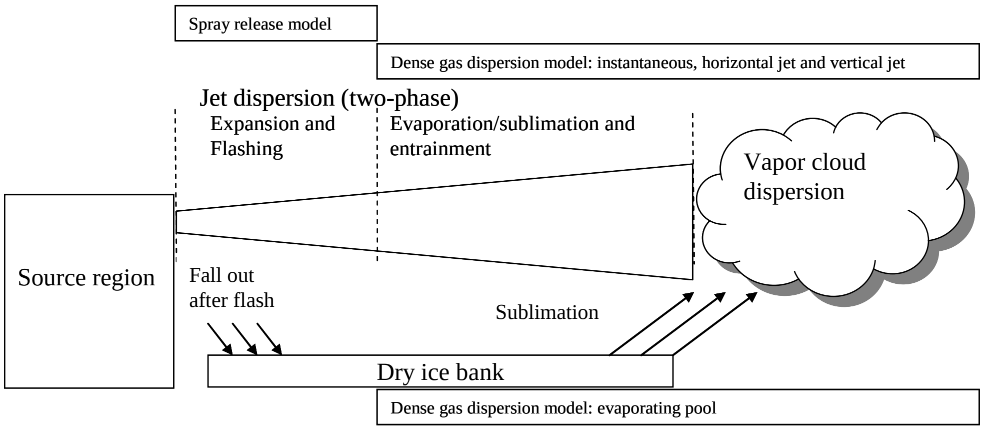

Figure 10: Overview of processes during outflow of pressurised CO_2.

These steps are indicated for CO_2 in Figure 10. However, at atmospheric pressure CO_2 can only exist as solid and gas, instead of liquid and gas, see phase diagram in Figure 11. This changes the outflow process, i.e. solid CO_2 is formed instead of droplets during the flashing and the rain out results in a solid CO_2 ice bank. See Table 12 for characteristic pressures and temperatures for CO_2. At atmospheric pressure solid CO_2 directly transforms into gaseous CO_2 without first forming a liquid.

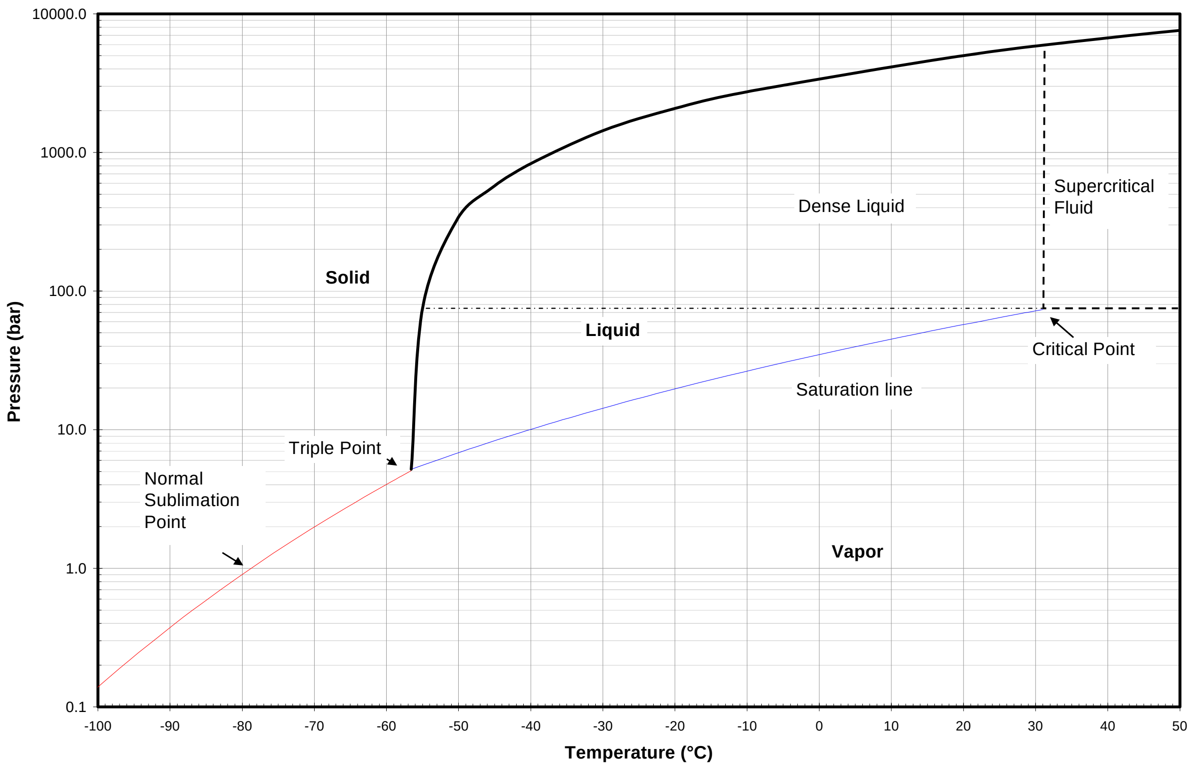

Figure 11: Pressure-temperature phase diagram for CO_2.

p_{triple}	5.18 bar
T_{triple}	-56.6 °C
$p_{critical}$	72.9 bar
$T_{critical}$	31.1 °C

Table 12: Overview of parameters for critical point and triple point of CO_2.

The main process conditions that determine the outflow from a pipeline are the operating pressure and temperature. As long as the pressure remains above the triple point pressure, CO_2 will behave as any other liquefied gas. However during a depressurization event the inventory pressure will drop below the triple point (5.2 bar). The formation of dry ice is a possibility. Exactly this possible solid formation process gives rise to the question whether existing release and dispersion models can be used for CO_2, or that improvements or changes should be made.

The amount of solid CO_2 that is formed depends on the starting conditions (p and T). Initial conditions can be found for which solid formation does not occur, or only a small mass fraction will become solid. In these situations the outflow and dispersion of CO_2 will be no different than any other heavy gas, e.g. propane, and normally available release and dispersion models can be used for the accidental release of CO_2.

On the other hand, for initial conditions which result in liquid and two-phase outflow the CO_2 release will be both solid and vapour at the final conditions. Then regular models for release and dispersion are possibly no longer valid and should be adapted.

7.3 Initial cloud of CO_2

According to RIVM (2007) the occurrence of a vertical jet release with momentum is the most likely scenario. In the event of buried pipelines a crater may be formed that is of great influence on the momentum of the release. The initial momentum of a jet release will diminish due to entrainment of air; in this way the released CO_2 is also diluted to non-lethal concentrations when the momentum becomes negligible.

According to Molag & Raben (2006) horizontal jets of CO_2 will appear from both sides of the pipeline after rupture. It is assumed that a crater is formed and the two jets will collide and loose their momentum. CO_2 will expand and cool down. In the event the two jets loose their momentum, dispersion out of the crater can be considered as emission from a surface source and not as a jet any more.

The above mentioned two approaches lead to different input parameters for the dispersion of the cloud. The scenario of a gas loosing all of its momentum and emerging slowly from the ground is considered to be a worst case scenario for buried pipelines. In contrast, a release with a large proportion of its momentum removed due to leak orientation, crater size and shape would likely lead to low dispersion rates and correspondingly long distances with theoretically hazardous conditions.

7.4 Dispersion of the cloud

CO_2 is a heavy gas under atmospheric conditions. In combination with the assumption that the jet will lose its momentum, a heavy gas model for modelling dispersion is appropriate (Molag & Raben 2006). However, the heavy gas models have restrictions because they give unreliable results under certain conditions, such as low wind velocity, complex terrain or congested buildings.

CFD (Computational Fluid Dynamics) modelling of the dispersion of CO_2 is a challenge, and presently under development. CFD modelling enables to take into account the influence of obstacles in the dispersion of CO_2. The two models can be used in combination to provide confidence in the consequence analysis. For every situation the best solution should be chosen.

7.5 Exposure to CO_2: probit functions and concentration thresholds

In the QRA probit functions are used to calculate the consequences of exposure of human beings to levels of toxic or oxygen dissipating gases. Also effects on respiration should be taken into account. The general probit function for inhalation of “toxic” gases is presented as:

$$Pr = a + b * \ln (C_n * t). \qquad \text{(probit Pr = probability)}$$

Where C is the concentration and t is the exposure time (varying dimensions); a, b and n are constants related to the toxicity of the toxic gas. Factor a depends on the dimensions of C and t.

Literature sources show both scenarios that include probit functions, and scenarios that include concentration thresholds (with or without a specification of the duration of the exposure). A concentration threshold is a fixed value. Concentration thresholds may use conservative endpoints for which an adverse impact is assumed on human health (Koornneef et al. 2010).

Risk calculations include also a vulnerability distribution that is expressed in the probability. An overview of probit functions and exposure thresholds for CO_2 is presented in Table 13. Due to the different end-points a direct comparison between the results of effect and risk calculations presented in Table 16 is **not possible**.

Literature sources	**Toxic data on CO_2 / Exposure threshold(s)**						
	Probit	**STEL**	**1% mortality**	**50% mortality**	**100% mortality**	**Toxic n value**	**No lethality**
Koornneef et al. (2010)	$4.45+\ln(C^{5.2}*t)$ C in [kg/m^3], t in [s]					5.2	
Molag & Raben (2006)	$4.45+\ln(C^{5.2}*t)$ C in [kg/m^3], t in [s]					5.2	
McGillivray & Wilday (2009)	$-90.8+1.01\ln(C^8*t)$ C in ppm, t in min		$1.5x10^{40}$ ppm^8.min^2	$1.5x10^{41}$ ppm^8.min^3		8	
Heijne & Kaman (2008)	$-98.81 + \ln(C^9 * t)$ C in ppm, t in min				10% (vol) 100.000 ppm	9	< 5% (vol) 50.000 ppm
Mazzoldi et al. (2008)		1.5% 15.000 ppm					

Table 13: Probit functions and exposure thresholds for CO_2

In the Netherlands the National Institute for Public Health and the Environment (RIVM 2007, 2009) has concluded that available data on the effects of CO_2 is insufficient to deduce a probit relation for CO_2. For exposures below 10% CO_2 no lethality is expected (Molag & Raben 2006).

Koornneef et al. (2010) state: In addition, uncertainty is caused by the absence of a dose-effect relationship as well as internationally standardized exposure thresholds for CO_2 for use in QRAs. This results in a large divergence of results in QRAs for CO_2 pipelines. In this study the risk contour is found at a distance between 0 and 124 meters with varying the probit function. The results of earlier risk assessments varied between <1 m and 7.2 km assuming different exposure thresholds.

The HSE in the UK has used a probit based on SLOT and SLOD values from literature (HSE 2009). These terms are important when assessing the Dangerous Toxic Load (DTL) for Specified Level of Toxicity (SLOT) and Significant Likelihood of Death (SLOD). The webpage http://www.hse.gov.uk/hid/haztox.htm describes these terms in more detail: “The DTL describes the exposure conditions, in terms of airborne concentration and duration of exposure, which would produce a particular level of toxicity in the general population. One level of toxicity used by HSE in relation to the provision of land use planning (LUP) advice is termed the Specified Level of Toxicity (SLOT)“.

(Table 14:)

	Description	Internal diameter (mm)	Operating pressure (barg)	Operating temperature (K)	Phase of CO_2	Length of isolable section (km)	Inventory full bore rupture (kg) or total mass released release rate (kg/s) duration (s)	Depth of soil coverage (m)	Crater formation

Literature sources	**Pipeline data / phenomena**								
	Description	**Internal diameter (mm)**	**Operating pressure (barg)**	**Operating temperature (K)**	**Phase of CO_2**	**Length of isolable section (km)**	**Inventory full bore rupture (kg) or total mass released release rate (kg/s) duration (s)**	**Depth of soil coverage (m)**	**Crater formation**
Koornneef et al. (2010)	NEN 3650	406 (16”)	110	290	Dense liquid	20	$4.5*10^5$ kg (instantaneous) $2.25*10^6$ kg (horizontal jet) $4.5*10^5$ kg (sublimating bank 20%)		no
Vendrig et al. (2003)	Onshore pipeline	760 (30”)	100	285	Dense liquid	10			
	Offshore pipeline	1020 (40”)	300	279	Dense liquid	10			
Lievense (2005)	NEN 3650								
Molag (2006)	NEN 3650	660 (26”)	16.5	283	Gas	16.9	190.000 kg (6146 m^3) 408 kg/s during 465 s. (two-sided outflow)	1.3	yes
			40		Gas				yes
Turner (2006a)		1070 (42”)					Horizontal release		
		610 (24”)					Horizontal release		

	Description	Internal diameter (mm)	Operating pressure (barg)	Operating temperature (K)	Phase of CO_2	Length of isolable section (km)	Inventory full bore rupture (kg) or total mass released release rate (kg/s) duration (s)	Depth of soil coverage (m)	Crater formation
McGillivray & Wilday (2009)		736.6	15	278	Gas	18		1.1	19° [4]
Heijne & Kaman (2008)	NEN 3650 - 2003	356 (14”)	max. 44	189 - 283	Gas	300 m and 73 m[5]		No coverage	no
		711(28”)				300 m and 73 m[6]		No coverage	no
		356 (14”)				4.4 [7]		No information	no
		711(28”)				4.4 [8]		No information	no
Mazzoldi et al. (2009)	Generic – not speci-fied		about 100 bar		dense liquid		1.080.000 kg – 1800 kg/s - 600 sec		

Table 14: Pipeline data and phenomena in literature sources.

4 length/ depth approach: average crater angle, θ (according Kinsman and Lewis, 2002)

5 Pipeline in tunnel, the tunnel is provided with hatches at both ends. It is assumed that the hatches are blown away in the event of a rupture of the pipeline

6 Pipeline in tunnel, the tunnel is provided with hatches at both ends. It is assumed that the hatches are blown away in the event of a rupture of the pipeline

7 Burried pipeline in pipeline lane

8 Burried pipeline in pipeline lane

(Table 15:)

Literature sources	Modelling aspects		Failure frequencies for pipelines (m^{-1} yr^{-1})		
	(Probability of) jet dispersion	**Models used / parameters**	**Generic frequency**	**Leakage (operating pressure (bar))**	**Rupture (operating pressure (bar))**
Koornneef et al. (2010)	Instantaneous - horizontal and vertical jet	Full bore rupture[9]: • Non—stationary two-phase outflow from large pipeline • Spray release model - adjusted[10] • Vapour mass fraction: 70 % Jet diameter: 0.6-0.8 m Puncture: • TPDIS and Spray release model– adjusted • Dense gas, based on SLAB • Vapour mass fraction: 21-22 % Software package used: EFFECTS 7.6 adjusted and RiskCurves (TNO 2007)	$6.1*10^{-7}$		$0.25*6.1*10^{-7}$ (110)
	Vertical jet	For all puncture scenarios a hole size of 20 mm is assumed. • Pipeline roughness: 0.045 mm, • wind speed (at 10 m height):2 m/s, • ambient temperature: 9°C, concentration • Averaging time: 600 s, • height of release and receptor: 1 m, • ambient relative humidity: 83 %, • wind direction is equal to direction of release, • roughness length description (roughness of terrain): 0.25 m (high crops; scattered large objects, upwind distance < 15 m., height of obstacles < 20 m), • discharge coefficient full rupture: 1, • discharge coefficient puncture: 0.62	$6.1*10^{-7}$	$0.75*6.1*10^{-7}$ (110)	
Vendrig et al.		• Full-bore pipe rupture (applied to all leaks of equivalent	$3.5*10^{-8}$	Small: $1.4*10^{-8}$ Medium: $9,5*10^{-9}$	$8.5*10^{-9}$

[9] Assesment done with software package EFFECTS 7.6 adjusted and RiskCurves (TNO 2007)

[10] Includes description of flashing and aerosol formation and evaporation. No fallout of solid CO_2 is expected

Literature sources	**Modelling aspects**		**Failure frequencies for pipelines (m^{-1} yr^{-1})**		
	(Probability of) jet dispersion	**Models used / parameters**	**Generic frequency**	**Leakage (opera-ting pressure (bar))**	**Rupture (operating pressure (bar))**
(2003)		diameter > 150mm) • Large leaks, 100mm equivalent diameter (covering leaks from 50 to 150mm) • Medium leaks, 30mm equivalent diameter (10 to 50mm), and • Small leaks, 7mm equivalent diameter (3 to 10mm)		Large: $2*10^{-9}$	
Molag & Raben (2006)		Dispersion out of the crater is modelled as pool evaporation of a heavy gas.		$0.75*6.1*10^{-7}$ (16.5)	$0.25*6.1*10^{-7}$ (16.5)
McGillivray & Wilday (2009)	0.4[11]	• Rupture scenario's assume a hole with a diameter of 150 mm. • Leakage scenario's assume a hole size of 50 mm • Weather classes: D5 en F2 • Software package used: Safeti-NL		4.65×10^{-8} (32) 4.65×10^{-8} (15)	3.39×10^{-8} (32) 3.39×10^{-8} (32)
Heijne & Kaman (2008)	Vertical outflow[12] Vertical outflow with high velocity	• For leakage scenarios a hole size of 20 mm is assumed. • Outflow calculations with multiple rate long pipeline model with time dependent outflow in 5 steps followed by user defined source. Software package used: Safeti-NL/ Phast Pro.	$6.1*10^{-7}$ $6.1*10^{-10}$ [13]	$6.3*10^{-8}$ (44)[14] $0.75*6.1*10^{-7}$ (44)[15]	$7*10^{-9}$ (44)[16] $0.25*6.1*10^{-7}$ (44)[17]
Mazzoldi et al. (2009)	Zero release velocity and release velocity of 49 m s^{-1} (jet release)	Software package used: CFD Fluidyn-PANACHE (3.4.1)			

Table 15: Physical effect modelling: overview of input data in literature sources.

[11] P_{jet} : 2 x (90-θ) /360

[12] Outflow out of a pipeline subway: vertical continuous outflow with low velocity.

[13] Pipe line in tunnel: reduction factor 100: damage third parties excluded/ additional wall thickness 50% reduction factor 10.

[14] Pipe line in pipeline corridor

[15] Underground not in pipeline corridor

[16] Underground in pipeline corridor: reduction factor van 8.71 for pipeline in corridor/ additional wall thickness 50% reduction factor 10.

[17] Underground not in pipeline corridor

(Table 16:)

Literature sources	Results of effect and risk calculations						
	Range distances to 10^{-6} contour (m)	**Ranges endpoint 2000 ppm (m)**	**Ranges endpoint 15000 ppm (m)**	**Ranges endpoint 70000 ppm (m)**	**Ranges endpoint 100000 ppm (m)**	**Risk 0.1 cpm based on SLOD (m)**	**Risk 0.3 cpm based on SLOT (m)**
Koornneef et al. (2010), Lievense (2005)	0 - 204 3.5						
Molag & Raben (2006)	21 - 90						
Vendrig et al. (2003) (onshore)		3000-3800†	1330-2000†				
Vendrig et al. (2003) (offshore)		3600-7200†	1650-2500†				
Turner (2006)				1903-2441			
McGillivray & Wilday (2009)						45-65	45-70
Heijne & Kaman (2008)	no10^{-6} contour						
Mazzoldi et al. (2009)			374-1290		52-852		

Table 16: Overview of results of effect and risk calculations, reported in literature sources.

† Large leak and full bore rupture

7.6 Review Effect and Risk Calculations

In most literature sources diameter of pipeline, operating pressure and temperature are available. Crater formation is only considered by McGillivray & Wilday (2009) and Molag & Raben (2006). The influence of the input parameters on modelling the release of CO_2 from a failing pipeline is determined by Koornneef et al. (2010). Variance in the maximum release rate of a pipeline failure, which ranges between 0.001 and 22 tonnes/sec, is mostly influenced by, in order of importance: the size of the orifice, the diameter of the pipeline (in the case of a full bore rupture), operating pressure, operating temperature and section length (Koornneef et al. 2010).

Table 14 to Table 16 show an overview of input data and results from several published risk calculations[18]. The following can be learned from them:

- With respect to the modelling of physical effects, information on the software packages used is available, but little information on used models and their input in QRA's – except better information for Koornneef et al. (2010).
- In Dutch QRAs leak in underground pipelines is modelled as a leakage with an effective diameter of 20 mm, whereas in other countries a large leak ranges from 50 up to 150 mm.
- Most literature references assume a vertical outflow except for Koornneef et al. (2010) and Molag & Raben (2006). Koornneef et al. (2010) assume dispersion out of a crater as pool evaporation of heavy gas. Koornneef et al. (2010) consider the following release types: horizontal release, instantaneous release, vertical release and sublimating bank. No fallout of solid CO_2 is expected. Sublimating dry ice banks and instantaneous releases result in the highest concentration near the source. These types of releases are without momentum. For vertical and horizontal releases highest concentrations are found further away from the source. The 10^{-6} contours vary from 0 up to 204 m.
- Koornneef et al. (2010) present the influence of intitial pressure and temperature on the flash fraction at the orifice exit for pressures above the critical pressure. The higher the initial pressure the sooner the maximum vapour mass fraction in the release is reached. With an increase in the intital temperature an increase in the initial and maximum vapour mass fraction is seen but at higher temperatures it takes longer before the maximum vapour mass fraction is reached. The effect of varying the vapour fraction on the final risk profile is large.
- A direct comparison between the results of effect and risk calculations presented in Table 16 is not possible because risk calculations include a vulnerability distribution that is expressed in the probability.
- The effect of meteorological conditions is not very clear yet, but Koornneef et al. (2010) state preliminary results show that when these conditions are varied the CO_2 concentration profiles surrounding the pipeline after release also vary considerably. Under F2 conditions higher concentrations can be expected at great distances downwind.

7.7 Knowledge gaps and uncertainties in modelling reported in literature

As long as the pressure remains above the triple point pressure, CO_2 will behave as any other liquefied gas. However during a depressurization event the inventory pressure will drop below the triple point (5.2 bar).

[18] Not all data could be incorporated in the tables. Where parameters are given (such as the vapour mass fraction) the conclusions in the reference of interest are given as well.

Below some statements found in literature about modelling with respect to QRA studies are mentioned:

- Saturated liquid inventories: If the pressure falls below 5.2 bar the HEM and ω -method models are invalid. There is considerable uncertainty around modelling of dense phase CO_2 releases (Johnsen 2008).
- Outflow models (e.g. Morrow model) in the event of rupture of pipelines are not suitable to incorporate the formation of solid CO_2. Furthermore, there is a lack of knowledge about the vapour and dry ice fraction in the release. These parameters have a large influence on the dispersion and consequently on the risk profile of CO_2 releases (Koornneef et al. 2010).
- A methodological choice that affects the QRA's outcome to a large extent is the direction and momentum of release. Currently, there is no consensus on the type of release that is characteristic for a CO_2 release from a failing pipeline. The results indicate that when varying the type of release (horizontal jet, vertical jet, instantaneous, sublimating bank) the calculated distances from the pipeline to the $1*10^{-6}$ risk contour may be larger than currently regulated for high pressure natural gas pipelines (Koornneef et al. 2010).
- Many dispersion models start with a mean value for the outflow instead of taking into account the course of the outflow in time.
- Validity of the outflow and dispersion models in the event of accidental releases from high pressure pipelines is uncertain. The hazard ranges and therefore risks are expected to be substantially larger for releases at higher pressure – which would therefore be in the dense phase (McGillivray & Wilday 2009).
- As representative substances for CO_2 propane and ammonia are sometimes used. If this is the case, it should be taken into account that the temperature behaviour of high pressure CO_2 is very different from propane and ammonia.

7.8 Knowledge development

As mentioned in the previous paragraphs of chapter 7, some knowledge gaps exist relating to the consequence modelling of CO_2, making it difficult to perform quantified risk analyses, especially for CO_2 stored or transported at a pressure above triple point [D3.3.1]. These knowledge gaps are known and acknowledged and work is being performed to close these gaps. One of the most important topics is the understanding of the behaviour of CO_2 upon a release: How will the outflow be? Will there be dry ice formation? Will a crater be formed? How does the outflow angle influence the dispersion? etc.

This paragraph will give an overview of ongoing or planned experiments and projects.

COSHER:

COSHER (acronym: CO_2- Safety, Health and Environmental Risks) is a project to support the development of validated models for safety zones around high pressure CO_2 pipelines (COSHER 2011). The main objective of the COSHER project is to define and execute large scale CO_2 release experiments and measurement programs. These experiments will result in a better understanding of the CO_2 outflow from pipelines and the dispersion of CO_2 clouds. This understanding can consequently be used to improve and validate safety models on CO_2 pipelines. Some parameters that will be studied are the direction of release (horizontal/ vertical release), impingement (vertical upwards or downwards release), reduction of momentum, semi-confined spacing. The aim is to be able to model CO_2 transmission pipelines with diameters smaller then 42'' and dense CO_2 (presure > 80 bar) as well as gaseous CO_2. The COSHER consortium is an international consortium with industry partners.

CO2PipeHaz:
CO2PipeHaz (CO2PIPEHAZ 2011a, CO2PIPEHAZ 2011b) is an European Seventh Framework Program. This project aims at developing and testing mathematical models for safety assessment of CO_2 pipelines. The international consortium consists of both industrial and research partners. The project started in December 2009, with a duration of 3 years. The focus of this project lies on the prediction of fluid phase, discharge rate and atmospheric dispersion during an accidental release of pressurised CO_2 from pipelines. Small scale experiments will be performed in controlled laboratory conditions. Large scale field trials will also be performed, using a CCS facility. The project combines experimental and numerical modelling approaches to develop and validate hazard assessment tools for CO_2 transportation pipelines.

The small scale experiments will investigate the flow patterns in a ruptured pipe and the near-field dispersion region. The large scale experiments will be performed at a CCS field with a 20 cm pipeline with both supercritical and gaseous CO_2.

CATO2:
CATO2 (CATO2 2011) is a Dutch national R&D program for CO_2 capture, transport and storage. The consortium consists of industrial partners, research institutes, CCS platforms and NGO's. Funding comes from the Dutch government and industrial partners. One of the work packages includes experimental work for release and dispersion calculations.

CO2RiskMan:
CO2RiskMan is a JIP led by DNV that aims to develop and communicate best available guidance to assist the emerging CCS industry. It implements coherent, risk-based fit-for-purpose safety and environmental hazard risk management strategies for the CO_2 stream from capture plant to injection well. The guidance covers strategy development and implementation with guidance provided on hazard identification, risk assessment, risk management, performance review and improvement. Each link of the CO_2 chain from capture plant to injection will be covered using common language and methodologies to ensure a holistic understanding and communication of risk that can be developed between the different risk 'owners' – be they a power station utility company, a pipeline company or e.g. an offshore oil company.

CO2PipeTrans:
CO2PipeTrans is a joint industry project and started in August 2008. It consists of two phases. The objective of the first phase (from August 2008 to September 2009) was to "provide guidance on safe, reliable and cost efficient design, construction and operation of pipelines intended for large scale transmission of CO_2 to meet the requirements given in the reference pipeline standards". The second phase (ongoing) focuses on closing knowledge gaps that were identified in phase 1 (DNV 2010). One of the work packages in DNV (2010), phase 2, will perform a dispersion test of CO_2 and the data from this test will be used to validate dispersion models. The dispersion data will become publicly available some time after the end of CO2PipeTrans to encourage modellers to update and validate dispersion models for transport of dense phase CO_2.

Witlox et al. (2011) present results from extended release and dispersion models and compares them to the results obtained with the current models used in Phast. These extended models allow for the occurrence of fluid to solid transition. Also the data on properties of CO_2 in the substance database has been extended, using properties such as solid density and solid enthalpy and heat of fusion. According to Witlox et al. (2011) the non-extended models result in a too low post-expansion temperature and a too high post-expansion liquid fraction, an under prediction of concentrations is the near-field and over prediction in the far-field. The extended models are claimed to be validated against experiments, but the results of the validation are kept confidential. They are not reported by Witlox et al. (2011). Hence, they cannot be verified or subjected to an open scientific discussion.

8 Risk analysis data on CO_2 pipelines – a case study

8.1 Description of the pipeline

The pipeline considered in this risk assessment is a theoretical CO_2 pipeline from Cologne (Köln) via Ruhr area towards the city of Emden, at the German shore of the North Sea. Table 17 presents the working conditions of the proposed pipeline.

Parameter	Value
Diameter (mm)	812.8 (32 inch)
Temperature in pipeline (°C)	5
Pressure in pipeline (barg)	200
Mass flow rate (kg/h)	900,000 (250 kg/s)
Total length (km)	360
Distance between spacers (km)	15
Depth of pipeline (m)	1.2

Table 17: Working conditions of the CO_2 transport pipeline.

In case of a leakage, the pipeline will be sealed to prevent outflow. The distance between spacers/ bulkheads will be approximately 15 km. The location of the pipeline is presented on the map within Figure 12.

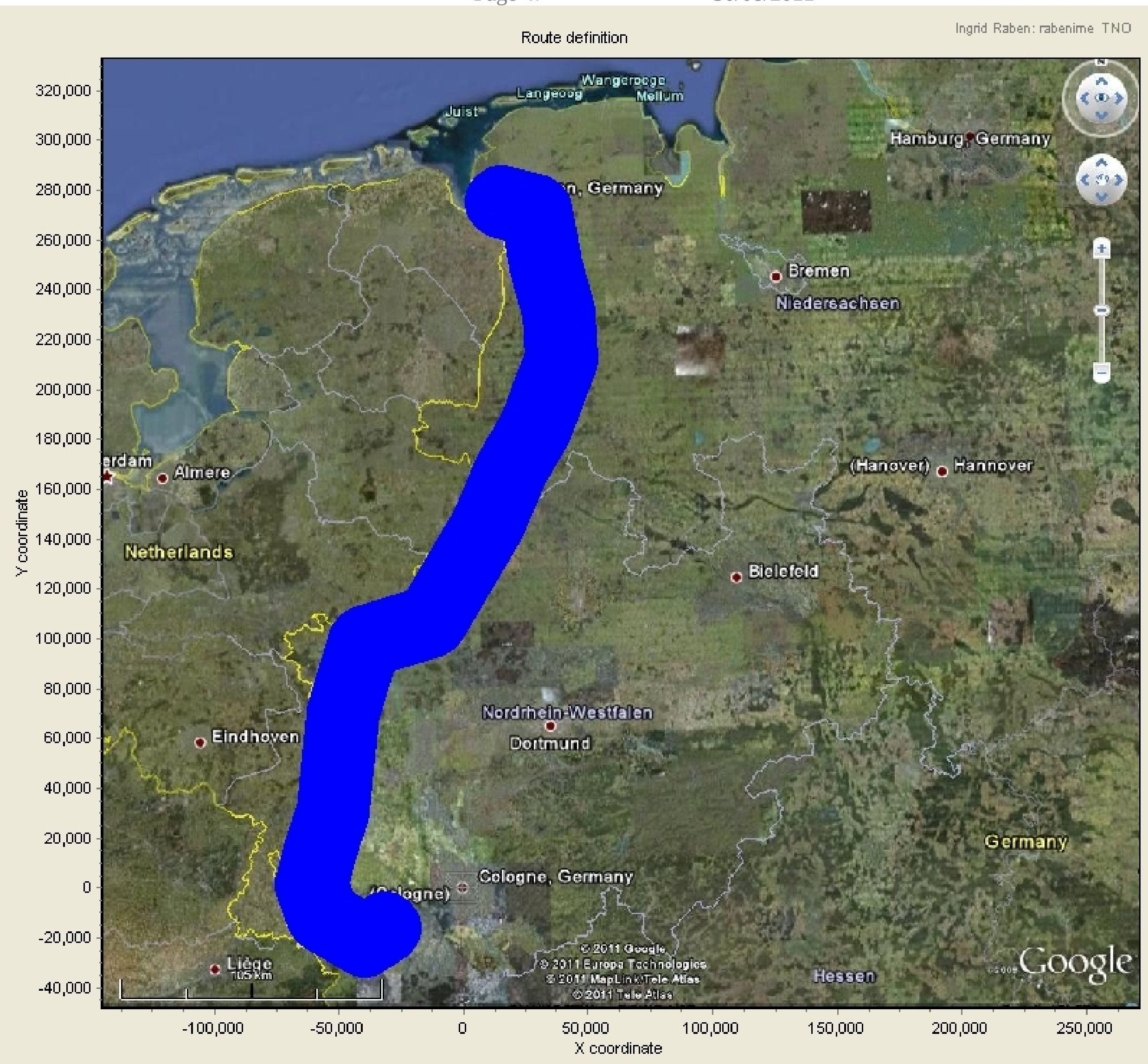

Figure 12: Proposed CO_2 pipeline from Cologne to Emden, NW Germany. Source: TNO

The proposed pipeline route is approximately 360 km long and would pass some hardly as well as some moderately populated areas. Decision criteria for this route where a moderate topography with no hills of elevations above 80m a.s.l. to be crossed. Also, big cities were excluded from the route to prevent crossing densely populated areas.

8.2 Case study

As described in the previous chapter, there are still quite some modelling issues pending regarding modelling of CO_2 pipelines:

- What are the failure frequencies of CO_2 pipelines?
- What happens after a failure of a pipeline? Questions rise such as:
    - will solid CO_2 be formed?
    - will a crater be formed and what might be its dimensions ?
    - what will be the outflow angle?
    - what will be the momentum?
    - Does CO_2 BLEVE? (BLEVE = *Boiling Liquid Expanding Vapour Explosion)*
    - etc.

The objective of this part of WP 4.2 is to perform a risk assessment for the proposed CO_2 pipeline through an area of northwest Germany. However, based upon the literature review in the previous chapter, it can be concluded that more development and experimental research is needed before validated and reliable results can be obtained from an in-depth risk assessment.

Further steps in the future should copy an approach applied in the UK:
- HSE and CCS operators are currently applying the existing major hazard regulation framework for new projects.
- Sensible best estimates are applied to emergency preparedness and land use planning.
- Close cooperation exists between all regulators and early adopters of CCS projects.
- Sharing knowledge with early demonstration projects and collaborative (JIP) research is vital to remove current uncertainties.
- Collaboration is key. International standards and guidance will facilitate demo projects.

9 Conclusions on Risk Assessment

At many points in the process of determining the risk of CO_2 transport uncertainties are present:
- Operating conditions: for most pipelines these are not known yet
- Failure frequencies: some data are available on the failure frequency of pipelines carrying CO_2. If these data are sufficient has to be decided case-by-case.
- Models describing outflow and dispersion of CO_2 show: the formation of solid CO_2 prevents using the standard, validated models used for other materials.
- The endpoint of which risk is accepted is not uniquely defined.

At these points more development and experimental research is needed (like done within CO2PipeTrans, see DNV 2010) to come to a validated and generally accepted way of performing risk calculation for CO_2 transport by pipelines.

Even though experimental work has been performed in Joint Industry Projects these data so far have not been made publicly available. Experimental programs with transparent data sharing in future will lead to a better understanding and modelling of CO_2 release scenarios.

10 General Conclusions

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 activities 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, 2.5 Mt/a in 2025, 10 Mt/a in 2032, and 20 Mt/a in 2040 and 2050.

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, most likely even after 2025. However, 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 and cross-border transport. Clear regulations for competent authorities as well as for the public and for the developing CCS business need to be defined and deployed. So far (July 2011), a legal CCS framework is missing in Germany and The Netherlands. The draft of the German CCS law plans to allow cross-border CO_2 transport. Also, expropriation for CCS purposes will be possible.

For the period 2020 – 2050, this report presents an outlook on the transport infrastructure for CO_2 in northwest Germany. The infrastructure is based on the most up to date databases and on current corporate and national CCS plans as well as on storage feasibility studies. Company plans of CCS developments were used as a basis in matching the gradually growing captured masses with storage capacity that gradually becomes available. The geographical distribution and timing of emission points (capture locations) and available storage capacity largely dictates the shape of the transport network. The aim of this project is to identify likely transport corridors and to estimate the order of magnitude of transported masses in a future CCS infrastructure. This future infrastructure is not designed in detail. CO_2 point sources and storage locations have been grouped together into clusters, connecting capture clusters with storage clusters.

Within Germany and the Netherlands, there is a large potential for CO_2 pipelines and inland CO_2 barging to both German and Dutch seaports. This is driven e.g. by ample troughput capacity exists on the considered waterways. Inland shipping is capable to circumvent the complexities and lengthy permit application procedures for pipeline transportation. A preferred scenario is to transport CO_2 from the Rhineland and Ruhr area down the Rhine to Rotterdam/Maasvlakte – as this route allows for the largest convoy size and subsequent highest volume transfers.

A benchmarking analysis of financial performance of gas and power transport companies shows that CO_2 pipeline transport investments might be an attractive financing opportunity for both private lenders and equity investors – provided that governments absorb the political risk.

At these points more development and experimental research is needed to come to a validated and generally accepted way of performing risk calculation for CO_2 transport by pipelines. Even though experimental work has been performed in Joint Industry Projects these data so far have not been made publicly available. Experimental programs with transparent data sharing in future will lead to a better understanding and modelling of CO_2 release scenarios.

(Politically motivated) prohibition against onshore CO_2 storage will reduce the amount of CO_2 stored per year by approx. 20%. Thus, an optimal, low-cost connection of CO_2 sources and sinks that is in line with climate protection targets is only possible if no political hurdles (which might be technically unjustified) are placed in the paths of CCS projects.

The IEA has established that CCS is the 2nd cheapest option to reduce CO_2 emissions. Timely and cost-effective transport infrastructure for CO_2 (on- and offshore) is essential for large scale deployment of CCS in Germany. Thereby, CCS can contribute very significantly to the CO_2 reduction goals of Germany and the EU while maintaining the profitable growth and export of the German industrial heart land as the motor of the national economy and Europe at large. We urge the leaders in Europe to communicate these goals clearly and establish rules and legislation that facilitate timely deployment of a large CO_2 transport infrastructure.

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