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EXECUTIVE SUMMARY

This report serves to highlight work completed within the EU FP7 CO2Europipe project, which aims to provide guidance to elements of an EU master plan for the development of large scale European CO_2 infrastructure. The contents of this report (1) covers the legal aspects of CO_2 transport and infrastructure development; (2) presents cost estimates for pipelines, compression and shipping from industrial partners; and (3) reviews current literature regarding the organizational issues of CO_2 transportation networks.

It has been expressed that during the demonstration phase of European CCS projects up until 2020, CO_2 transport infrastructure will be restricted to local cost-effective point-to-point pipelines. Depending of course on the success of the demonstration projects, post 2020 may see the first large scale deployment of CCS in the power sector. Due to the presence of clusters of CO_2 point sources in areas such as the Rotterdam/Antwerp harbours, and the industrialized German Ruhr area, there may be a requirement for public policy that encourages the development of optimized networks. Developments of networks are expected to reduce costs, utilize limited space and reduce investment barriers for market actors planning to implement CO_2 capture technologies.

There have been significant advances in the regulation of CO_2 transport and the development of CO_2 transport infrastructure. The removal of CO_2 transport for the purposes of geological storage, from the classification of waste from within the European regulatory waste framework will facilitate the transportation of CO_2. The calculation of emissions stemming from CO_2 transportation via pipelines under the EU ETS have recently been outlined, however there is no guidance concerning how emissions will be calculated for CO_2 shipping. Regarding the organizational development of transport networks, there remain uncertainties as to how individual member states will approach the issue of providing third-party access to pipelines, and how user tariffs will be regulated if no further EU wide guidance is released.

If large, interconnected regional networks are necessary, over-sizing for flows more than 10 years is most likely needed. It is highly unlikely that over-dimensioning of pipelines for the intention of sharing capacity between different parties will occur unless the government assumes at least part of the financial risk. To stimulate the development of multi-user pipelines, public-private business models for CO_2 infrastructure should be developed, covering contractual, risk-sharing and financing possibilities. A robust policy roadmap, or equivalent, is fundamentally important for private industry and the public sector alike to be certain of the goals that the government aspires to, and hence to be able to better manage the financial risk, or otherwise, that will be required in the achievement of those goals.

PROJECT SUMMARY

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

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

Project partners

Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek- TNO	Netherlands
Stichting Energieonderzoek Centrum Nederland - ECN	Netherlands
Etudes et Productions Schlumberger	France
Vattenfall Research & Development AB	Sweden
Gasunie Engineering BV	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 Veder CO_2 Shipping BV	Netherlands
E.ON New Build & Technology Ltd.	United Kingdom
Stedin BV	Netherlands

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1 INTRODUCTION

One of the key conditions governing the proliferation of CCS in Europe is the development of a CO_2 transport network, which will likely include a combination of pipelines and transportation via ship, where technically and economically feasible. Given the correct incentives, a ramp-up of CCS deployment in Europe may lead to a substantial demand for transport capacity running up to 2050 and beyond. Currently the European regulatory environment surrounding the transport of CO_2 remains underdeveloped, and information on the size of the investments required and the division of costs is limited. This report serves to highlight work completed within the EU FP7 CO2Europipe project, which aims to provide guidance to elements of an EU master plan for the development of large scale European CO_2 infrastructure.
The aim of this report is to review existing legal provisions relevant to the development of a CO_2 transport network, present the latest cost estimates for pipelines, compression and shipping from industrial partners, and provide a review of current literature regarding the organizational issues of CO_2 transportation networks.
Some of the main points this report addresses include:

1. The current regulatory environment controlling the transportation of CO_2, and the development of CO_2 transport network. (Section 3)
2. A selection of individual costs assessments of compression, on/offshore pipelines, CO_2 shipping and injection (Section 4)
3. The organizational aspects of CO_2 transport infrastructure, in terms of design/strategy, ownership, operation and management, financing, supervision (Section 5).

A three-fold approach has been used to compile the information contained in this report. A literature survey and analysis of European and member state regulations acts as a basis for the report. Experts from industrial concerns involved in the CO2Europipe project consortium have provided insight into the various cost components of CO_2 transport via pipelines and shipping. Finally, three workshops have taken place[1] involving several members of the CO2Europipe project consortium, whereby investment and organization theories have been tested against a panel of stakeholders from industry.

[1] Workshops took place at the ECN facilities in Amsterdam on the 2nd July and 10th November 2009, and on the 26th January 2010.

2 THE RATIONALE FOR CO_2 PIPELINE INFRASTRUCTURES IN EUROPE

2.1 The European Union Emission Trading Scheme (EU ETS)

The only broad market based policy incentive to reduce CO_2 emissions in the EU is the EU ETS. The price of a CO_2 emission allowance[2], known as a European Union Allowance (EUA) however, is currently not high enough to stimulate investment in this technology. Post 2012, due to the possibility of more ambitious international climate agreements, and changes in the allocation system for allowances in the EU ETS, it would seem logical to assume the EUA price will increase. The question remains whether the price will increase enough to create a sound business case for CCS at a commercial scale. Without government support or further modification to the EU ETS (i.e. a price ‘floor’, or additional sector involvement), private investors will be reluctant to deploy CCS technologies due to the high capital expenditure and the volatility of the ETS market.

Experts predict that the price of CO_2 in Phase III (2013-2020) of the EU ETS could fall between €10-40 per ton CO_2 (ECN/PBL, 2010) with €20 as a more central estimate. The economic crisis, its impact on energy demand are reasons for this relatively low value compared to previous forecasts prior to the financial and economic crisis. The price of a CCS demonstration is likely to have a CO_2/ton abatement cost of between €60-90 (Mckinsey & Company, 2008; Seebregts & Groenenberg, 2009; Seebregts et al., 2010). The CO_2 price in Phase IV (2021 and thereafter) is highly uncertain.

2.2 Government support for CCS

Considering the level of interest displayed by the European Commission, Member State governments and industry regarding the abatement potential of carbon capture and storage (CCS) technologies, there is a distinct possibility of substantial deployment. Financial support for CCS from governments is necessary given the immaturity of the technology and the current lack of incentive for industry to invest large amounts. To support the demonstration of CCS, in 2009 the EU announced funding for six demonstration plants throughout Europe, with an aim of commercializing CCS by 2020. Of late, a budget of €1.05 billion has been earmarked, provided by the European Economic Recovery Programme (EERP) (European Commission, 2008). CCS projects can also expect significant co-funding (up to 50%) through the allocation of 300 million emission allowances between in 2011 and 2015 (European Commission, 2009). Support for CCS demonstration projects has also been announced by individual member states, with the UK announcing a funding mechanism to deliver up to four CCS demonstration projects (HM Treasury, 2009), and the Netherlands aiming to realize two CCS demonstration sites by 2015.

[2] Equal to 1 ton of CO_2

2.3 Possible CO_2 Transport Network Developments to 2050

It has been expressed that during the demonstration phase of European CCS projects up until 2020, CO_2 transport infrastructure will be restricted to local cost-effective point-to-point pipelines (Mckinsey & Company, 2008). Depending of course on the success of the demonstration projects, post 2020 may see the first large scale deployment of CCS in the power sector. Due to the presence of clusters of CO_2 point sources in areas such as the Rotterdam/Antwerp harbours, and the industrialized German Ruhr area, there may be a requirement for public policy that encourages the development of optimized networks. Developments of networks are expected to reduce costs, utilize limited space, broaden participation and deepen deployment of CCS (Chrysostomidas et al. 2009).
The Energy Technology Perspectives (ETP) Blue Map scenario, which assessed strategies that reduced GHG emissions by 50% before 2050, concluded that in order to achieved the emission reductions most efficiently, CCS would have to abate one fifth of the total emissions (IEA, 2008). Building on the results of the Blue Map scenario, the IEA developed the Technology Roadmap for Carbon Capture and Storage (IEA, 2009). The roadmap envisions that for CCS to contribute to the lowest cost mitigation portfolio to achieve the target set under the Blue Map scenario, 3000 CCS projects must be realised by 2050.

Within the same roadmap, estimates have been made concerning global developments of pipeline infrastructures. The European[3] requirement for CO_2 transportation pipeline has been calculated, based on an annual abatement via CCS of approximately 35Mt/CO_2 and 1Gt/CO_2, in 2020 and 2050 respectively. In 2020, the number of pipelines required to achieve this level of abatement is estimated at 10 to 15, with a total length of between 1200km and 1600km, carrying CO_2 from 14 capture sites. The exponential increase in CCS deployment by 2050, leads to the capacity demand requirement for CO_2 transportation being met by 125-220 pipelines, with a total length of 20,000km - 30,000km (IEA, 2009).

Work completed in the CO2Europipe project[4] concentrating on CO_2 source-sink matching to 2050 in Europe, uses scenarios based on extrapolated projections from the PRIMES economic growth model developed by the University of Athens to explore potential pipeline capacity requirements (Neele et al. 2010). Three scenarios have been developed, one based on primarily national onshore storage of CO_2 (Reference), a scenario where only offshore storage takes place (Offshore), and a third scenario whereby offshore storage takes place with possibilities for EOR. The scenarios also assume that a suitable legal framework and sufficient economic incentives are available.

[3] OECD Europe
[4] Please see CO2Europipe D2.2.1 (Neele et al. 2010)

Table 2-1 Projection of European pipeline requirements (Neele et al. 2010)

	Total pipeline length [km]		
	Reference scenario	Offshore-only scenario	EOR scenario
2020	2.300	4.200	5.300
2030	15.000	20.000	21.000
2050	22.000	33.000	33.000

Based on the projection of 1222 MtCO_2/yr being captured in North-Western Europe in 2050, it has been calculated that 21,800 km of pipelines will need to be built to transport the CO_2 to onshore storage locations. If offshore storage becomes the only option for storage, the length of backbone pipelines required rises considerably.

The IEA (2009) outlines a number of 'actions and milestones' intended for policy makers, which may be necessary to facilitate the establishment of CO_2 pipeline networks. Such 'actions and milestones' include (IEA, 2009):

- Conduct analysis of source/sink distribution to identify clusters in OECD countries by 2012
- Incentivise the linking of source and/or sinks through CO_2 transport hubs in OECD countries from 2012 to 2020
- Perform a country- or region-wide analysis of the optimal layout of a pipeline network connecting major sources with storage sites in OECD countries by 2012
- Facilitate the phased roll-out of a pipeline network from 2012 to 2020 in OECD countries.

From the points above, it is clear that in order to reach the projected deployment targets, the IEA (2009) expects both the development of pipeline networks and the encouragement of CCS clusters. Mckinsey and Company (2008) also provide a useful visualization of a possible trajectory of European CO_2 pipeline development (Figure 2.2).

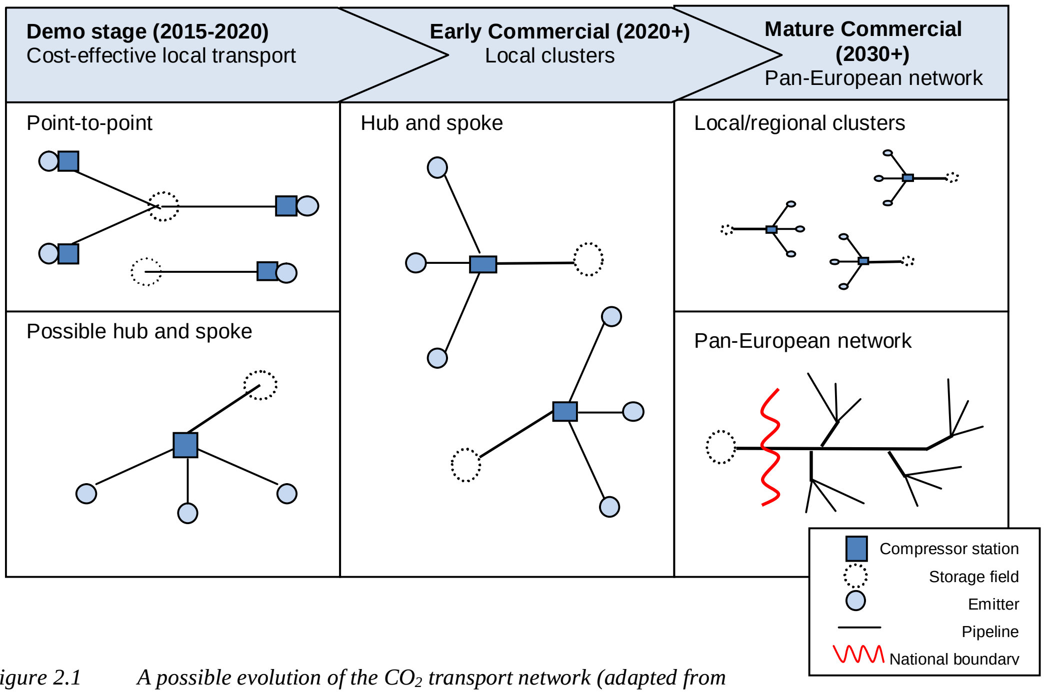

Figure 2.1 *A possible evolution of the CO_2 transport network (adapted from Mckinsey and Company, 2008)*

Within certain European countries, source/sink distribution analyses have been completed, or are being continually improved as additional data on geological storage capacity becomes available. As part of the ongoing CO2Europipe project, investigations into the optimal layout of pipeline networks, and the possibility of establishing CO_2 transport hubs are ongoing[5].

[5] A full analysis of the possible CO_2 network topologies in Europe, please see CO2Europipe D2.3.1 (van der Burgt et al. 2011).

3 LEGAL ASPECTS OF CO_2 TRANSPORTATION AND INFRASTRUCTURE DEVELOPMENT

The development of a comprehensive regulatory framework is a fundamental step to ensure community and industry confidence regarding the capture, transport and storage of CO_2 (IEA, 2004). Although technologies that have the ability to capture carbon from industrial sources have been utilized over the last 30 years or so, the concept of CCS for the purpose of reducing greenhouse gas emissions is a relatively new concept, and hence little or no regulation exists. In addition, large long-term CCS projects have the potential to interact with a variety of regulations and laws at the local, state/provincial, national and international levels (Vine, 2004).

With the emergence of CCS as a significant potential contributor to the global mitigation portfolio, in recent years there have been modifications to existing regulation which restricts the disposal of CO_2 in geological formations. The 1996 London Protocol, is an international agreement that prohibits the deliberate disposal of all wastes into the sea, with exception of a number of categorically listed materials. The geological storage of CO_2 was initially prohibited under the protocol, however in 2006 an amendment was made to the protocol which allowed CO_2 streams to be sequestered in sub-seabed formations. The 1992 OSPAR convention, a regional agreement that regulates the deliberate dumping of pollutants into the North-East Atlantic Ocean maritime area, was also amended to allow the disposal of CO_2 into sub-soil geological formations. Within the EU, there have also been modifications to the Water Framework Directive[6] and Waste Framework Directive[7] through the enactment of the EU Directive on the geological storage of CO_2[8].

To keep within the scope of CO2Europipe project, the remainder of this section will focus on European regulation, or foreseen regulatory developments, that specifically relate to both the transportation of CO_2 (section 3.1), and also the development of the transport infrastructure (section 3.2). For comprehensive coverage of the legal aspects of CCS in general, please refer to Mace et al. (2007), IEA (2007).

3.1 Legislation of CO_2 transportation

3.1.1 The EU Directive on the Geological Storage of Carbon Dioxide

There is currently no dedicated EU legislation, or technical guidelines, that cover the transportation of CO_2 (UCL, 2010). Transportation of CO_2 is covered to a certain extent in the recent EU Directive on the Geological Storage of Carbon Dioxide[9] (hereafter referred to as the CCS Directive). The legal provisions contained within the Directive must be transposed into member state legislation by the 25th June 2011. Importantly, the Directive contains a number of amendments to existing Directives, and as a

[6] Directive 2000/60/EC
[7] Directive 2006/12/EC
[8] Directive 2009/31/EC
[9] Directive 2009/31/EC

consequence removes a number of legal uncertainties regarding the transportation of CO_2.

Before the finalization of the CCS Directive, questions were raised regarding the classification of CO_2 as a waste under the EU Waste Framework Directive. Although the classification of CO_2 as a waste would not prevent transportation of the substance within Europe, it means that CO_2 transportation would have to conform to the EU's regulatory programme for wastes. This programme includes the Landfill Directive[10], Hazardous Waste Directive[11] and Transfrontier Shipment of Waste Regulation[12]. If CO_2 were to be classed a waste, operators would have to obtain permits and licenses for a number of Directives, and this would lead to particular complexities in transporting CO_2 via pipelines.

Article 35 of the CCS Directive, amends Article 2(1)(a) of the Waste Framework Directive, categorically removing from the definition of 'waste', carbon dioxide captured and transported for the purposes of geological storage, provided it is geologically stored in accordance with the CCS Directive (UCL, 2010). As the definition of waste used in the Waste Framework Directive is also used in the Landfill Directive and the Hazardous Waste Directive, such regulation is no longer applicable to the transportation of CO_2, so long as it conforms to the other regulations of the CCS Directive. Article 36 of the CCS Directive, removes CO_2 transport for the purpose of geological storage from the scope of the Transfrontier Shipment of Waste Regulation. The amendments to the definition of waste to exclude CO_2 transport (in conformity with the CCS Directive), are considered to be significant actions to enable the roll out of CCS within Europe.

The CCS Directive also loosely defines the required stream composition that can be legally transported. Article 12(1) states in part:

> *'A CO_2 stream shall consist overwhelmingly of carbon dioxide. To this end, no waste or other matter may be added for the purpose of disposing of that waste or other matter.'*

Although clearly prohibiting the co-disposal of waste gases in a CO_2 stream, the Directive does not set absolute quantitative restrictions on the substances that compose the CO_2 stream, but uses qualitative criteria to guide operators. The Directive does recognize that the CO_2 stream may contain incidental associated substances from the capture process, or substances used for monitoring and verification purposes, however all incidental or added substances must be below levels that would:

a) *'adversely affect the integrity of the storage site or the relevant transport infrastructure;*

[10] Directive 1999/31/EC
[11] Directive 91/689/EC
[12] Regulation No.1013/2006

b) *pose a significant risk to the environment or human health; or*
c) *breach the requirements of applicable Community legislation.'*

In legal terms the use of qualitative criteria for a gaseous stream composition seems inappropriate, as the term 'overwhelmingly' used in Article 12(1) could be interpreted differently between operators. Brockett (2009) informs that during the drafting of the CCS Directive, the European Parliament's Environment Committee had proposed an amendment to the Directive, calling for a CO_2 concentration of ≥95% and above, and the elimination of H_2S and SO_2. This amendment has not been adopted, on the basis that certain applications of CCS, particularly for the cement and steel industry[13], may have considerable problems reaching such levels of CO_2 purity. Furthermore the complete removal of H_2S and SO_2 is not feasible (Brockett 2009). For clarification, the commission intends to produce guidance on the practical applications of the qualitative criteria outlined in Article 12. It is also expected that documents specifying the Best Available Techniques (BAT) will be developed for capture installations, which will include CO_2 compositions (Brockett, 2009), however given the early stage of development of most capture technologies, this is unlikely to reassure operators of demonstration projects.

3.1.2 The 1996 London Protocol: Article 6 Amendment

In November 2006, it was agreed by contracting parties to add an eighth category to Annex 1 of the London Protocol, which placed *'CO_2 streams from CO_2 capture processes for sequestration'* on a list of wastes that could be considered for dumping[14]. However at that time, Article 6(1) provided that *'Contracting Parties shall not allow the export of wastes or other matter to other countries for dumping or incineration at sea'*. Given a large scale-up of CCS throughout Europe, and that certain European countries may not have access to suitable geological storage sites, the ability to transport CO_2 across borders was considered imperative by a number of contracting parties. At the 31st Meeting of Contracting Parties in October 2009, Norway submitted a proposed amendment to the London Protocol, which added an additional paragraph (2) to Article 6 as follows (in part[15]):

> *'Notwithstanding paragraph 1, the export of carbon dioxide streams for disposal in accordance with Annex 1 may occur, provided that an agreement or arrangement has been entered into by the countries concerned.'*

The amendment was adopted as a Resolution (Resolution LP.3(4)) by vote. However, in order for the Resolution to come into force (for parties that accept it), it must be ratified

[13] CCS applications in many industrial sectors, particularly the steel and cement sectors, are currently in the early stages of development. There is not sufficient information on the CO_2 reduction potential of such industrial process with CCS, and the costs associated with such applications are uncertain.
[14] In accordance with provisions provided in Sub-section 4 of the protocol.
[15] The sub-sections (2.1 and 2.2) to the new paragraph also provide provisions for permitting in accordance with the London Protocol, and measures to take when exporting to a non-contracting party.

by two-thirds of the Contracting Parties. At present, only Norway has ratified the Resolution.

3.1.3 Monitoring and verification of CO_2 Transport under the EU ETS

As of 2013, CCS will be fully included in Phase III of the European Union Emissions Trading Scheme (EU ETS). This means that any operator who captures CO_2 from a registered installation to a geological storage site will not have to surrender European Union Allowances (EUAs) equal to the amount of CO_2 not emitted. Operators within the EU ETS must monitor and report their emissions conforming to legally binding guidelines set by the European Commission. The monitoring of emissions resulting from transport pipelines is necessary for the reconciliation process under the EU ETS, but also for internal management purposes.

The last set of finalized Monitoring and Report Guidelines (MRGs) were released in 2007[16] to be used during Phase II of the EU ETS (2008-2012). Although no MRGs referring to CCS were provided, Member States willing to unilaterally apply for inclusion of a CCS project in Phase II of the EU ETS were able to do so, however that member state would have to complete a number of procedures in advance. One of these procedures would be to develop suitable monitoring and report guidelines for the capture, transport and storage of CO_2 involved in a project. The UK government decided to 'opt-in', and as a result, the Department of Business Enterprise and Regulatory Affairs commissioned a set of monitoring and reporting guidelines (Zakkour, 2007).

In June 2010, the European Commission released an amendment to the original MRGs for the EU ETS released in 2007. The amendment,[17] in addition to providing further guidance on the determination of emissions or amount of emissions transferred using continuous measurement systems (CEMS), also contains 'Activity-specific guidelines' for the determination of emissions from the transport of CO_2 through pipelines to geological storage sites[18], permitted under the CCS Directive[19]. Transport networks are defined as having a minimum of one starting point and one ending point, connected to other installations carrying out one or more of the activities capture, transport or geological storage of CO_2. The starting and ending points can include bifurcations of the transport network, but also national borders, which is relevant for the verification of emissions transported within transboundary CO_2 networks. The 2006 IPCC GLs approach[20] state that when CO_2 is transported across borders, Country A should report the amount of CO_2 captured and any emissions from transport and/or temporary storage that takes place in Country A, and the amount of CO_2 exported to Country B. In using continuous measurement systems, and for complete accuracy, this may warrant monitoring at border crossings.

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16 Decision 2007/589/EC
17 Decision 2010/345/EU
18 see Annex XVII of Decision 2010/345/EU
19 Directive 2009/31/EC
20 2006 IPCC GLs, Vol. 2, Ch. 5, p. 5.20

The activity-specific guidelines in the amendment to the EU ETS MRGs list the potential emission sources from CO_2 transport pipelines, which are:

- Installation emissions; combustion and other processes at installations functionally connected to the transport network, e.g. fuel use in booster stations.
- Fugitive emissions; from the pipeline seals, valves, measurement devices, intermediate compressor stations and intermediate storage facilities.
- Vented emissions; from the pipeline for maintenance or emergency reasons.
- Leakage events; emissions released due to the failure of one or more components of the transport network.

Calculation methods for transport emissions

In order to accurately report potential emissions from CO_2 transport pipelines, two approaches are permitted via the recent amendment to the EU ETS monitoring and reporting guidelines. In choosing which method to apply, the operator must demonstrate to the competent authority that the choice of method leads to more reliable results and a lower degree of uncertainty of overall emissions.

Method A is based on a mass-balance calculation by measuring the CO_2 entering and exiting the pipeline, using the formula:

$$Emissions\ [tCO_2] = E_{own\ activity} + \sum_i \square \ | \ \sum_j T_{OUT,j}$$

With,

$Emissions$ = Total CO_2 emissions of the transport network

$E_{own\ activity}$ = Installation emissions from the transport networks own activity, such as fuel use in booster stations, not stemming from the CO_2 transported.

$(T)_{IN,i}$ = Amount of CO_2 transferred to the network at entry point i,

$T_{OUT,j}$ = Amount of CO_2 transferred out of the network at exit point j,

In terms of accuracy, operators would be required to use continuous measurement systems capable of providing a level of uncertainty of CO_2 flow over the reporting period of less than ± 2,5%[21]. Zakkour et al (2005) mention that the method of using

[21] Corresponding to Tier 4, as defined in Annex XII of Decision 2010/345/EU

direct measurement enables the operator and regulator to check that unacceptably high levels of fugitive emissions do not occur.

Method B is a calculation-based methodology, which would require the development and application of default emission factors for the various components of the CO_2 transport chain. These emission factors must be expressed in g CO_2/unit time per piece of equipment, and be reviewed every five years. The calculation methodology is specified as:

$$Emissions\,[tCO_2] = CO_{2\,fugitive} + CO_{2\,vented} + CO_{2\,leakage\,events} + CO_{2\,installations}$$

Descriptions of the four different potential emission sources are outlined in bullets on the previous page. This approach was first outlined by Zakkour et al (2005), who point towards the current CO_2 enhanced oil recovery operations in the Permian Basin, West Texas, for potential availability of emission factors for fugitive emissions and pipeline leaks.

Calculating emissions over a common carriage network
Given the development of extensive CO_2 transport network throughout Europe, this may add to the complexities in ensuring that all network users surrender sufficient European Union Allowances (EUA) for fugitive emissions. Zakkour et al (2005), provide a practical example of how fugitive emissions could be accounted for a multiple user common carriage network with a single sink, using a measurement-based method. The equation used is:

$$EUAs = T - \left(\frac{I \times E}{\sum E}\right)$$

Where:

EUAs = total amount of EUAs to be surrendered to Member state competent authority
T = amount of CO_2 produced at the installation (tCO_2)
I = amount of CO_2 metered at the injection wellhead (tCO_2)
E = the total amount of CO_2 exported from the installation
$\sum E$ = total amount of CO_2 put into the network by all users (tCO_2)

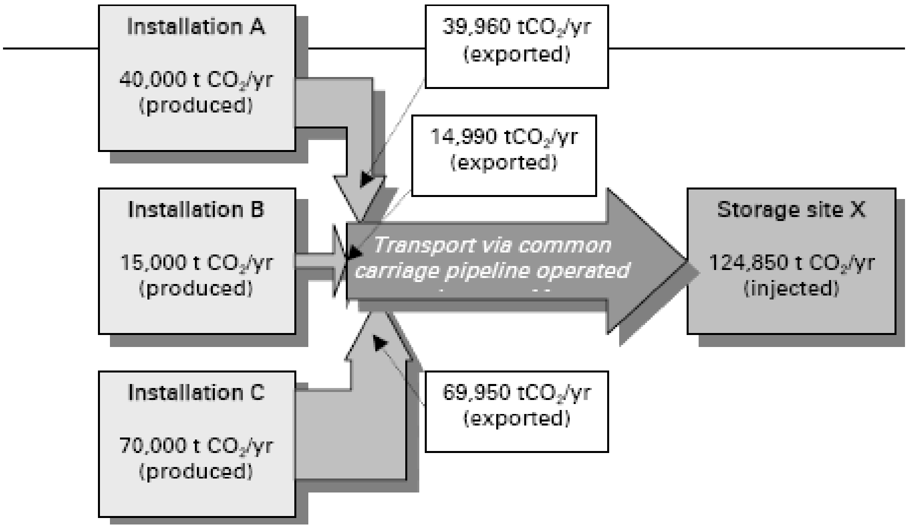

Figure 3.1 Example of fugitive emissions amongst multiple installations (Zakkour et al. 2005).

Using the equation outlined above, the fugitive emissions for installation A can be calculated as:

$$\mathit{Installation\ A\ (EUAs)} = 40{,}000 - \left(\frac{124{,}850 \times 39{,}960}{124{,}900}\right) = 56$$

Importantly, this approach assumes that all users accept the fugitive emissions of the network being attributed on an equity basis. This approach may raise issues for example, if 'Installation C' is far closer to the injection point than 'Installation A', and thus Installation C could argue that this should result in fewer fugitive emissions being attributed to its usage. In order to resolve this situation, a calculation-based methodology could be used, however Zakkour et al (2005) state that[22] given the number of uncertainties and lack of experience in calculating emissions factors from CO_2 transport, a measurement approach is the most feasible option in the near term.

3.2 Legislation of CO_2 transportation infrastructure development

This section focuses on current regulation regarding the development of CO_2 transportation infrastructure that is relevant to decision makers and CCS project developers. In this report, CO_2 transport infrastructure is defined as the pipelines (and associated safety and control equipment), booster stations (compressors or pumps), CO_2-capable transport ships, any intermediate storage facilities, the CO_2 injectors and well heads.

3.2.1 The EU Directive on the Geological Storage of Carbon Dioxide

The EU CCS directive provides limited guidance on the development of transport infrastructure. Within the directive, there is no reference made to the technical standards

[22] After consultation with members of industry.

for the design, construction, monitoring or the maintenance of pipelines. There is at present no regulation regarding the routing of onshore CO_2 pipelines, or on how to include the public within decision-making processes concerning CCS activities. However, the EU CCS directive does include concrete requirements for Member States to extend their environmental impact assessment (EIA) legislation to cover CO_2 pipelines, and also issues of third-party access and transboundary issues are touched on. All the articles and amendments contained in the EU CCS directive must be transposed into member state law by the 25th June 2011.

Environmental impact assessments

Article 31 of the directive is associated with the amendment of the existing EU Environmental Impact Assessment (EIA) directive[23], which defines public and private projects that are subject to an EIA. The article stipulates that pipelines with a diameter greater than 800mm and over 40km in length for the transport of CO_2, will be subject to a mandatory EIA, implemented through an addition to Annex I of the EIA directive. The amendment also states that CO_2 transportation pipelines for the purpose of geological storage with physical dimensions that fall outside of the criteria outlined above, are subject to a screening procedure by the national authorities to determine whether the proposed pipeline project requires an EIA. Similar amendments have been outlined for capture installations and geological storage sites.

According to Article 7 of the EIA directive, for projects that are likely to have significant environmental impacts in another Member State, information must be provided to the potentially affected Member State and the possibility for involvement in environmental decision-making procedures must be made possible. This legal provision is often referred to as the ‘Espoo procedure’ stemming from the UNECE Convention on Environmental Impact Assessment in a Transboundary Context, the principles of which were incorporated into the EIA Directive in 1997.

Third-party access and dispute settlement

Chapter 5 of the CCS Directive entitled ‘Third-party access’, covers the issues of access to transport networks and storage locations. The Directive recognises that, given a significant increase in the price of emitting CO_2 under the EU ETS, access to CO_2 transport networks as well as storage sites, could become a condition for entry into or competitive operation within the internal electricity and heat market. Article 21 of the directive states that Member States should take necessary measures to ensure that potential users are able to access transport facilities, and that the granting of access will be done in a transparent and non-discriminatory manner determined by the Member State. The article also states that access to the network will follow the objectives of fair and open access.

Open access means that the owner of the transport pipeline or network would not be able to restrict the use of the transport network for its own purposes, and must provide access to third-parties. With the exception of technical incompatibility, or a lack of

[23] 85/337/EEC

capacity, the owner must provide duly substantiated reasons for refusing access. In addition, paragraph 4 of the article adds that operators refusing access due to lack of capacity or lack of connection must make any necessary enhancements as far as it is economic to do so or when the potential customer is willing to pay for them.

Article 22, stipulates that Member States must have an independent authority capable of settling disputes between operators and potential users of a network. However, the CCS Directive provides no guidance over setting tariffs for pipeline capacity, or whether operators would be able to reserve capacity for their own future requirements. A lack of clarity on tariff setting leads to uncertainty for developers, and may perhaps delay investment. Other than the necessity to adhere to the principles of fair and open access, and the ability for a third-party to negotiate access to a transport system, each individual Member State can devise further detail within national legislation.

In the UK, the Department for Energy and Climate Change (DECC) have proposed to amend an existing piece of legislation used to negotiate third-party access to oil and gas networks. The Petroleum Act 1998[24], allows the Secretary of State to set access charges on the incremental cost of an existing pipeline (NERA, 2009), which could have detrimental effects on early investment, given that investors would need to set tariffs based on a rate closer to the average cost of the entire pipeline rather than the incremental cost of additional capacity (NERA, 2009). However, a guidance document for the Act produced by DECC (2009), states that if a pipeline was built oversized or maintained with a view to taking third-party business, the Secretary of State would normally allow tariffs to be set at a level that would earn the owner a reasonable return on investment, reflecting the risks involved. This approach to regulating tariffs is more suitable to stimulate investment in CO_2 pipelines given the significant market risks involved.

In the Netherlands, the principles of the Directive have been transposed into the Dutch Mining Law ‘Mijnbouwwet’[25]. It is understood that Dutch policy makers assume that potential owners and users of transport and storage facilities have a common interest in sharing such investments. However this has been criticized, since potential users could be competitors in electricity generation or industrial production. In a situation of vertical integration, whereby an electricity company invests in a pipeline and gains access to a favourable storage location, there would be an incentive for the initial investor to block access to such infrastructure (vertical foreclosure).

According to Brockett et al (2009), during the development of the EU CCS Directive, the Commission was aware that access to CO_2 transport networks and storage operations could become a condition for competitive operation in the EU energy market. However, a decision was made by the Commission that given the early stage of CCS as a technology, a ‘light regulatory touch’ and the application of the principles of

[24] Section 15, clause (7)
[25] Kamerstukken 2009-2010, 32 343, nr. 2.

negotiated rather than regulated access seems most appropriate. If unregulated access to transport and storage facilities does appear to lead to anticompetitive behaviour, then the Commission will come forward with further proposals as appropriate (Brockett et al 2009).

4 COST ESTIMATIONS OF CO_2 TRANSPORT INFRASTRUCTURE

A cost assessment of the various components of a CO_2 transmission system is given in this chapter. The cost estimations have been provided by the project members from industry and are entirely indicative and may vary considerably due to specific details of each application. The underlying assumptions between the various component cost analyses are inconsistent, and should be referenced individually.

Figure depicts a possible CO_2 transport route from capture to injection point, including on and offshore pipelines, and an optional liquefaction and shipping route.

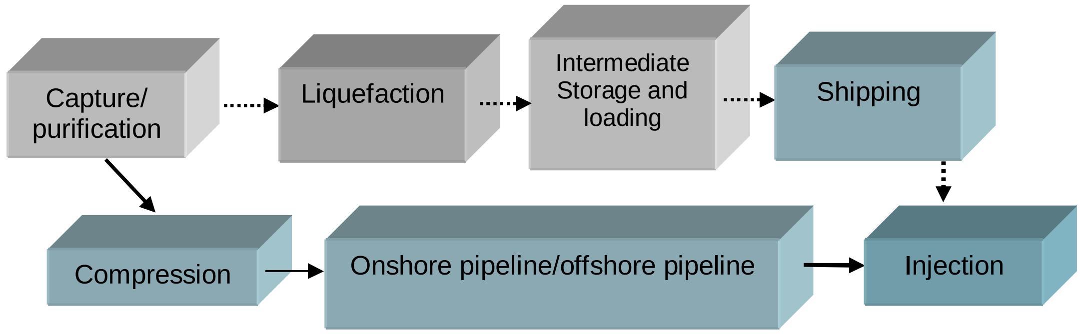

Figure 4.1 A CO_2 transmission system, with both shipping and pipeline routes.

The following elements in the CO_2 transport chain are considered in this assessment, (highlighted is blue in Figure):

1. Compression
2. Onshore transport
3. Offshore transport
4. Shipping
5. Injection

4.1 Compression costs

Cost estimates for a number of compressors were made by Siemens AG in 2010. The price estimates are based on a manufacturer standard. The capital cost estimates should be considered with an accuracy of +/- 20%. It excludes dehydration units, noise hoods and sour condition due to H_2S, but includes re-cooling to 32°C by water cooling. The compressor capacities of 1.5 and 3 $MtCO_2$/yr are arranged in single trains, whereas the 6 and 12 $MtCO_2$ are arranged as 2 and 4 trains respectively. Data is presented for the discharge pressures of 150 bar. To raise the discharge pressure to 200 bar, an increase in the capital costs of 1,5% is expected.

Table 4.1 Equipment costs of various size CO_2 compressors[26]

	1.5 $MtCO_2$/yr	3 $MtCO_2$/yr	6 $MtCO_2$/yr	12 $MtCO_2$/yr
Total cost M€	9.1	13.7	26.3	51.6

Based on the equipment costs only the cost of increasing compressor capacities also show economies of scale. For example, a doubling the compression capacity from 1,5 to 3 Mt CO_2, increases the investment required for the compressor unit by just 33%. However doubling the compression capacity from 3 to 6 or 6 to 12 $MtCO_2$/yr demonstrate less profound economies of scale.

4.2 Pipeline costs

The approximate costs of pipelines are given in Euros per inch of pipeline diameter per meter of pipeline length (€/"/m), have been estimated by Dutch gas network operator Gasunie Engineering BV. The costs are based on maximum operating pressures of 150 bars for onshore transport and 200 bars for offshore transport. The CAPEX of onshore pipelines is 50 €/"/m, with offshore pipelines costing 75 €/"/m. For an approximation, the following rule of thumb of the CAPEX build-up of a CO_2 pipeline with a diameter greater than 16" can be used.

Table 4.2 Cost estimates for a 16” on and offshore CO_2 pipeline.

[26] Excluding OPEX

5	Onshore	Offshore
Total Investment	50 €/"/m (€800,000/km)	**75 €/"/m (1,200,000/km)**
Material	20-50%	**20-50 %**
Engineering	10-30 %	**5-15 %**
Construction	50-60 %	**40-60 %**
Total OPEX	**7000 €/km/yr**	

A more detailed representation of on and offshore pipelines costs have been calculated in a recent report by the Zero Emissions Platform (ZEP, 2011). The list of assumptions used in this calculation can be found in Annex I of this report. The costs presented do not include onshore compression (a significant cost), but assumes 200 bar inlet pressure and 60 bar outlet pressure. The costs per ton CO_2 transported have been calculated using a Weighted Average Capital Cost of 8%, and an operative lifetime of 40 years. As mentioned above, the scenarios in Figures 4.3 and 4.4 assume a 200 bar inlet pressure, and thus exclude the costs of compression[27].

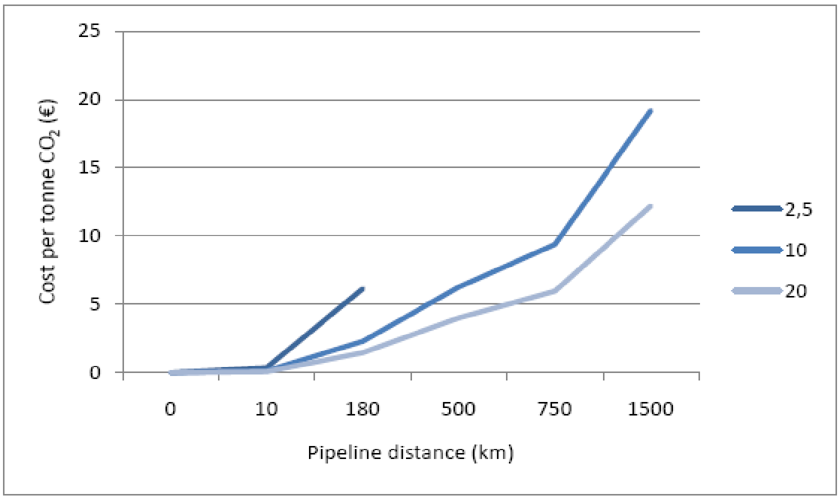

Figure 4.3 *Onshore costs per ton CO_2 transported over a range of distances for pipelines with capacities of 2,5 Mt, 10 Mt and 20 Mt per year*[28]

[27] A full list of the assumptions used in this calculation can be found in Annex I of this report.
[28] The costs for the 2.5 Mt onshore pipeline were only calculated for distances of 10 and 180 km.

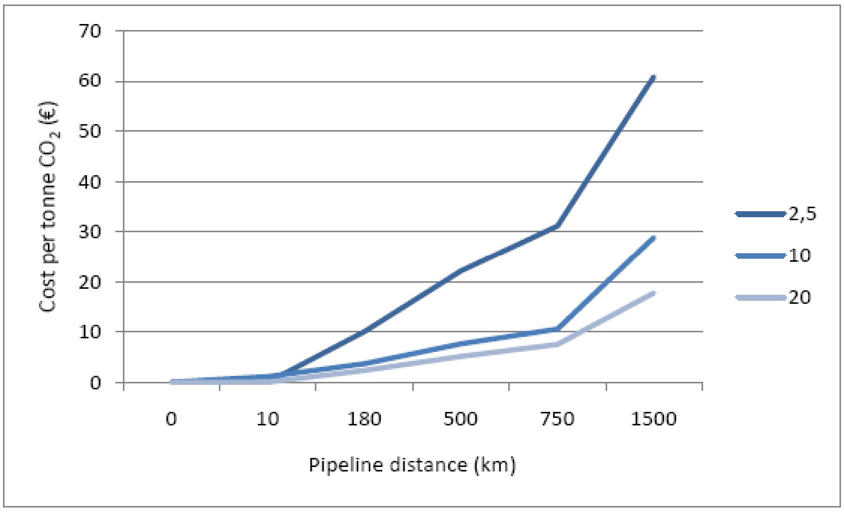

Figure 4.4 *Offshore costs per ton CO_2 transported over a range of distances for pipelines with capacities of 2,5 Mt, 10 Mt and 20 Mt per year*

From the cost calculations by (ZEP, 2011), over long distances the average cost of transporting a ton of CO_2 decreases as the capacity of the pipeline is increased. For offshore pipelines (Figure 4.4), over long distances the economies of scale between a 2.5 Mt pipeline (16″ diameter) and a 10 Mt pipeline (26″ diameter) are quite substantial, with the cost per ton CO_2 transported in the smaller pipeline approximately 66% higher than the larger pipeline.

There are however, significant limitations in calculating generic costs estimates for pipelines and pipeline networks. A number of factors such as the impact of terrain, gradients and other barriers such as land restrictions and conflicts with existing land and sea infrastructure, may have significant impacts on the costs of a pipeline. Accurate cost estimations for pipeline infrastructures can only be achieved on a case-by-case basis, and this highlights the importance of conducting case studies for potential pipeline routes.

5.1 Shipping costs

There is currently uncertainty regarding the volume growth of captured CO_2 and the availability of suitable sinks for storage. From this uncertainty, a shipping based CO_2 transport solution could be considered as a viable option to open up the market, for the short term and as a more flexible long term solution. For this concept, ships will be loaded at CO_2 bulk terminals or at the industrial facilities and from there sail to the location of underground storage areas, such as (i) depleted oil and gas fields (ii) producing oil fields for enhanced oil recovery purposes, and (iii) saline aquifers.

5.1.1 The role of CO_2 shipping

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

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

Alternative use of assets: Ships represent a certain residual value (in time), especially combined carriers that can be employed in alternative trades (i.e. LPG[29]). Residual value reduces the upfront investment risks. However the costs for the onshore CO_2 terminal, liquefaction and offshore conditioning do represent fixed investments.

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

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

5.1.2 Ship configurations

Dedicated and combined ships

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

Offshore and onshore discharge

Ships are generally designed to load their cargo in one port and discharge it in the next (onshore discharge). As an alternative, ships can be modified or purposely built to discharge at offshore locations like platforms on a standalone basis via single point moorings directly into the well. Despite having additional investment and operational costs, the advantage of a ship is that it can discharge at different locations and the requirement for CO_2-infrastructure (i.e. pipelines) is reduced. In the offshore base case

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

the conditioning of the CO_2 (in order to meet the offshore storage field requirements) is performed on board of the ship. In a few alternative offshore scenarios the conditioning of CO_2 is performed on the platforms by making use of the available non-commercial gas (e.g. field pressure too low for economically exporting the gas to shore). A case-by-case cost review will be necessary in order to determine the best lay out.

Ship sizes

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

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

Typically these vessels will have the following dimensions:

Table 4.3 Typical vessel dimensions and specifications.

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

5.1.3 Cost structure

The cost components of this assessment of the cost of shipping are outlined below:

Depreciation mechanism for combined Carriers

The value of a combined tanker after CO_2 service is determined by the price (on the market) of an LPG carrier of similar tank type, size (cbm) and age (see Figure 4.5). The figure shows that during CO_2 transport a ship's value depreciates much faster against regular LPG transport. Higher depreciation during CO_2 trade is caused by the requirement to depreciate CO_2 related investment during the CO_2 service contract lifetime. CO_2 related investments are for example dynamic positioning systems, CO_2 onboard conditioning equipment and offshore discharge installations that allow for connection to the offshore infrastructures.

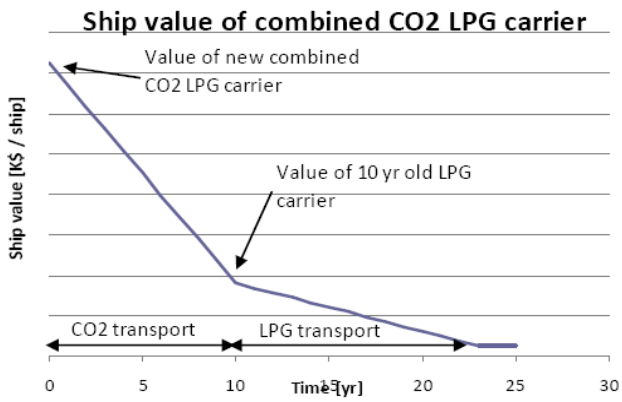

Figure 4.5 *Graphical representation of the ships' value in time for a combined CO_2/LPG carrier, which is utilized for CO_2 transport for the first 10 years and for LPG transport after 10 years.*

Capital related expenses (CAPEX)

CAPEX includes the vessel and its onboard conditioning equipment, a Weighted Average Cost of Capital (WACC) of 10% is used in the annuity based repayment profile for the asset financing. Building interest is assumed to be 5% of the total investment. The economic lifetime of the vessels is set at 25 years. Construction costs are based on 2010 price levels.

Operational expenses (OPEX)

The fixed operational expenditures consist of crewing, maintenance, management, insurance and dry docking (bi-annual surveys and every 4 – 5 year dry dockings is common market practice) costs. All costs are based on nominal prices for 2010.

The variable OPEX depends on fuel, port, other transit costs and the costs of consumables. The variable OPEX is mainly driven by the fuel consumption of the ship for propulsion, and dynamic positioning. Offshore discharge consumes a substantial amount of energy and is dependant of the field's injection requirements, since no specific reservoir is considered here these injection costs are excluded just as the dynamic positioning cost as these too are highly dependent of the discharge location

5.1.4 Transport capacity and cost

In order to compare the ships' transport capacities at varying distances, the ships are assumed to be fully utilised. Using the different ship configurations described above, the annual transport capacity for different distances can be seen in Figure 4.6. It is assumed that the combined CO_2/LPG ships have the same round-trip duration and capacity as a dedicated CO_2 carrier. These capacities represent the annual volumes that a vessel can transport between a loading port and an offshore discharge location.

Offshore discharge will lower a ship's annual transport capacity because of the longer mooring and discharge operations offshore. The latter is highly dependent of the environmental conditions at the discharge location offshore that influence the uptime of the discharge operations during the year and as such the figure represented below is to be seen as a general case; only a case by case analysis will allow for detailed figures. Furthermore offshore injection rates are dictated by the reservoir under consideration and as such highly case specific.

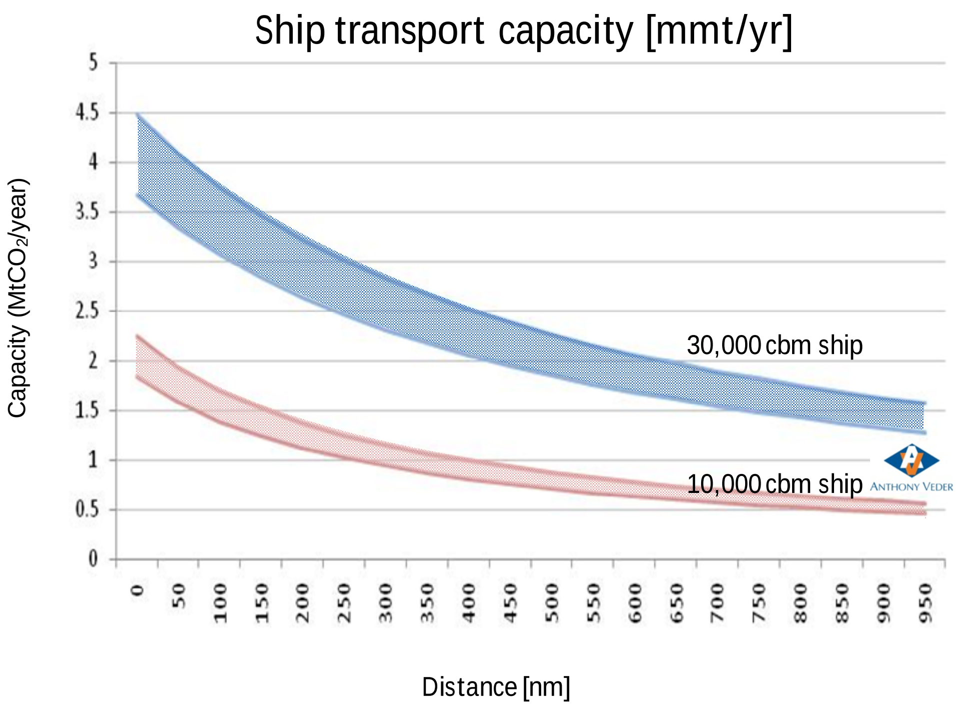

Figure 4.6 *Annual transport capacity ($MtCO_2$/year) for fully utilized ships at different distances*[30].

With the corresponding cost indications provided below.

[30] Assumptions for 30,000cbm vessel: speed 15 kts, loading and discharge rate 2000t/hr; for 10,000cbm vessel: speed 14 kts, loading and discharge rate 1000t/hr

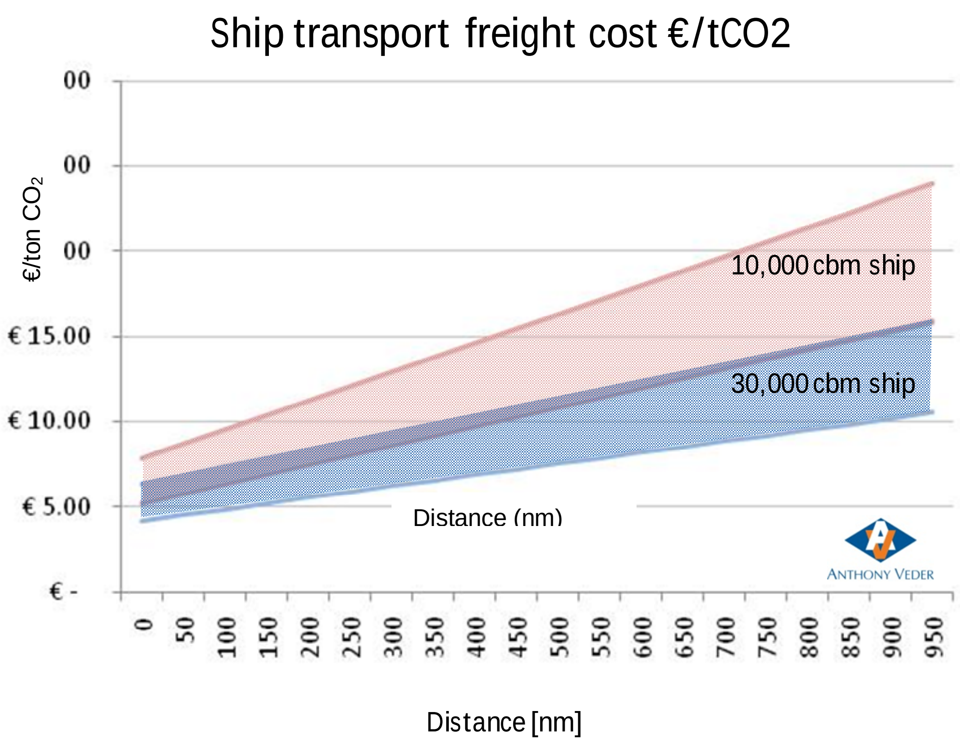

Figure 4.7 Freight costs (€/ton CO_2) from port to different offshore locations (excluding conditioning costs[31]).

These costs include CAPEX and OPEX as described in the previous paragraph; again these costs are highly indicative since they are dependent of where the vessel is to sail (environmental conditions). Injection costs are excluded since these are dictated by the specific reservoir under consideration. The larger vessel offers lower freight costs, and therefore, assuming full capacity utilization, is the preferred vessel size of the two under consideration here.

5.2 Injection

5.2.1 Off-shore injection cost

Cost estimates for injection of CO_2 were reported in the study of Tebodin (Tebodin, 2009) and EBN (EBN, 2010). The former study focuses on the re-use of new and existing platforms on the Dutch continental shelf. Three types of platforms were considered:

- SEP: sales export platform, large platform with extended gas processing facilities
- SAT: satellite platform, medium sized platform with basic gas processing facilities

- WOS: Wellhead on a stick, medium sized platform with limited processing facilities.

For each platform it was assumed that natural gas was present[32], either from the well or the gas transportation infrastructure with a minimum arrival pressure of 85 bar. All costs below are given million EUR (2009).

Phases considered in the cost estimation:

1. Mothballing of existing platforms[33]
2. Hibernation of existing platforms[34]
3. Modification of existing platforms for CO_2 injection
4. CO_2 injection phase
5. Abandonment

The overall cost estimates should be taken with a - 20% to + 50% margin of accuracy

Table 4.4 and Table 4.5 provide cost estimates for the re-use of existing platform on the Dutch continental shelf.

Table 4.4 CAPEX for reuse of existing platforms.

CAPEX (mEUR)	**SEP (8 wells)**	**SAT (4 wells)**
Mothballing	4.6	2.6
Removal of equipment	1.8	1.2
Installation of equipment	19.0	12.0
Total cost	**25.4**	**15.8**
Average cost per injection well	3.2	4.0

Table 4.5 OPEX for reuse of existing platforms.

OPEX (mEUR / year)	**SEP (8 wells)**	**SAT (4 wells)**
Pre-injection phase		
- Hibernation	1.5	0.7
Injection phase		
- CO_2 injection (incl seismic survey)	15.7	6.0
- Natural gas consumption	0.7	0.4
Total cost injection phase	16.4	6.4
Average cost per injection well	2.1	1.6
Well maintenance, once off: 1.5 Million		

[32] The natural gas is used to fuel the heater skids which are used heat the CO_2 prior to injection.
[33] This includes activities such as; isolation of process equipment from all incoming and outgoing lines (wells, pipelines, manifolds etc.); draining, cleaning and purging of equipment; removing loose equipment to minimize maintenance requirements; install required safety equipment, for example life rafts, for hibernation period; disconnect utility, control and safeguarding systems; stop power generators; prepare platform for marine access; isolate and shut-in production wells; install minimum power generation (solar panels, wind turbines) for navigation aids and minimum lighting (Tebodin, 2009).
[34] This is the phase between mothballing and the conversion of the platform for CO_2 injection.

The cost estimate for a new CO_2 injection platform was based on a compact platform designed to accommodate four injection wells. This is a minimum sized mono-tower platform with limited processing facilities.

Table 4.6 Cost estimate of new injection platform.

Four well mono-tower	**CAPEX (mEUR)**	**OPEX (mEUR / year)**
Construction	39.5	
Wells	120	
CO_2 injection		5.8
Natural gas consumption		0.4
New platforms total cost	**159.5**	**6.2**
Average cost per injection well	39.9	1.5

A subsea completion is a protective frame that sits over the top of the wellheads. From the protective frame, the pipeline is then ‘tied’ into the wellhead. Subsea completions are only suitable for use when CO_2 heating can be completed on a nearby platform. The costs estimates below are estimates including 4 newly drilled wells.

Table 4.7 Cost of subsea completion.

6	CAPEX (mEUR)
Materials & fabrication	0.8
Miscellaneous	0.5
Onshore preparations	0.5
Offshore install (rig & crane vessel 100t)	2.5
Wells (4)	120
Total incl 25% weather	**124.3**

Breaking the costs down to Euro per ton CO_2 injected, an assessment has been made for several fields on the Dutch continental shelf of the so-called K12-L10 clusters. The total stored CO_2 was calculated as 89 Mt, with an average cost of 8.3 Euro per ton CO_2 injected.

6.1.1 On-shore injection costs

On-shore injection costs were also assessed in the EBN report (EBN, 2010). The figures are adjustments of the costs calculated for the off-shore situation by Tebodin (2009). The table below shows the on-shore CAPEX and OPEX from existing sites of gas exploration in the North of the Netherlands.

Table 4.8 Costs for on-shore injection of existing sites in the North of the Netherlands (EBN, 2010).

Injection phase	Cost type	5 wells	2 wells
Mothballing installations	CAPEX	2.6	1.4
Mothballing phase	OPEX	0.1	0.08
Conversion to CO_2 injection	CAPEX	10.9	5.5
CO_2 injection	OPEX (fuel)	3.0	1.2
CO_2 injection	OPEX (other)	7.5	3.0
Workover (1 every 5 years)	OPEX	7.5	3.0
Abandonment	CAPEX	10.1	4.4

The majority of the injection costs are between 2 and 3 Euro per ton, for several emission and injection scenarios.

7 ORGANIZATIONAL ASPECTS OF CO_2 TRANSPORT NETWORKS

7.1 Economies of scale and deliberate over-dimensioning

Perhaps the most prominent factor in the optimization of CO_2 transport networks is the exploitation of economies of scale in pipelines. Mckinsey & Company (2008), state that a saving in CO_2 transport cost of 30% can be achieved, if two emitters combine their output into one 36 inch pipeline instead of two pipelines with diameters of 24 inches each. The fixed investment costs (approximately 80% of total costs) primarily through the excavation of the pipeline corridor and the construction of the pipeline, compared to the marginal costs of increasing the pipe diameter also support the concept of utilizing combined pipelines (NERA, 2009).

Chrysostomidis et al. (2009) developed an economic model to compare the average service costs of a scenario involving the transportation CO_2 from 10 IGCC plants, being built in stages over a period of 8 years. The first scenario featured the incremental installation of primarily point-to-point pipelines as and when they were required, and the second involved the construction of a backbone capable of transporting the CO_2 from all eventual plants. Although initially underutilized (~40%), if the backbone would be fully utilized in the 8th year of operation, the average service costs were \$7.7/tCO_2 compared to the incremental installation point-to-point pipeline approach at \$10.5/tCO_2[35].

However, there are a number of economic barriers that may inhibit the deployment of an oversized CO_2 transport network. Firstly, private investors cannot be expected to build a transport infrastructure that is beyond current or guaranteed near-term capacity requirements. Without contracts that a ‘second comer’ would purchase capacity rights, it would be highly unlikely that a decision to oversize would pass commercial evaluation criteria. The uncertainty of external capacity demand, in terms of volume and timing would pose great financial risks to the project developer.

It must also be noted that economies of scale in pipelines can be offset by diseconomies of scale in other parts of the CCS chain, particularly if sources and sinks are widely dispersed (NERA, 2009). Also, if installations are strategically placed close to an existing pipeline, the transport cost maybe offset by the additional costs of electricity conveyance.

7.2 Ownership and tariff setting

Whether the tariff set for capacity procurement would be regulated or not would also lead to uncertainty that the developer could be able to recover the costs of the additional investment. For example, if the tariff is based on the incremental costs of capacity, this will provide a disincentive for ‘early adopters’, as incremental costs are far less than the average costs of the pipeline (based on cost per unit volume). For the initial project

[35] A discount rate of 7.5% was used.

developer, a tariff based on just less than the new entrant costs (i.e. the cost of a new pipeline) represents the most economically efficient outcome (NERA, 2009).

There are methods for reducing the financial risks brought about by demand uncertainty. For example, long term contracts can be established between the project developer and secondary users that commit to capacity requirement at a given tariff. Similarly, the UK offshore oil and gas regimes oblige pipeline developers to 'market test' the demand for new capacity, thus encouraging the formation of investment coalitions that pool their pipeline capacity requirements. The US interstate pipeline regulations impose an obligation to hold 'open seasons', encouraging multilateral investment from the project outset. Joint implementation of a pipeline project utilising near full capacity, removes the incentives for a 'late comer', while still exploiting economies of scale. In the case that interest is expressed from multiple parties, the project developer would have to rank bids based on the project NPV, accounting for capacity requirement, commencement date, transport distance and the duration of capacity requirement (NERA, 2009).

The formation of coalitions and joint implementation maybe limited in the case of CCS, especially in the early stages of the technology's proliferation. This is primarily due to the low probability of more than one CCS project coinciding with another within close proximity, both requiring capacity within a similar timeframe. Given a time lag between pipeline completion and capacity requirement, the project feasibility will thus be governed by a cost-benefit analysis between pipeline savings and the cost of temporarily unused assets. Nevertheless, in point source clusters such as the Rotterdam harbour and the Ruhr area, such coalitions could prove fruitful. Shipping could provide a role in getting projects of the ground prior to having a pipeline in place.

It may be economically efficient to separate ownership of the pipelines and the CO_2 being transported, often termed 'unbundling'[36]. Unbundling is currently encouraged in the European gas and electricity markets, as it improves competition and prevents vertical foreclosure (NERA, 2009). In the near-term, the potential for unbundling will be minimal due to lack of CCS installations. If however, a ramp-up of CCS in Europe is realised including an extensive network of multiple-user pipelines, the entry and exit of CO_2 producers may lead to the adoption of unbundling to promote efficient capacity usage. The division of pipeline and CO_2 ownership may also occur if a single entity, including the government, were to fund an entire CO_2 transport network.

7.3 Public sector involvement in CO_2 transport networks

With the average lead time for the permitting and construction of a new coal power plant in Europe estimated at approximately 6 years (IEA, 2007), demand for a CO_2 transport network will develop over a large time scale. In light of this, experts have

[36] A review of the welfare effects of unbundling gas transport and storage can be found in Breton and Kharbach, (2008).

argued the necessity of the government to invest directly in CO_2 transport infrastructure, or strongly intervene via regulations, in order to spread the burden of risk between private and public entities.

7.3.1 The rationale for a government-led approach

Government intervention in the form of regulations and/or direct investment in CO_2 transport infrastructure has been widely commented on in recent literature (Broek et al. 2010, Chrysostomidis et al. 2009, NERA, 2009). From a broad perspective, unlike the existing utility and service transport networks, market-led investments into CO_2 infrastructure are currently unfeasible due to the low price of carbon, and the lack of demand from CO_2 utilising industries (horticulture, carbonated beverages). Assuming greater incentives for CCS deployment in the future, individual project developers will likely focus on investing in point-to-point pipelines at high capacity utilization, assuring short term economic efficiency. In some cases, this may not lead to an optimized transport network. An argument exists for government intervention, and perhaps investment to overcome the risk of demand uncertainty and promote long term economic efficiency.

Chrysostomidis et al. (2009), compared different financial approaches to investment in a backbone pipeline system to carry CO_2 from 10 IGCC plants being built gradually over 8 years. Five financial scenarios included the baseline scenario with a debt to equity ratio 70:30 (typical for private large scale investments), a balanced debt to equity ratio, a 30:70 debt to equity ratio, a public private partnership (40% debt, 10% equity, 50% government guaranteed bonds) and 100% government funding.

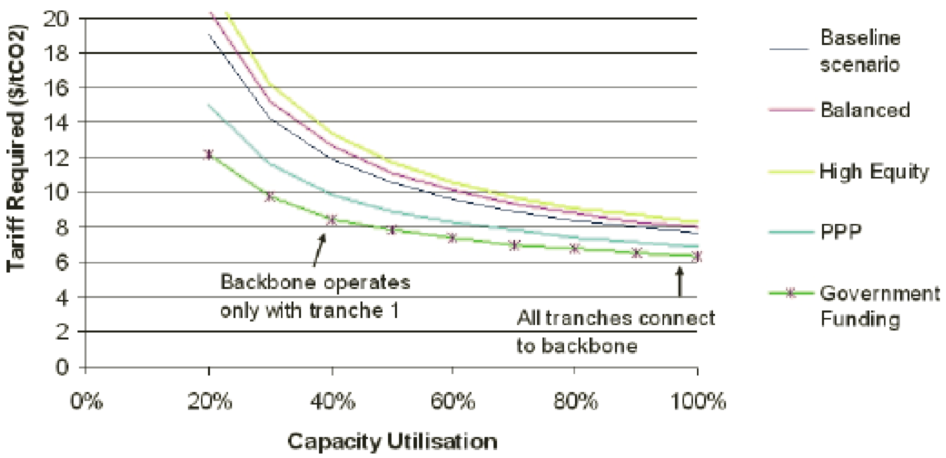

Figure 5.1 *Tariff required for different capacity utilisation for a backbone pipeline system under various financing scenarios (Chrysostimidas et al., 2009).*

The graph above depicts that based on different sources of capital, pipeline backbones that are fully or partly funded by the government may lead to the lowest transport tariff. However the model is only based on technical and financial assumptions, and presumes that the government has sufficient equity to fund the entire project. The reason the government funding leads to lower tariffs is because the government can borrow money at lower interest rates, however this exercise does not take into account factors such the efficiency of the investment and transaction costs. Therefore although this example demonstrates the effect of the cost of capital in a pipeline project, it is only part of an argument for government investment.

The analysis also demonstrates the risks of under utilization of capacity, for example in the case of the high equity scenario, the tariff is 14$/t$CO_2$ at 40% utilization, compared to approximately $8/t$CO_2$ at 100% utilization. As the capacity utilization increases, the average cost per tCO_2 decreases.

Access to capital at lower interest rates is not the sole rationale for government investment. Given the many risks attached to over-dimensioning assessed in Section 5.1, it is highly unlikely that private entities, or even a consortium of private entities, would invest in a CO_2 transport infrastructure that greatly exceeds internal capacity requirements. Government intervention, in the form of regulation or planning support will not reduce the risks of non-utilization of capacity, fluctuating CO_2 prices and issues of liability. However, a long-term commitment to CCS by governments which is able to span several electoral terms, could facilitate the development of both CCS as an abatement option and with it the required transport infrastructure. A clear long-term commitment by governments would reduce the investment risks perceived by industry.

From workshops held within the CO2Europipe project, current European gas network operators and power companies stated that government funding would be required if over-dimensioning should take place. Co-investment by the government could absorb the additional risk borne from over-investment in a pipeline by private parties. Through co-investment, the government would have a greater level of certainty that sufficient capacity is provided for future CO_2 transport requirements. Direct involvement will also give the government an enhanced oversight of the operation, and would be better informed regarding the setting of tariffs for third-party access.

An example of a state-led organizational model for a CO_2 pipeline network is depicted in Figure 5.2.

Figure 5.2 State-led concept of a CO_2 pipeline network (modified from Ecofys, 2008)

7.4 A market-led approach

In a report produced for the UK government, NERA (2009), argues against the case for direct public investment. The report states that the only way in which public investment will improve efficiency is if the government is better informed about the probability of future demand of CO_2 than private entities. The only information the government may poses that private entities would be unaware of, is the future value of government policy support for CCS. This case of asymmetric information could be overcome by publishing all known policy commitments or by offering long-term financial commitments to back up its statements (NERA, 2009).

To challenge the statement made by NERA (2009), although public and private investors would be faced with the same level of financial risk brought about by uncertainty of demand, it is the perception of this risk, which would perhaps support public investment. The government in most cases will have a larger portfolio of investments, have much lower performance targets and a longer term vision than a typical private entity (Sijm, J., Pers Comm.). Nevertheless, willingness by governments to invest directly in infrastructure projects may differ between European member states.

Furthermore a cross-border European CCS network would be a long term project (30-40 years), it would perhaps be scrutinized for intergenerational equity (particularly as CCS is a climate change mitigation option). Currently social discount rates in Europe are approximately 3%, which is far less than what would be required for private ventures (Zhuang, 2007). Due to this, the hurdle rate for a CO_2 transport network would be less with direct investment from governments. However it is currently unclear if the development of a CO_2 transportation network would be considered as a public good, and the establishment of the EU ETS with a price on CO_2 indicates that the EU considers CO_2 reduction in certain industry sectors as a private business and not as a public responsibility.

An example of a possible market-led organizational model for a CO_2 pipeline network is depicted in Figure 5.3.

Ownership	Consortium of market actors, including emitters, oil and gas companies, transport companies and project developers
Operator	Consortium of market actors contract a company to manage and operate, or do it themselves
Transport Coordination	There is no central direction. The owners decide themselves the route for pipelines or to use ship transport
Storage Coordination	There is no central direction. The owners decide themselves who they will contract for the storage, or storage firm sits within the consortium
Capacity control and tariff setting	Negotiated access. Parties inside the consortium already have access. Consortia decide tariff for external users. Third party access possible under Article 21 2009/31/EC Directive, although not guaranteed.

Figure 7.3 Market-led concept of a CO_2 pipeline network (modified from Ecofys, 2008)

7.5 Realistic network developments

Aside of economic theory, it is very difficult to point towards an optimum structure for the ownership and operation of a CO_2 transport network. Assuming a fiscal incentive for CCS deployment emerges, the configuration of investor, owner and operator will differ between member state, dependant on *inter alia;* state capacity for infrastructure development, the interest of incumbent private entities in CCS, the administration's approach towards investment in large scale infrastructure projects and of course the condition of state finances.

In the majority of cases, private investment in over-dimensioned pipelines will not be deemed financially feasible due to the risks of under utilization of additional capacity, and consequential uncertainty of making a return on investment. Government regulation or planning support is unlikely to provide sufficient assurance to investors, meaning that if over-dimensioning is to occur, some form of government expenditure will be required. This assumption is supported by interviews with members of gas transport operators and energy companies from within the CO2Europipe project. There are two main pathways for the state to support the construction a CO_2 pipeline network:

- Financial support mechanisms: capital grants, recycling of environmental tax revenues (such as auction revenues from carbon allowances), low cost government financing like guaranteed bonds or project revenue guarantees (Chrysostomidis & Zakkour, 2008).

- Direct investment: The government would invest wholly or partially in the development of the network. The pathway also includes the possibility of

Public-Private Partnerships (PPPs), whereby the transport infrastructure would be funded through a joint venture between the government and one or multiple parties from the private sector.

Within the last two decades, roughly 1400 PPPs have been signed in the European Union, with an estimated capital value of €260 billion (Kappeler & Nemoz, 2010). PPPs normally involve projects that are in the public interest, such as roads, school, hospitals and particularly water projects in developing countries. A (or part of a) CO_2 transport pipeline network, could be seen as providing a public good, as CCS can be understood to be able to contribute significantly to achieving national emissions targets. PPP structures usually involve a long term (20-40 years) contract between a public body and the PPP contractor, which seems an adequate timeframe for the construction and operation of CO_2 transport infrastructure. The PPP members often establish an independent entity or special purpose vehicle (SPV), which will implement the project through subcontractors.

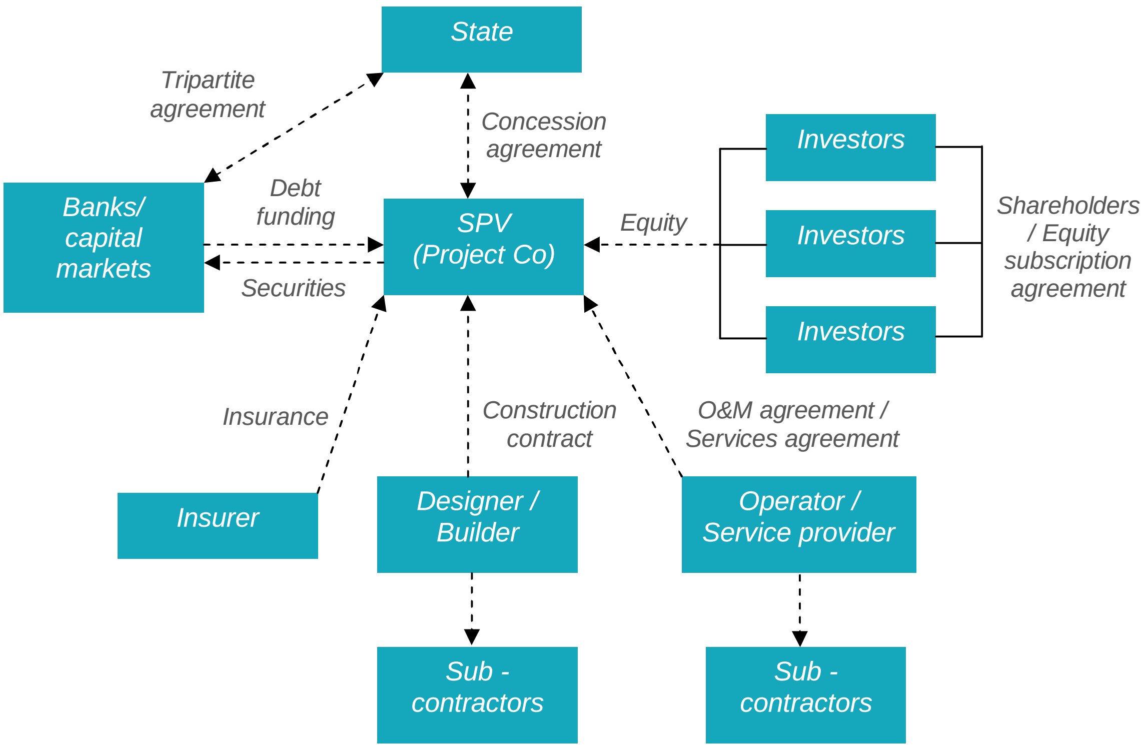

Figure 7.4 Structure of a typical PPP (modified from Chrysostomidis & Zakkour, 2008)

The use of a hybrid approach to investment in the form of a PPP, allows the most beneficial elements of both the market-led and state-led models to be combined. For example, the government can provide a source of low cost capital to the project, which may lower the hurdle rate of the investment decisions, thereby raising equity from private entities. In return, the government will be able to exercise a level of control over the planning, ensuring sufficient capacity is provided and enforcing transparent tariff setting. Competition can be incorporated into the organizational model through the process of tendering for sections of the pipeline development, or through operational lease contracts to be renewed periodically.

8 CONCLUSION

There have been significant advances in the regulation of CO_2 transport and the development of CO_2 transport infrastructure. The removal of CO_2 transport for the purposes of geological storage, from the classification of waste from within the European regulatory waste framework will facilitate the transportation of CO_2. Proposed amendments to the 1996 London Protocol, if ratified, will also allow the export of CO_2 for the purposes of geological storage between signed parties. The calculation of emissions stemming from CO_2 transportation via pipelines under the EU ETS have recently been outlined, however there is no guidance concerning how emissions will be calculated for CO_2 shipping.

The EU CCS Directive also provides criteria regarding the necessity for Environmental Impact Assessments (EIA) for CO_2 pipeline infrastructure developments, and there is sufficient guidance for EIA requirements both nationally and in a transboundary context. However on the issue of third-party access to networks, the Directive provides relatively little guidance to Member States on how access would be regulated, if at all. National proposals on third-party access to CO_2 pipelines of the Netherlands and the UK have been evaluated, and their suitability could be questioned on the basis of economic theory, as they potentially deter investment by the first mover. It is of course unclear how such approaches will function in practice. The UK strategy on third-party access was released by DECC in early 2011, after a consultation phase with industry stakeholders. Given that third-party access regimes may differ between member states, it would be advisable to evaluate third-party access proposals on a European scale. Issues on access to cross-border pipelines may arise if significantly divergent policies are enacted between members states, however given that many states have still to devise national regulations, it is unclear to what extent EU intervention could be necessary.

According to cost estimates provided by industrial partners in this project, a 16 inch diameter onshore pipeline has a typical cost of €800,000/km in Europe, with offshore pipelines costing an additional €400,000/km. However these estimated pipeline costs are variable due to location specific conditions such as terrain and gradient. The cost for shipping CO_2 across a range of distances up to 950km are provided for two different realistic ship sizes of 10,000 cbm and 30,000 cbm capacities. Injection costs have been sourced from literature, and for a number of specific scenarios in the Netherlands, onshore injection costs averaged between €2 and €3/tonCO_2, and offshore costs averaged at approximately €8/tonCO_2.

Given the economies of scale shown in both pipelines,, the over-dimensioning of pipelines may potentially lead to lower life-time costs of a CO_2 transport network. However, there are a number of barriers that may prevent industry in investing in over-dimensioned pipelines. Naturally, any investment decision will depend on the internal rate of return (IRR), however an IRR analysis will be hindered by the uncertainty on when the additional capacity will be utilized by a third-party. A lack of clarity on whether regulations will allow tariffs to be charged which reflect figures closer to the average cost of the pipeline, rather than the considerably lower incremental costs of pipeline capacity may also exacerbate this problem in the short term. Of course, contractual agreements between parties could be made prior to the investment, although this may not always be possible.

If CO_2 pipeline developers are to take advantage of economies of scale and over-dimension pipelines, the intentions of governments regarding their level of involvement and regulation of tariffs for third-party users need to be consolidated.

8.1 Recommendations for policy makers

A number of studies have looked upon other examples of large scale transportation infrastructures (NERA, 2009; Chrysostomidis & Zakkour, 2008), using natural gas and oil pipeline networks as potential analogues to assist in the design of legislation and organizational models for CO_2 transport. Although there are learnings to be taken from implementing gas and oil pipeline networks, from an investment perspective the transport of hydrocarbons is unsuitable as an analogue given the high profits associated with delivering such commodities to the market, compared to the present uncertainty on price of EUAs and thus CO_2 volumes.

CCS is one of the few technologies that is entirely climate change driven, which means development and deployment will not happen without policy intervention. A market price for CO_2 emissions, such as generated by the EU ETS, is an effective deployment tool. However, current EUA prices will need to rise significantly to promote CCS deployment in the future. Although a transport network is not required today, government intervention is required now to organize a future European CO_2 transport infrastructure that will support the level of CCS deployment required to meet EU CO_2 reduction goals.

From research conducted and summarized in this report, a number of key findings and recommendations can be provided to prepare and potentially facilitate development of an optimized CO_2 transport network, under the presumption that the future CO_2 price is sufficient to promote CCS deployment. These recommendations are divided into legal, financial and organizational statements, reflecting the scope of this report.

Legal:

- Developing stable long-term regulatory and economic frameworks - A robust policy roadmap, or equivalent, is fundamentally important for private industry and the public sector alike to be certain of the goals that the government aspires to, and hence to be able to better manage the financial risk, or otherwise, that will be required in the achievement of those goals.

- Eliminate barriers to growth from issues of interoperability - A successful transport and storage network will depend on the agreed standards and requirements being implemented and adhered to with the facilitation of a competent and confident authority. In the context of building a new network, any such authority has the opportunity to eliminate barriers to growth from issues of interoperability. In addition, it is important to learn from previous issues in integrating the EU countries' individual gas transmission networks. This includes tackling regulation of cross-border transportation of CO_2. Further legal recommendations include:

- Align and implement (ratify) necessary international agreements and country legislation.
- Evaluate proposed third-party access regimes on a European scale, in order to prevent regulatory misalignment with regards to cross-border pipelines. This may also be resolved on a bi- or multilateral level between the states involved.
- Provide additional guidelines on the level of co-contaminants to be transported in a CO_2 stream.
- Clarify how emissions generated through shipping CO_2 will be taken into account in the whole chain.

Organizational:

- Assessing availability of local storage capacity early on - In promoting efficiently integrated networks, a key success factor will be knowledge of potential storage sites, the minimum theoretical storage capacities that are available, and how this relates to the location of potential sources of CO_2. Assessing availability of local storage capacity early on is necessary to be able to determine the level of intervention and coordination required to develop the optimum CO_2 transport infrastructure for a region. This work requires European cooperation, information sharing and funding to ensure a timely and integrated assessment.

- Identification of clusters of CO_2 Sources - The development of CCS clusters has great potential for cost sharing, taking advantage of economies of scale, and the provision of access to CO_2 infrastructure to both energy and importantly, industrial stakeholders. It is important to raise awareness and interest on CCS with branch organisations and authorities in existing industrial agglomerations, creating dialogue on possible cooperative actions. This action can be supported by identifying service and equipment suppliers with the necessary expertise and willingness to facilitate partnerships between power and industrial stakeholders.

Financial:

- Additional government funding for demonstration projects expected to be operating by 2020 – Despite funds having been made available through the European Economic Recovery Programme (EERP), New Entrants Reserve (NER) and some EU Member States it is unclear how subsequent precommercial CCS projects will be financed. Given expectations that the EUA price will not rise to the required level for CCS projects to be financed commercially in the medium term, government support in the form of additional funding should be announced in time for additional projects to be operating by 2020.

- Government support for large, interconnected regional networks - If large, interconnected regional networks are necessary, over-sizing for >10 year flows is most likely needed. It is highly unlikely that over-dimensioning of pipelines for the intention of sharing capacity between different parties will occur unless the government assumes at least part of the financial risk. To stimulate the development of multi-user pipelines, public-private business models for CO_2 infrastructure should be developed, covering contractual, risk-sharing and financing possibilities.

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10 ANNEX 1

Assumptions used in the ZEP (2011) pipeline cost estimations are as follows:

Offshore

Pipeline sizes:

	Offshore Main Pipeline				Onshore Pipeline(s)	Offshore Branch Pipeline
vol \ km	180	500	750	1500	10	10
2.5 MT/year	12"	16"	16"	18"	(same size as offshore pipeline)	N/A
10 MT/year	22"	26"	26"	30"	(same size as offshore pipeline)	N/A
20 MT/year	26"	32"	34"	40"	2 x 10 km x 22"	(same size as offshore main line)

Design Factors

- 200 barg inlet pressure, 60 barg outlet pressure
- Design pressure: 250 barg
- Pipeline Internal friction: 50 µm
- Pipeline Material: Carbon Steel
- External Coating 3 mm Polypropylene (PP)
- Concrete Coating (70 mm / 2600 kg/m3) to be used for pipelines exceeding 16". No concrete coating for pipelines below 16"

Environmental factors:

- First 50 km shallow with sand waves with remaining route flat
- Burial requirements:
  - o 100% burial for pipeline dimensions equal to, or below 16"
  - o 100% burial in sand wave area for all sizes
  - o Other areas no burial
- Landfall
  - o 1.5 km in cofferdam trench
  - o 2.0 km in near-shore trench (shallow water)

Market Factors

- Steel price
  - o 16" : 160 EUR/meter

- o 40" : 700 EUR/meter
- External coating (Anti corrosion/weight)
- o 16" : 90 EUR/meter
- o 40" : 200 EUR/meter
- Installation cost
- o Pipeline installation costs: 200 to 300 EUR/meter
- o Trenching costs: 20 to 400 EUR/meter

Contingency

- 20%

Based on this, cost estimates have been established for the alternative pipeline lengths and transport capacity requirements, with the following cost elements;

- Accumulated cost prior to execution
- Offshore Linepipe, Equipment & Materials
- Offshore Linepipe, Coating, Transport and Preparation
- Offshore Pipeline Installation
- Offshore Survey, Tie-ins and intervention
- Onshore Linepipe, Equipment & Materials
- Onshore Linepipe, Coating, Transport and Preparation
- Onshore, Civil Work & Pipeline Installation
- Template(s) & Control Cable(s)
- Project Management & Services
- Contractor Detail Engineering
- RFO (ready for operation) & Commissioning
- Insurance

Onshore

Pipeline sizes:

	Distance				
CO_2 vol	**10 km**	**180 km**	**500 km**	**750 km**	**1 500 km**
2.5 Mt/a	12 "	12 "	---	---	---
10 Mt/a	20 "	24 "	24 "	24 "	24 "
20 Mt/a	24 "	32 "	32 "	32 "	32 "

The following constraints and assumptions apply to the calculation of the total cost of a CO_2 transmission pipeline.

- flat topography
- simple soil conditions (e.g. no bedrock, no costly drainage, etc.)
- unobstructed right of way and permitting acquisition
- project duration: 3.5 years
- no site roads
- compression is not included
- no special structures (such as micro tunnelling, culverts, etc.)
- pipeline construction is from May to September
- costs have an accuracy of +/- 30%
- operating costs: 6 000 EUR/km

Design Factors
- inlet pressure: 100 barg
- minimum pressure: 80 barg
- pipeline material: carbon steel
- maximum temperature of the CO_2: 50 °C