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Author(s)		
Name	**Organisation**	**E-mail**
Filip Neele	TNO	Filip.neele@tno.nl
Tom Mikunda	ECN	Mikunda@ecn.nl
Ad Seebregts	ECN	Seebregts@ecn.nl
Stijn Santen	CO2-Net	Stijn.santen@co2-net.com
Anton van der Burgt	Stedin	Anton.vanderburgt@stedin.net
Ola Nestaas	Gassco	Oln@gassco.no
Sigve Apeland	Gassco	Sa@gassco.no
Sarah Stiff	E.ON New build and Technology Ltd	Sarah.stiff@eon-uk.com
Carl Hustad	CO2-Global SA	cwh@co2-global.com

Abstract

This report presents the overall results and recommendations from the EU FP7 CO2Europipe project. The aim of the project is to study the requirements for the development of a large-scale CO_2 transport infrastructure in Europe, between 2020 and 2050. An analysis of the demand for CO_2 transport was derived by linking the expected CO_2 captured volumes in the period between 2020 and 2050 to the locations where CO_2 can be stored in the subsurface. This resulted in a series of maps of plausible transport corridors, on the assumption that CO_2 capture and storage (CCS) will play a significant role in the reduction of CO_2 emission. The requirements for the development of this infrastructure were derived on such levels as technology, policy, regulations and organisation.

The most important conclusions are related to the finding that the EU CCS transport infrastructure is to be led by a relatively small number of countries, who share the largest burden in the areas of CO_2 capture, transport and storage. These include the countries bordering the North Sea, and those countries relying heavily on coal or lignite for their power supply (Germany, Poland the Czech Republic). It is crucial that these countries take the lead and are supported to do so, not only now, but during the whole CCS infrastructure development.

EXECUTIVE SUMMARY

The aim of the CO2Europipe project was to define the road towards large-scale CO_2 transport infrastructure. To this end, the infrastructure development was studied at a number of levels, ranging from technical and organizational to regulatory and policy. A forecast of this infrastructure by 2050 was constructed and served as the long-term CCS goal in this project. This report presents the main conclusions of the project. The report is based on separate reports completed within the project, on realistic small-scale or regional CCS developments, as well as on specific areas of expertise within the CCS field, such as on technical or regulatory issues.

Long-term CCS transport infrastructure
Maps of CO_2 transport requirements in NW Europe were constructed, using predictions of the increase in CCS projects due to increasingly strict emission reduction targets in the period 2020 - 2050. Following the end of the (current) demonstration phase, major CO_2 transport and storage infrastructure development is assumed to start from the large-scale introduction of CCS by 2020 and continue until at least 2050. An extensive CO_2 transport infrastructure network will be required if CCS is to play a significant role in achieving the European CO_2 emission reduction goals. Many thousands of kilometres of new high-pressure pipeline will need to be constructed. The main effort in the construction of pipelines would be expected between 2020 and 2030 since the larger part of the network needs to be in place by 2030. The rate of construction may need to be as high as 1200 – 1500 km/yr in some regions. Furthermore, shipping will have a significant role in initial phases until volumes become large enough to justify pipeline investments.

Infrastructure developments
Different types of transport infrastructure could develop over Europe, depending on the location and density of capture installations and storage sites. In most areas a network connecting multiple capture locations to several storage sites is expected to emerge.

Key players
The distribution of capture efforts, of construction of transport infrastructure and of injection across the Member States reveals that there may emerge a relatively small number of key players. These key players in the development of CCS infrastructure are the countries on the North Sea where the majority of the potential storage capacity resides, whilst additional key players can be identified from their reliance on coal and lignite (e.g., Germany, Poland and the Czech Republic).

During the project, a number of concepts and hypotheses have been tested and developed regarding the evolution of a European CO_2 infrastructure. Their outcomes have led to the following overall conclusions.

Political leadership

EU leadership
Given the international character of CCS, it is concluded that strong co-operation is required between Member States, providing clear signals at a pan-European Union level which encourage development to happen. In particular, the planning of CO_2 transport infrastructure and the availability of CO_2 storage sites to projects must be tackled in a

manner consistent with the energy needs of Europe over the next few decades. A robust policy roadmap, or equivalent, is fundamentally important for private industry and the public sector alike to efficiently manage the financial and associated risks, and continued leadership at European level in providing this guiding framework will significantly reduce the uncertainties currently facing potential CCS developments.

Commitment of key players
Commitment by individual Governments to large-scale deployment of CCS is essential in order for CCS to develop at a pace sufficient to meet EU emission reduction targets. With an uneven spread of the effort in capture, transport and storage across the Member States it is essential that key players in Europe (among which are Germany, Poland, the United Kingdom, Norway and the Netherlands) take the lead. As mentioned above, a clear commitment, at a national as well as a European level, will help develop infrastructure that takes into account future transport and storage demands, including those from neighbouring countries.

Master plans

Master plans provide the vision
One of the ways in which EU and Member State support the development of CCS and CCS infrastructure can take shape is through the development and maintenance of Master Plans. These will provide information regarding the timing and size of expected volumes of captured CO_2 together with the planned locations for storage. This will help alighnment within the industry, focus the efforts and improve the efficiency of network development.
At the EU level, a CCS Master Plan is recommended to be part of the energy infrastructures plan. At the Member State level, the Master Plans should include cross-border issues, set the timeline for the development of capture efforts and infrastructure construction while also providing relevant information on storage.
These Master Plans will provide the EU and Member States with clarity of vision on the development of CCS and help disseminate information so that industry may reduce the perceived risk associated with developing CCS projects.

Storage capacity qualification
Future emission sources (capture locations) can be assumed to be located at or near current emission points. Suitable storage locations, however, are known with certainty only once storage capacity is proven. Future-proofing transport infrastructure also relies on the early availability of storage capacity. Given the timeline of at least five years for the characterization and testing of a single storage location, it is of the highest priority that Member States support the qualification of storage locations, to reduce the uncertainty in the location of future injection points. Harmonisation and standardization of the method of storage qualification (e.g., following the guidelines of DNV CO2Qualstore) will help decrease the time needed for storage qualification. Particular attention should be paid to qualification of saline formations, which are predicted to take 60-80% of the total amount of CO_2 to be stored, though lacking detailed study work until today.

Business model for CCS industry

Preparing for multi-user networks

The development of CCS clusters is foreseen to start in the period 2020 – 2030, when emission reduction targets cause most European countries to start large-scale capture of CO_2. The clusters are likely to evolve from the earlier projects that have resulted in mostly one-on-one projects (i.e. one source - capture site, linked to one sink – storage site). This evolution, however, may require that the organisational models originally developed for point-to-point CCS solutions are reconsidered. This should be understood early in the development of CCS, to enable a smooth transition from early (simple) to later (complex) infrastructure types. A business model is proposed that could attract sufficient capital, providing a sound return on investment. It is recommended that an expert authority is set up, to coordinate cross-border infrastructure investments, to ensure optimum transport capacity utilisation.

Regulatory certainty and stability

Creating a stable and level playing field

A recurring theme during the analysis of CO_2 infrastructure development has been the need for regulatory certainty, including the compatibility between regulatory regimes of different Member States, and the minimisation of legislative barriers that may impede the rapid development of such infrastructure. The development of European standards and identification of best practices for and relevant to CO_2 transport, where these do not already exist, will also encourage appropriate regulation and create greater certainty. Guidance and recommendations are also being produced specifically for the management of CO2 in the CCS chain, by several organisations internationally recognised for their health and safety expertise. It is expected that such expert guidance, plus experience from the early CCS demonstration projects will enable appropriate and consistent regulation to be developed.

Cross-border transport

Based on the location of storage sites around Europe, it is concluded that that a large fraction of pipeline infrastructure will cross Member State boundaries. International co-operation will be essential to ensure that technical solutions to the managed flows of CO_2 are cross-border compatible. This co-operation is also required to ensure that sufficient transport capacity is available to accommodate the increasing CO_2 flows that would occur as a pipeline route traverses industrial regions on its way to a storage area. A central issue is the liability for stored CO_2, which needs to be arranged between Member States. An amendment in 2007 to the 1996 London Protocol allows for the sub-sea storage of CO_2 and its cross-border transport. This will provide the conditions for developing the vast storage capacity in the North Sea. However, the amendment remains to be ratified by most of the Contracting Parties and will not come into force for some time. An interim solution to this problem must be sought by Europe with some urgency.

Onshore storage

The current tendency towards delaying the permitting of onshore CO_2 storage would, if continued, create transport infrastructure biased towards offshore storage locations and hinder countries not bordering the North Sea. The result would be that required onshore pipeline capacity would increase dramatically, with an associated higher cost (increasing from an estimated 50 billion euro to 80 billion euro) and risk. Allowing onshore storage would result in significantly lower overall costs due to shorter transport distances.

Cost saving through infrastructure sharing
The development of CCS clusters has great potential for cost sharing and for provision of access to CO_2 infrastructure to both energy and industrial stakeholders. This is demonstrated in D4.1.1 with an economic analysis to concludes that large volumes from different sources lead to lower costs per ton of CO_2 and higher system stability due to smaller throughput variation. Large-scale cross-border CCS in Europe requires amongst others, offshore CO_2 transport and storage in the North Sea with CO_2 from Rotterdam, Groningen Eemshaven and North German harbours.

Recommendations
Recommendations have been formulated in the areas of cross-border transport, third-party access, future-proofing infrastructure through early creation of hubs and interoperability on technical and organisational levels. Last, but not least, the issue of liability for transported and stored CO_2 must be regulated.

Financing CCS infrastructure

EU-ETS; EU financial support
The EU-ETS is the mechanism by which the EU may create the financial basis for CCS projects. However, the price of CO_2 emissions is not expected to increase sufficiently rapidly to render CCS commercially feasible. Additional mechanisms should be put in place to support the development of CCS projects after the first wave of demonstration projects. To further increase the attractiveness of CO_2 transport projects for investors, EU coverage for financial guarantees is recommended.

Commercial opportunities

CO_2-EOR and CCS: mutual benefits
Enhanced oil recovery (EOR) with CO_2 can be an enabler for the development of CCS. The revenues from the additional oil produced can help finance the (early) CO_2 transport infrastructure, with added benefits of additional tax revenues, stability of security of energy supply and greater competitiveness of the EU Member States. The window of opportunity for the application of CO_2-EOR in the major oil fields in the North Sea requires both a rapid and early ramp-up of capture efforts and a concentration of the supply of captured CO_2 towards the oil fields. Early in the development of CCS, an organised, cross-border effort is needed to fully exploit the opportunities of CO_2-EOR. It is recommended to look into the feasibility of aligning CCS development and CO_2-EOR options. A dedicated tax and revenue and burden sharing system could be developed, to render investments in CO_2-EOR projects in the North Sea attractive. Such measures could result in kick-starting both CCS and CO_2-EOR at the same time.

Safety and risk management

Harmonising risk assessment of onshore pipelines

Transport of CO_2 poses health and safety risks. A significant part of the trunk lines will be located onshore. Under certain conditions, leakage or rupture of a pipeline can result in the release of CO_2 with the potential to affect humans and the environment. A number of issues were found that require action for a timely development of the onshore part of the transport infrastructure. It is recommended to harmonise risk assessment methods used by Member States. A number of knowledge gaps were identified, most of which are being addressed by ongoing research and industrial projects, as well as the planned demonstration projects. In addition to those efforts, it is recommended to collect ‘best practices’ regarding the safety and risk management of CO_2 pipelines and to set up a database of failure frequencies and experiences.

Technical challenges

Closing knowledge gaps

CO_2 pipeline transportation and injection has been standard practice in the United States, where it has evolved during the past 35 years to become a multi-billion dollar industry handling over 30 million tons per year. CO_2 ship transportation is also well known. Knowledge gaps from these processes lie mainly in understanding the effects of impurities in the CO_2 stream on materials in the transport system, and in the operational areas, where injection into depleted gas fields or saline formations and offshore off-loading and injection from a ship are important aspects. These issues can currently be dealt with by implementing slightly more conservative design, and do not represent barriers to constructing CO_2 transport systems today.

Implementation and scaling of CO_2 pipeline networks in a new arena (e.g. pan-Europe) and for other CO_2 compositions could reveal new challenges. Optimisation along the whole value chain is essential for decreasing overall costs. The impact should also be considered of fluctuations in power demand (reflecting emissions and captured volumes) on the capture process, transport requirements and storage capacity, as well as on the resulting costs.

Recommendations at a technical level include the following:

- Conduct additional research to understand the effect of impurities in the CO_2 stream on the behaviour of CO_2 and on the required transport system.
- Data should be collected to validate simulation tools for the behaviour of CO_2 mixtures within the transport and injection system.
- Standards are to be developed for qualification of soft materials in a transport system.
- Concepts are to be developed for depressurisation of transport systems.
- Testing of materials and of ways to prevent the propagation of fractures in a CO_2 pipeline.
- Technology qualification is required for offshore ship offloading systems.

Roadmap

The conclusions have been translated in terms of recommendations for actions of the European and Member State Governments, to create the environment that is favourable for the development of CCS. A chronological list of these recommendations is given, which can be seen as a roadmap for the development of CCS, as far as the role of EU and Member State Governments are concerned.

Acknowledgement
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1 INTRODUCTION

1.1 Human induced climate change

It is broadly agreed upon that the increase in anthropogenic greenhouse gases (GHGs) is to a large extent responsible for the increase in global surface temperatures over the past 100 years[1]. Annual emissions of carbon dioxide (CO_2), the most important GHG, have grown by approximately 80% between 1970 and 2004. Anthropogenic interference with the climate system is understood, with varying levels of scientific confidence, to result in sea-level rise, increase in the frequency of extreme weather events, threatening ecosystems and decreasing ice sheet coverage (IPCC, 2007). In order to prevent dangerous man-induced climate change, the Intergovernmental Panel on Climate Change estimates that global CO_2 emissions need to decrease by between 50% and 85% of their 2000 levels by 2050 (IPCC, 2007).

Energy demand is expected to double by 2050 as a result of population growth and economic development. Despite the increasing share of lower CO_2 energy sources (such as renewables and nuclear power) in the energy mix, significant part of the energy demand will have to be met using fossil fuels such as coal, oil and gas. CO_2 emissions from electricity generation can be significantly reduced already now, by replacing old coal-fired power plants with natural gas-fired plants. Carbon dioxide capture and storage (CCS) is a method to reduce emissions from power plants and industrial processes even further. The costs for developing CCS are high and therefore governmental support or funding is required to develop (demonstration) projects. However, the cost of mitigating climate change without GHG abatement will be significantly higher (Stern, 2007).

1.2 Carbon capture and storage as a CO_2 abatement option

Over the last decade, a number of reports have highlighted CCS as a technology with the potential to make deep emissions reductions (IEA, 2004; IPCC, 2005). Applications of CCS in the power sector, in particular coal-fired power plants, have been the target of the vast majority of research and development funding and policy initiatives aimed towards demonstrating and commercializing the technology. More recently, research has been conducted to assess the potential application of CCS to various industrial applications such as steel and cement production, and also to oil refining and natural gas processing installations (UNIDO, 2010).

Currently, most applications of CCS are not economically feasible. The additional equipment used to capture and compress CO_2 also requires significant amounts of energy, which increases the fuel needs of a coal-fired power plant by between 25 and 40% and also drives up the costs (IPCC, 2005). However, it must be noted that although CCS applications will raise the costs of energy generation and industrial production, the

[1] An average surface temperature increase of 0.74 °C between 1906 and 2005 (IPCC, 2007).

IEA (2008) has calculated that an exclusion of CCS from the global mitigation portfolio will increase the cost of achieving climate stabilization by 70%. Based on this information, inclusion of CCS in the portfolio can be justified from a long-term economic efficiency standpoint.

1.3 The transportation of CO_2

Once CO_2 has been captured from a power generating or industrial installation, it must then be transported, either by pipeline or ship, to suitable storage areas. The transportation of CO_2 is considered to be technically feasible, and therefore has received far less attention in terms of research and development compared to the capture and storage components of CCS. CO_2 is most efficiently transported in dense phase (high density, liquid or otherwise). CO_2 is likely to be transported at high pressures in pipelines made of carbon steel. CO_2 has been transported through pipelines in the United States for use in enhanced oil recovery (EOR) operations since the 1970s, and approximately 3000 km of CO_2 transportation pipeline has been installed. Only small-scale CO_2 carrying vessels exist today and no large-scale CO_2 transport vessels are currently in operation, however such vessels have similar designs to other gas transporting ships such as liquefied Petroleum Gas Carriers (LPG) and thus present no technical challenges for being built.

Although few technical barriers to the transportation of CO_2 are foreseen, challenges exist in terms of health and safety standards, operational efficiency, public perception and communication, planning and permitting, CO_2 quality standards and investment and organisation of potential CO_2 transport networks.

1.4 Funding the demonstration of CCS in the EU

At present, major emitters of CO_2 are not given sufficient incentives through market based economic instruments to invest in expensive abatement technology such as CCS. To support the development of CCS in Europe, the European Commission and certain EU Member State governments are providing funding for research and the implementation of demonstration projects. 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). Selected 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) to a fund for innovative renewable and CCS projects. Known as ‘NER300’ this financing instrument is managed jointly by the European Commission, the European Investment Bank and Member States.

1.5 Facilitating a European-wide CO_2 transport infrastructure

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, on the success of these demonstration projects, post 2020 may see the first large-scale deployment of CCS in the power sector. Developments of clusters are expected to reduce costs, utilize limited space, broaden participation and deepen deployment of CCS (Chrysostomidis et al. 2009). In theory, building pipelines with sufficient capacity to transport CO_2 from multiple sources will lead to lower transportation costs, as investors can take advantage of the economies of scale.

Furthermore, a number of European studies (including CO2Europipe and GeoCapacity) highlight that if CCS is to support EU CO_2 abatement targets, the absence of sufficient and suitable storage sites in a large number of Member States will require the cross-border transportation of CO_2. In addition, the possibility of conducting CO_2 enhanced oil recovery (EOR) in certain parts of the North Sea may create sizeable demand for CO_2 from multiple EU countries. Therefore cross-border transportation of CO_2 requires multilateral agreements and calls for further EU coordination focusing on harmonizing regulatory frameworks.

1.6 Reader guide

This report presents the most important conclusions from the CO2Europipe project, recommendations for EU and national authorities' actions to promote CO2 transport infrastructure and the CO2Europipe roadmap towards a future, large-scale transport infrastructure for CO_2. The conclusions and roadmap are based on the requirement for transport and storage, as formulated in an analysis of the development of capture efforts and the availability of storage capacity that is presented in section 3.

The project goals and setup are outlined in section 2 while a vision of the longer term, large-scale CO_2 transport infrastructure is described in section 3. The conclusions from the project are given in section 4, along with recommendations and timelines for actions to be taken by relevant parties. A roadmap towards the long-term infrastructure goal, in terms of actions and timelines, is summarised in section 5, and overall project conclusions are briefly presented in section 6.

The entire list of deliverables from the project, with a brief description of their content, is given at the end of this report, in section 8.

2 THE CO2EUROPIPE PROJECT

The aim of the CO2Europipe project has been to explore and define 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, aims to prepare for the optimum transition from initially small-scale, local initiatives starting their operations in the period 2015 – 2020 and then evolving towards the large-scale CO_2 transport and storage that must be anticipated to commence from around 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, was studied by developing business cases for a number of realistic scenarios.

Where other carbon capture and storage (CCS) studies have focused on storage capacity or capture techniques, this project describes the challenges of optimizing the infrastructure that is required for the transport of CO_2 from the major emission points in Europe to the most relevant storage sites. The transport of CO_2 in large-scale networks needs to be analysed to arrive at the best options, in terms of overall cost (including social and environmental impact), and allow for the building onto or inclusion of infrastructure developed in early local initiatives. The organisational, financial, legal, environmental and societal hurdles that also need to be overcome to arrive at this optimal state are investigated. The project explains how international industrial cooperation aligned with regulation and standardization is required to allow both society and the industry to effectively realize the required CO_2 transport infrastructure against at lowest cost and economic impact.

Furthermore the project seeks to demonstrate that international cooperation and aligned regulation can lead to significant advantages in terms of reduced cost, reduced environmental impact, improved CCS local business cases, more efficient planning of the required transport capacities and more efficient use of existing CO_2 storage capacity. Only a clear regulatory, technical and business favourable framework can create the most effective industrial response, and ensure that CCS can be realized against the lowest possible costs for energy users and taxpayers. The conclusions of the project are based on a scientific and practical analysis of the existing data about the size of major regional CO_2 sources and of data about the size and availability (timing) of storage sites (data from previous EU projects, as well as international databases) and common networking principles to help plan major CO_2 transmission corridors.

Summarising, this project has the following objectives (with the relevant project reports listed between brackets):

1. describe the infrastructure required for large-scale transport of CO_2, including the injection facilities at the storage sites (D1.1.3, D2.1.1);
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 (D2.1.1, D3.1.1, D4.2.1);

3. provide advice on how to remove any organizational, financial, legal, environmental and societal hurdles to the realization of large-scale CO_2 infrastructure (D1.1.2, D3.1.2);
4. develop business case for a series of realistic scenarios, to study both initial CCS projects and their coalescence into larger-scale CCS infrastructure (D4.1.1, D4.2.1, D4.2.2, D4.3.1, D4.3.2, D4.4.2, D4.4.3);
5. demonstrate, through the development of the aforementioned business cases, the need for international cooperation on CCS (D1.1.1, D4.1.1, D4.2.1, D4.2.2, D4.3.2, D4.4.2, D4.4.3);
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 (D1.1.2).

2.1 Project partners

The project consortium consists of the partners listed below.

Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek- TNO	Netherlands
Stichting Energieonderzoek Centrum Nederland	Netherlands
Etudes et Productions Schlumberger	France
Vattenfall AB & Vattenfall Research and 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, Nacap BV	Netherlands
Gassco AS	Norway
Anthony Velder CO_2 Shipping BV	Netherlands
E.ON New Build and Technology Ltd	United Kingdom
Stedin BV	Netherlands

3 LONG-TERM CCS TRANSPORT INFRASTRUCTURE

3.1 Introduction

The study of the development of a future, large-scale CO_2 transport infrastructure is based on a vision of this infrastructure, which was in turn based on the assumption that CCS will play a major role in emission reduction as described in, for example, the EIA blue map scenarios (IEA, 2008). The horizon for this future transport infrastructure for CO_2 is 2050, with the infrastructure in 2050 representing the long-term goal. This section provides a brief overview of the CO2Europipe vision of the longer term CCS Transport Infrastructure. A more detailed description of the method and results is given in a separate CO2Europipe report (D2.2.1).

3.2 Captured volumes

The first step in developing the infrastructure vision was to predict the captured volumes of CO_2 in the period 2020 to 2050. It was assumed that future capture installations will be located in current industrialised regions. Current emission levels from these regions were used as a basis to estimate future captured volumes. Data on current CO_2 emission sources was provided by the emission database compiled by the recently concluded EU FP6 project Geocapacity. The list of emission points included large CO_2 point sources like power plants and industrial installations, which were grouped together into regional source clusters. These clusters were assumed to represent the future locations of capture installations.

National CO_2 capture efforts were projected from 2020 until 2050. In the short term, for the year 2020, the small-scale CCS projects (status as of October 2009) provided the starting point. On a longer term for the period 2025-2050, energy use scenarios were combined with assumptions for economic growth, energy demand and fuel-mix in power generation and in large industry, to obtain the national levels of capture efforts. Up to 2030, a PRIMES scenario from the CCS Impact Assessment published in 2008 was used as a starting point. That scenario was modified up to 2030 for countries like the Netherlands, Belgium, Germany and Norway based on more up-to-date information from recent national energy scenarios. For the period after 2030, the scenarios have been extrapolated assuming:

- Continued (increasing) energy saving and efficiency measures (e.g., the energy demand increase between 2030 and 2050 is equal to the increase between 2020 and 2030).
- Further increase of renewable energy in the market.
- In EU Member States where nuclear power plants are being phased out, (eg Germany and Belgium), part of that capacity is replaced by fossil-fuel power plants incorporating CCS.
- All new coal power plants deploy CCS
- For some EU Member states co-firing of biomass is used for coal power plants. Hence, to some extent, deployment of CCS to these power plants can result in a negative CO_2 emission.

- Approximately 80% of CCS is deployed in power generation; the remaining 20% is based upon on large point sources in industry.
- The CO_2 emissions in 2050 are about 80% lower than the CO_2 emissions in 1990, for the all the countries involved in this CO2Europipe scenario.
- The largest share of national captured volumes is assumed to be taken by source clusters currently planned for small-scale demonstration projects and / or clusters with existing large emissions.

This leads to a development in the captured volumes ranging from about 50 Mt/yr by 2020 to more than 1 Gt/yr by 2050. This development is in agreement with projections given by the IEA (2009) for Europe and for the North Sea countries (One North Sea, 2010).

The number of capture installations required to reach the volumes predicted by CO2Europipe, is likely to be greater than 300 by 2050. This rapid growth of CCS in Europe, and also in other parts of the world, is also foreseen in similar road maps published recently, and is the direct result of the ambitious CO_2 emission reduction targets that have been set for 2030 and 2050.

3.3 Storage capacity

The Geocapacity database provides data on storage capacity and the availability for subsurface storage reservoirs (sinks) for north-west and central Europe. More recent country specific studies[2] were used in addition to the Geocapacity database, to produce maps of available storage capacity for the period 2020 – 2050. Storage reservoirs (sinks) include gas fields, oil fields and aquifers. To reduce the uncertainty in the storage capacity estimates and storage availability, sinks were separately clustered for the different sink types. For each sink cluster, storage capacity and injection rate are assessed throughout the period 2020 – 2050. For the purpose of this project, assumptions were made on the availability and injectivity of storage reservoirs.

It is noted here that the data regarding the location and properties on storage capacity have much higher uncertainty than the emission data, with the information on the saline formations associated with the highest uncertainty. Before any storage site can be used, and before an optimised network can be developed, more detailed and verifiable data must be available.

3.4 CCS scenarios

The CO_2 captured volumes from the source clusters are linked with the available injection capacity of the sink clusters, taking into account availability and size of storage capacity, as well as the (estimated) ability of the storage reservoirs to store the annually produced volumes. This exercise reveals a network of transport corridors, covering north-west and central Europe. South-west and south Europe were not

[2] Additional data were used for Germany and The Netherlands.

included in the current study, as these are assumed not to become linked to the storage capacity in central and north-west Europe, due to the large distances involved and the mountain ranges in between.

Three different storage scenarios were evaluated:

- Reference scenario: storage takes place both onshore and offshore. The location of capture installations and storage sites was based on current plans and projects for the development of CCS that exist within the Member States;
- Offshore-only scenario: onshore storage was excluded from the assessment to investigate the impact of current public concerns and stringent permitting issues that might result from these concerns;
- EOR scenario: in addition to the offshore-only scenario it is assumed that EOR is economically attractive and will therefore deploy part of the captured CO_2.

3.5 Onshore and offshore storage

Maps of indicative CO_2 transport flows were constructed for the timeline 2020, 2030 and 2050 for the three scenarios. For each scenario the infrastructure network required in 2020 is limited in size and extent. The map of the transport infrastructure for the reference scenario in 2030 is shown in Figure 3.1, while Figure 3.2 shows the infrastructure for the same scenario in 2050. The two maps show the transport corridors (arrows), with the volumes transported (numbers alongside the arrows are in Mt/yr).

By 2030, more stringent emission reduction targets necessitate the development of large-scale CCS and the significant capture efforts will require an extensive infrastructure network to link all industrial clusters to storage locations. By 2050 the network is similar to the network in 2030, but the potential transported volumes have become (significantly) larger. Transport corridors might involve transporting tens to hundreds of megatonnes of CO_2 annually. In 2030 the total yearly captured volume in north-west and central Europe is estimated to be of the order of 400 Mt/yr; in 2050 the volume is estimated to be about three times larger (1200 Mt/yr) in the same region.

In the reference scenario, most of the West European countries have sufficient national storage capacity to store their CO_2.[3] Belgium could need to transport part of its CO_2 to the Netherlands. Poland may need to transport CO_2 through Germany in the early phase of CCS development, while between 2030 and 2050 sufficient domestic saline formation storage capacity is developed and export of CO_2 is no longer required. Although transport from Sweden, Finland and the Baltic States to the North Sea is foreseen. Romania and Hungary do not have sufficient national storage capacity. Storage in Slovakia could be an option for these countries.

[3] Most of the West European countries have sufficient national storage capacity by relying on capacity in saline formations. The uncertainty in the capacity of saline formation is rather high; should the capacity in these formations be limited then this could have an impact on the development of the transport network.

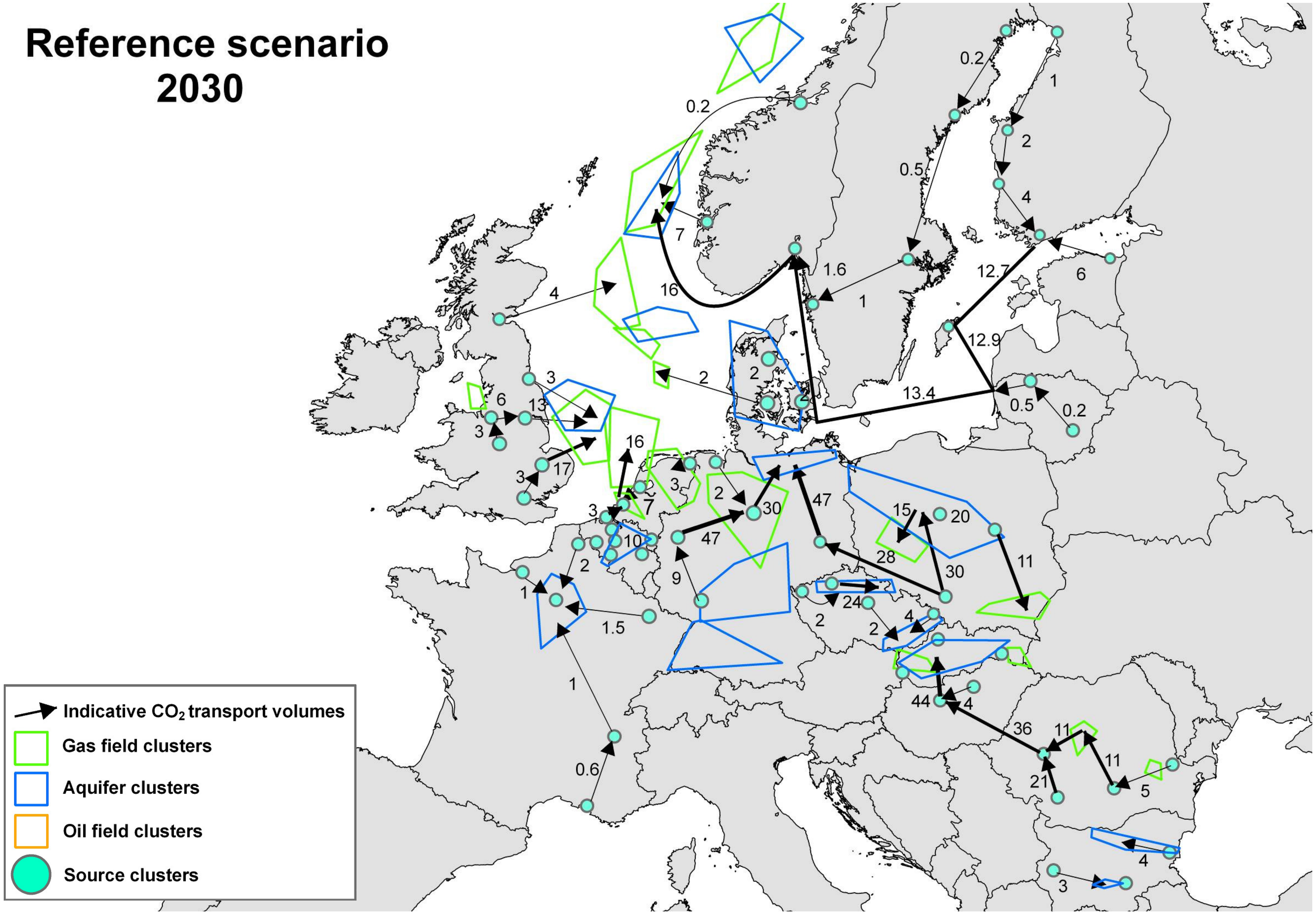

Figure 3.1 Map of large-scale CO_2 transport infrastructure for 2030. Arrow represent the major transport corridors; the numbers indicate the transported volumes in Mt/yr. Blue circles represent clusters of capture installations, polygons represent clusters of storage sites: saline formations (blue), gas fields (green). Oil fields are not shown on this map. In this scenario, both onshore and offshore storage is assumed possible.

Reference scenario 2050

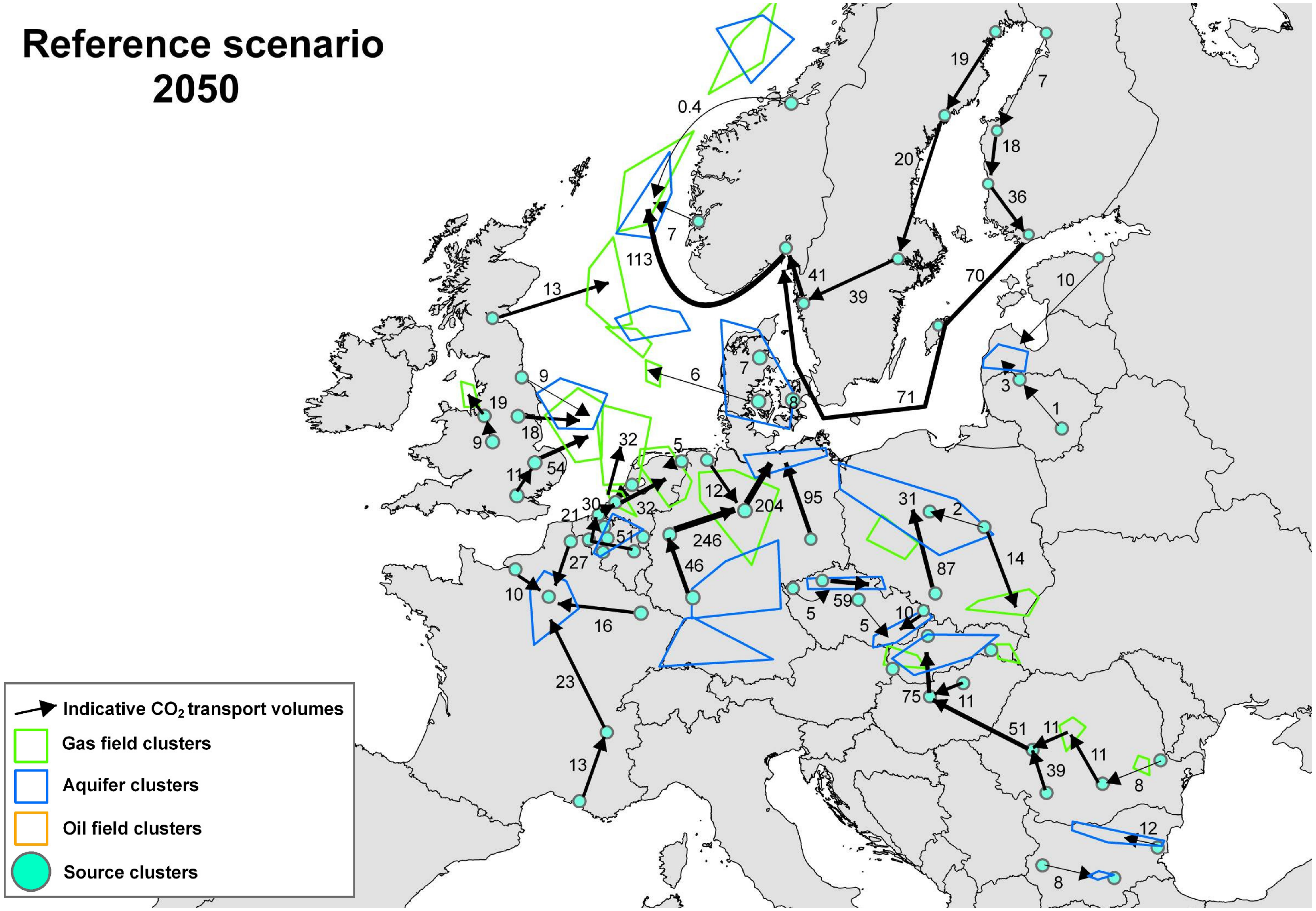

Figure 3.2 *Map of large-scale CO_2 transport infrastructure for 2050. Arrow represent the major transport corridors; the numbers indicate the transported volumes in Mt/yr. Blue circles represent clusters of capture installations, polygons represent clusters of storage sites: saline formations (blue), gas fields (green). Oil fields are not shown on this map. In this scenario, both onshore and offshore storage is assumed possible.*

Table 3-1 Transport network length (trunk lines only) for the scenarios considered here. Reference scenario: storage is done both onshore and offshore. Offshore only: onshore storage is not permitted. EOR: no onshore storage, and CO_2 is preferentially transported to the large oil fields in the North Sea.

	Total trunk line 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

3.6 Storage capacity used

The cumulative amount of CO_2 that is likely to be stored between 2020 and 2050 is small compared to the total storage capacity. While the total volume of CO_2 stored by 2050 in this study is 18 Gt, the estimated storage space is of the order of 300 Gt. Dependent on the scenario, 13-25% of the gas field capacity will have been utilised along with only 4-5% of the aquifer capacity. The use of oil fields is limited to the EOR scenario. Based on current knowledge of storage capacity, abundant capacity would be available if CCS is to play a role in emission reduction strategy also after 2050.

However, it should be emphasised that the storage capacity estimates represent 'theoretical' capacities, together with theoretical injection rates. Most of the storage capacity is represented by large, deep saline formations ("aquifers") that have not been explored and tested as yet. *Since aquifers take care of 60-80% of the total amount of CO_2 to be stored, verification of aquifer storage capacity through exploration and drilling is one of the more urgent issues in the near future.*

3.7 Transport network construction effort

The total length of trunk pipeline required for the scenario with both onshore and offshore storage is about 22000 km by 2050 (Table 3-1). The total transport distances for the offshore-only scenarios increases this by about 50%. Countries with the largest amount of pipeline to be constructed are Germany, Norway and Poland. This is primarily due to the large flows that need to be transported, requiring several parallel pipelines in some cases. As several countries do not have sufficient national storage capacity, cross-border transportation is also initially required. For the reference scenario, cross-border transport would start around 2030, while it would also be needed in the start-up phase in 2020 for the two offshore-only scenarios. *This shows that international collaboration will be important at an early stage if CCS is to be established on a larger scale. Co-operation is therefore required to ensure compatibility of CCS transport infrastructure, as well as to ensure that sufficient transport capacity is available.*

The largest effort in the construction of pipelines is expected between 2020 and 2030 because a greater part of the network will need to be in place by 2030. Furthermore it is estimated that the maximum rate of construction would need to be in the order of 1200 – 1500 km/yr for the regions considered.

Cooperation among the countries is required at several (e.g., technical and regulatory) levels. Planning and construction bottlenecks are expected to arise due to permitting issues. Furthermore, on the capture side, the equivalent of the order of 300 capture installations producing 4 $MtCO_2$/yr each are prognosed by 2050 in order to capture about 1200 Mt/yr. The construction rate for these installations is about 10 per year within the region considered.

3.8 Ship transport

Transport of CO_2 can be realized by both pipelines and ships. Ship transport would be an alternative, for example, during the initial phases of a project where volumes do not justify the investment in a pipeline where the storage capacity of a sink is limited or where the economics are more favourable to use a ship (this being highly dependent on the project at hand). Ship transport can connect several sinks in parallel that require small or fluctuating volumes of CO_2, or are in a remote area. Storage sites that are amenable to supply by ship include, but are not limited to, producing oil fields for enhanced oil recovery purposes. The feasibility of transport by ship to depleted gas reservoirs remains to be demonstrated, though initial injection simulations are positive; if demonstration is successful, ship transport to smaller and medium size storage locations or locations far from a CO_2 trunk line could complement transport by pipeline. Ship transport can also be used during the start-up of CCS plants or a cluster of sinks during the construction / modification of a pipeline network that often have lengthy realisation periods.

3.9 Infrastructure lay-out

The maps of expected transport infrastructure in Figure 3.1 and Figure 3.2 suggest that different types of network can be expected to emerge in Europe. It depends on the density of CO_2 sources regions on the one hand, and the location of storage capacity on the other, and on whether the transport solutions will be of the one-on-one type (one source region linked to one storage region), or of a more complex structure with several source regions linked through a network to several storage regions.

It should be noted that in the approach used here clusters are formed of both capture installations and storage locations. Therefore, it is implicitly understood that 'sources' and 'sinks' of CO_2, shown on the map as a single symbol, represent several specific capture installations or several storage sites. A one-on-one network connection on the maps in the figures represents several sources linked to several sinks, through a single backbone pipeline. For those transport links on the maps with a yearly volume greater than a few Mt/yr, it is likely that the CO_2 originates from more than one capture installation.

3.9.1 One-on-one transport 'networks'

The first CCS projects are likely to construct networks "one-on-one" systems, i.e., point to point from source to sink. Until 2020, during the demonstration period, this will be the dominant network type unless government/EU support or guarantees are available to enable infrastructure oversizing. Domestic pipeline transportation is expected to predominate. Although designed on a one-on-one basis, these pipelines and storage sites will still be subject to regulations concerning third party access requirements.

Once CCS is introduced on a large scale, i.e., after a successful demonstration phase, the analysis presented in the maps in Figure 3.1 and Figure 3.2 suggest that the transport networks will rapidly evolve to become more complex, sharing both transport and storage infrastructure. According to the reference scenario (Figures 3.1 and 3.2), this will be the situation by 2030.

3.9.2 Complex transport networks

Whereas networks of the one-on-one type will be common before about 2030, the increasingly strict emission reduction targets of 2030 and 2050 should lead to an increasing number of capture installations. The resulting increasing CO_2 volumes are likely to be transported along existing corridors. As a result, the maps for both 2030 and 2050 show networks having a more complex typology.

For a large part of the area covered by the maps in the figures, shared transport infrastructure is the most likely development. Countries with insufficient storage capacity will need to construct pipelines to storage locations in neighbouring countries. Almost by definition this will lead to pipelines connecting several capture installations, through a shared cross-border pipeline or a shared corridor of several pipelines, to the storage location. Examples can be found in the Baltic region, where a large number of capture locations are connected by pipeline and ship transport to storage locations in the North Sea. Other examples are located in East Europe, where insufficient storage capacity requires long-distance pipelines to storage locations in Central Europe.

These results indicate that well before 2030, the regulatory environment must be favourable for cross-border transport. Also, well before 2030 (and earlier if onshore storage is not available), a common design basis must be adopted that allows systems throughout Europe that will eventually form part of the cross-Europe, multi-user CCS chain, to be compatible.

It may be difficult to change organisational models (developed for one-on-one solutions) to suit more complex networks due to the difficulty in changing established models with proven experience and momentum.

3.10 Consequences of offshore-only storage

The infrastructure of the two offshore-only scenarios forms a network of transport corridors which are all directed towards the North Sea, where the largest offshore storage options are located. Due to the location of offshore oil fields close to gas fields and aquifers, the infrastructure for the two scenarios is chosen to be similar and investigates transporting large volumes from deep within Europe to the North Sea coast, and then to continue in offshore pipelines to the North Sea gas fields, saline formations

and oil fields. Many of the transport corridors should require transport capacities of tens to hundreds of megatonnes annually. The networks in these offshore-only scenarios serve to highlight the importance of onshore storage for a large part of Europe.
By not using available onshore storage,

- The predicted average transport distance per tonne of CO_2 in the offshore only scenario is more than double that for the scenario including both onshore and offshore storage by 2030.
- Total cost of constructing the transport network will increase from an estimated 50 billion euros to approximately 80 billion euros.
- The total length of transport trunklines is about 50% larger
- Cross-border transport would start around 2020 (compared with 2030 in the reference scenario).

3.11 Key players in Europe

The maps show that there is an uneven distribution of capture efforts, of transport network construction and of capture efforts in Europe. The abundance of storage capacity, whether it be in depleted gas fields, oil fields or saline formations is biased towards the North Sea. Capture efforts are largest for countries with a strong industrial basis, or relying strongly on coal or lignite in the power production industry. The key players that can be identified from the infrastructure development are Germany and Poland (capture, transport, storage), the United Kingdom (capture, storage), Norway (transport, storage), Poland (capture, transport). The Baltic region will see a large degree of cross-border transportation, over larger distances.

3.12 Conclusions

The construction of a future, large-scale CO_2 transport infrastructure for Europe leads to the following conclusions.

1. CO_2 storage capacity is not a limiting factor in the development of large scale CCS infrastructure although timely and adequate characterisation must take place
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 if onshore storage is available.
4. International cooperation and alignment of infrastructure developments is required for an efficient CCS transport infrastructure in Europe.
5. Pipeline and shipping are to be seen as complementary and needed to facilitate the high network demands that are projected.

Finally, an important conclusion that is drawn from the maps of CO_2 transport infrastructure is that the largest part of the effort of constructing the infrastructure lies with only a few Member States. These countries will have the opportunity to take the lead in Europe, not only in creating the first elements of the transport infrastructure, but also in aiding its industry towards a low-carbon strategy for sustainable growth and continuing this effort for several decades into the second half of this century.

4 CONCLUSIONS AND RECOMMENDATIONS

The previous section presents the vision of a future, large-scale CCS transport and storage infrastructure. The conclusions and recommendations presented in this section were obtained by projecting this vision from today's environment, defined at various levels such as policy, regulations, organization, legal and financial and formulating the required changes to each of these levels in order to realize the vision.

A key element in this process is the identification of the critical phase in the development of CCS, which is when new CCS projects need to extend beyond existing projects, thereby creating a need for more complex transport and storage systems. This phase is likely to start after the demonstration phase, which ends around 2020. Enabling the extension of existing infrastructure by third parties also requires a favourable environment, at levels such as commercial and regulatory. Both European and Member State governments must take action as early as possible to create the environment that allows third parties to access existing CCS transport and storage systems. These actions, discussed in the following sections, address issues that are found at several levels: regulatory, financial, technical. Above all, however, is the need for political leadership.

4.1 Leadership in Europe – key players in CCS

The vision of the future, large-scale CCS transport and storage infrastructure presented above, and the analysis of the efforts involved in capturing, transporting and storing the CO_2 clearly show that most of the effort is concentrated in a small number of Member States. These countries are 'key players' in the context of CCS. Their early and continued support of CCS is essential for its development into becoming a significant contributor to greenhouse gas emission reduction. The key players are not only located around the North Sea, which represents the area with a large fraction of the European storage capacity, but also include Member States that heavily rely on coal or lignite for their power supply.

It is essential for the deployment of a CCS infrastructure in Europe that the key players take the lead. They will not only provide the transport infrastructure for others, such as countries bordering the North Sea and serving as gateways to its vast storage capacity, but also incentivise other countries to follow. Early (and continued) CCS activities in these key countries are necessary to kick-start the overall European CCS infrastructure.

Recommendation

- The key players in Europe should demonstrate leadership in the development of CCS. Their initial and continued efforts in developing the infrastructure for CCS are essential and will catalyse developments in other Member States.
  Actor: Key players for CCS, including North Sea countries (Germany, UK, The Netherlands,Norway), Poland etc.
  Timeline: 2012 – 2050

4.2 Providing the vision: master plans

The development of more complex transport infrastructure projects, involving several suppliers and storage locations, will require support from the European and Member State governments, as is discussed below.

EU and MS master plans for CCS development
Storage operators , power companies and gas transport companies all have a role to play in the future CCS value chain (D2.3.1, D3.3.1). As far as such parties exist today, they currently have different business criteria, management processes and investment horizons. The organisational differences require an authority that effectively coordinates the business development of the CCS transport network. CO2Europipe estimates illustrate that large-scale transport investments over more than 2000 km could be achieved with return on capital of 8 % based on the following arguments:

- All ZEP industry partners have agreed on a WACC (weight averaged capital cost) of 8 % for a cost analysis of pipeline transport infrastructure
- A benchmarking analysis of several European gas- and power network transport companies reveals that these companies are able to attract sufficient capital for all their investments at a return on capital of less than 8 % (e.g. The Norwegian gas pipeline infrastructure has a regulated return on capital of 7 % before tax and has always been financed to a large extent by by private oil & gas companies)

Naturally, this assumes that the rest of the CCS chain can be made commercially feasible (ZEP, 2010; D4.1.1) This would require alignment in the business planning of the potential parties involved (e.g. energy utilities, transporters and storage providers).

To reach such an alignment, road maps for the development of CCS infrastructure should be constructed, both at a European and a Member State level. These road maps, or Master plans, describe the proposed transport and storage network, regionally, nationally and on a European scale and provide guidelines or forecasts regarding future supply of and storage options for CO_2.

For the pan-European CO_2 transport network a cumulative investment of 50 billion euro is estimated for onshore and offshore storage in the period of 2020 – 2050. If CO_2 storage would be restricted to offshore only this would lead to longer and more expensive pipelines leading to a cumulative investment over the same period of 80 billion euro[4].

[4] Most studies allocate the compression costs (OPEX based on electricity costs and CAPEX based on compressors, pumps and heat exchangers) to capture costs. The CO2Europipe reports however, allocate the compression costs to transport costs for the following reasons:

- Transport (and storage) without compression is not possible
- Throughput, OPEX and CAPEX are interdependent. Therefore an infrastructure design should be based on transport costs including compression

Designing a transport infrastructure network should therefore always be based on the total cost of ownership (OPEX and CAPEX) related to the depreciation period and the anticipated transport volume

Several studies show that CO_2 pipeline transport capacity exhibits a strong economy of scale (D3.3.1, D4.3.1, D4.3.2, and D4.1.1.). This is due to the fact that pipeline CAPEX increases almost linearly in price with pipeline diameter for long and large diameter offshore pipelines. However the potential throughput of liquid (or dense phase) CO_2 at given pressure conditions increases strongly (non-linearly) with the pipeline diameter. Due to this economy of scale the annual costs at maximum capacity for small pipelines (diameter less than 10") is predominant capital costs while predominant operating costs (compression energy) for large diameter pipelines (30" and more). This implies that transport costs per ton CO_2 decrease strongly with increasing pipeline diameter (assuming high capacity utilization) and also that the scale of CO_2 transport has an impact for the optimum routing of pipelines.

This behaviour is the driving force, from a socioeconomic perspective for large infrastructure networks matching sources and sinks via industrial clusters (so-called CO_2-hubs). Such a network is also more robust with respect to variations in throughput of different CO_2 emitters.

In order to realize a network instead of point-to-point connections, strong coordination between the industrial clusters in different countries will be required. However, from an individual business point of view, a company might be inclined to design one pipeline to one storage location at a capacity that just matches the maximum captured CO_2 emission. This would lead to a suboptimal network and shows the necessity of national and supranational coordination. It can be concluded that an overall master plan for the design of the network is required that deals properly with these issues and also storage location properties.

Recommendation

- A master plan, as part of energy infrastructure, should be developed for the proposed transport and storage network that includes storage qualification of storage reservoirs and that addresses the critical decisions points in time related to field abandonment, time for storage qualification, project development and permitting etc. This would serve the goals of acceptable return on capital for the industries involved and lower CCS costs for society.
  Actor: European Commission (DG Energy), Member States, industry stakeholders
  Timeline: 2012 – 2020

Storage capacity must be qualified

An important element of the master plans will be the qualification of storage capacity. In order to plan the storage infrastructure, a clear legal position and a solid early assessment of storage potential is necessary. The long-term legality of storage - whether or not onshore storage is allowed – is a pre-requisite. Pipeline networks potentially

over that period. For these reasons transport costs may seem higher, at first sight, compared to other reports.

crossing several member States will be more common if the permitting of on-shore storage is delayed compared to off-shore storage (D2.2.1).

The opportunity time window for CO_2 storage in depleted gas fields is different from that of CO_2-EOR (D4.1.1) but both require investment decisions before 2020 to avoid lost revenue, high mothballing and decommissioning costs combined with limited opportunity for CO_2 reductions (D3.1.1, D3.3.1).

Detailed knowledge of potential storage sites needs to be in place, confirming the minimum theoretical storage capacities that are available, and how this relates to the location of potential sources of CO_2. An open database of storage locations, with underlying data, is likely to encourage the CCS industry to explore storage options. Assessing availability of local storage capacity at an early stage 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. Given the timeline of typically five to ten years for the characterization and testing of a single storage location, it is of the highest priority that Member States qualify their storage locations, to reduce the uncertainty in the location of future injection points. While a mature CCS industry could be relied upon to qualify storage capacity for future demand, during the first phases of the development of CCS there may be a need for governments to actively support storage capacity qualification for early projects.

Recommendations

- Member States should actively support the characterisation and qualification of domestic storage capacity, with a total volume sufficient for the planning and development of a transportation network during the early phases of CCS infrastructure development.
  Actor: Member States
  Timeline: 2012 – 2025

- An open database of theoretical storage options, containing as much as possible detailed underlying data, should be set up.
  Actor: DG Energy, Member States
  Timeline: 2012 – 2020

- Harmonisation and standardization of the method of storage qualification (e.g., CO2Qualstore) will help decrease the time needed for storage qualification. Existing information on depleting gas- and oil fields from different member states should be represented in a similar format and process to allow a good comparison.
  Actor: Independent Standards Organisation, national resource holders
  Timeline: Recommended Practices 2012-2015, Standards 2015-2030

4.3 Developing a business model for CO_2 transport industry

The development of CCS clusters is foreseen to start in the period 2020 – 2030, when emission reduction targets will necessitate that most European countries to start large-scale capture of CO_2. The clusters are likely to develop from the earlier demonstration projects that have resulted in mostly one-on-one projects. This, however, will require that the organisational models originally developed for point-to-point CCS are reconsidered. This should be understood early in the development of CCS, to enable a smooth transition from early (simple) to mature (complex) infrastructure types.

Business model for CCS transport industry

There are two simple models that can be envisioned to incentivise pipeline investments and that have a significant implication on the investment and financing approach that is proposed;

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

In Case (1) the power company invests in capture, compression, pipelines, storage facilities and all other equipment to make CCS possible. The other alternative Case (2) is to set up a separate company that only transports CO_2 as a service for emitters and storage parties. The vertical integration model is generally preferred in the beginning of CCS which is dominated by isolated demo projects. Later on, when a large scale network evolves, a common carrier model will be preferred.

A standalone transport company might benefit from both economy of scale and one single permitting process by gathering all major CO_2 flows into 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. From a financial perspective a government entity is beneficial but not essential as a shareholder as long as there are government guarantees to protect the loans against political risk. This covered contractual agreement gives the certainty to the emitter that the transport operator will not fail financially. In the proposed business model (just like in the current gas and power business) transport contracts are completely separated from commodity contracts.

The proposed business model, as explained in D4.1.1 and D2.3.1, assumes a guaranteed fixed return for the infrastructure network owner based on transport fees (from emitters) that are independent of CO_2 value and EUA prices. This business model could enable attraction of sufficient capital for financing the network as CO_2 price risk is removed. Consequently, faster growth with higher CO_2 volume transport is also enabled.

The remaining risks are: i) project risk, ii) operational risks, iii) technical risks, iv) regulatory risk, and v) commercial risk (low capacity utilization). It is assumed that (i) to (iii) have been dealt with in the demonstration projects from 2015 until 2020 as most experts on capture as well as storage agree that 3 – 5 years of operations is sufficient to design confidently for larger units although it is too early to create rules on these experiences. The commercial risk (v) of low utilization (less contracted capacity than actual capacity) could be circumvented by an EU wide expert authority that is tasked with synchronising all investment decisions for CO_2 transport infrastructure as described in D4.1.1.

The largest effort in the construction of pipelines is expected between 2020 and 2030. The rate of construction may be as high as 1200 – 1500 km/yr in some regions (D2.2.1, D3.1.1). In the context of the overall EU infrastructure investments, CO_2 transport construction only represents a small percentage. However, infrastructure development needs to be considered integrally, onshore pipeline construction is very disruptive and dependent on stakeholder, public and environmental protection acceptance.

Recommendation

- Set up an expert authority that coordinates cross-border transport and storage infrastructure investment plans and their associated investment decisions to ensure high infrastructure capacity utilization.
  Actor: North Sea member states (NSBTF)
  Timeline: 2015 - 2020

The political risk (such as if governments do no longer commit to CO_2 reduction and CCS) can be removed by government guarantees, e.g. reserved capital that will be transferred to the infrastructure owners in case the political commitment disappears.

Using the above business model a weighted average capital cost (WACC) of 7 % -- as is typically for gas- and oil pipelines in the Norwegian offshore area -- seems feasible. The recent ZEP report used a WACC of 8 % (assuming a very long depreciation period of 40 years) that was the result of consensus between many industrial parties. This equals a WACC of 7 % using a shorter depreciation period of 26 years in terms of equal yearly payments on interest and depreciation when including annuity loans.

Gas- and power transport are to a large extent regulated businesses and the EU tends to enforce EU-wide regulation (e.g. unbundling) and it is possible that CO_2 transport will be treated in a similar manner. Cross-border transport project consortia for power (Britned) and gas (BBL) demonstrate that commercial management is feasible and that certain exemptions from regulated returns have been approved[5]. These examples show that also regulated businesses in gas and power transport can set up commercial ventures and this too might act as an example of an investment approach for CO_2 transportation.

It can be concluded that using the above business model, sufficient capital could be attracted for financing at reasonable costs. It can also be concluded that large industrial clusters in The Netherlands (Rotterdam), Germany (NRW) and offshore Norway favour standalone transport companies/consortia while CO_2 transport in Poland and Czech Republic favour business models based on vertical integration. The reason for this is

[5] See www.britned.com, www.bblcompany.com.

that in the latter regions there is less clustering in CO_2 capture and the power companies are large and integrated.

4.4 Shaping the regulatory environment

The development of CCS clusters has a great potential for cost-sharing and for provision of access to CO_2 infrastructure to both energy and industrial stakeholders. This is demonstrated in D4.1.1, where the economic analysis concludes that large volumes from different sources lead to lower costs per ton of CO_2 and higher stability of the transport system, due to smaller throughput variation. Large-scale cross-border CCS in Europe requires amongst others, offshore CO_2 transport and storage in the North Sea with CO_2 from Rotterdam, Groningen Eemshaven and North German harbours.

Development of clusters requires regulatory support such as open access to existing infrastructure, monopoly and liability management and cross-border cooperation. These considerations have led to the conclusions and recommendations discussed below.

Ratification of the London Protocol
An amendment in 2007 to the 1996 London Protocol allows for the sub-sea storage of CO_2 and its cross-border transportation. This will provide the conditions for developing the vast storage capacity in the North Sea. However, the amendment remains to be ratified by most of the Contracting Parties and will not come into force for some time. An interim solution to this problem must be clarified by Europe with some urgency. Ratification of the London Protocol amendment for CO_2 will enable the development of large-scale, multi-national transport and storage activities in the North Sea. At present, the North Sea rim is the preferred location of several of the EU Demonstration Projects. In addition, any delay in the permitting of onshore storage in several of the nations bordering the North Sea suggests that the second wave of CCS projects are most likely to also evolve around the North Sea Basin storage capacity, thereby adding, but not extending the early transport infrastructure.

Recommendation

- Member States should ratify the amendment to the London Protocol for cross-border transport and subsea storage of CO_2. This will enable large-scale, offshore CCS transport and storage activities, especially in North Sea Basin.
  Actor: European Commission and Member States
  Timeline: 2015-2020

Creating a stable, long-term regulatory environment
Development of a commercial CO_2 transportation infrastructure will require producers of CO_2 undertaking a payment commitment (e.g. a take or pay or minimum volume contract) sufficient to make a financial recovery of the investment at a reasonable rate of return (D3.3.1). If such a payment obligation is secured, the organisation of the ownership and operation could follow the model of an upstream petroleum or gas pipeline (D2.3.1, D3.1.1, D3.3.1, D4.1.1, D4.3.1) with the only difference that governments need to cover the political risks in the case of CO2 transport and need to ensure that the whole CCS chain is economically viable. A joint venture of owners (with or without state participation) could be formed, and an independent operator could be appointed. (D2.3.1, D3.3.1, D4.1.1, D4.2.1).

Costs and financing aspects of the development of a large-scale CO_2 transport network need to be resolved before larger scale CCS will be able to develop.

- Investments in large-scale CO_2 transport infrastructure and strong tax incentives (e.g. EU-ETS) need overall European public planning, as investments are not likely to be carried out by industrial partners alone (D3.3.1, D4.1.1, D4.2.1, D4.3.1, D4.4.1).
- Also, cost differences may arise between earlier and later CCS projects, due to (necessary) picking of 'lower hanging fruit' in the early stages, so mechanisms need to be in place to prevent undue cost escalation (D2.2.1, D2.3.1, D3.3.1).
- To prevent costs for redesigning and rebuilding to connect non-compatible infrastructure among countries, it is important to harmonise the technical solutions used across the EU as early as possible (D2.1.1, D2.2.1, D3.1.1).

Recommendation

- In order to build a sizable and commonly usable infrastructure to meet the demand of industry as more CO_2 will be captured, the master plan is essential in combination with a stable regulatory environment that is effective in signalling the future requirement and demand for CCS before private investors will consider building infrastructure to anticipate this forward demand (D 3.3.1).
  Actor: European Commission and Member States
  Timeline: 2015-2020

Harmonisation of Member States CCS regimes

Harmonisation of CO_2 transport and storage access regimes is essential for project developers and investors considering a CCS project that requires the cross-border movement of CO_2. Likewise, with the uptake of CCS, harmonized rules for CO_2 infrastructure charging will create the required level playing field between different CO_2 emitting industries.

Recommendations

- Implement third-party access regimes on a European scale, based on unbundling of CO_2 transport and infrastructure construction and using regulations, experience, protocols, business models and standards from the gas- and power sector. This may also be resolved on a bi- or multilateral level between the states involved.
  Actor: European Commission in association with independent review body
  Timeline: 2015-2020

- Support the development of economically attractive financial, business and risk mitigation models for multi-user CO_2 infrastructures, by enabling agreements between Member State governments for potential regulation of tariffs and taxation for all users.
  Actor: Member State Governments
  Timeline: 2015-2020

Onshore storage

The current tendency towards delaying the permitting of onshore CO_2 storage would, if continued, create transport infrastructure biased towards offshore storage locations and hinder countries not bordering the North Sea Basin. The result would be that required onshore pipeline capacity will increase dramatically, with an associated higher cost (increasing from 50 billion euro to 80 billion euro) and risk. Allowing onshore storage would therefore result in significantly lower overall costs due to shorter transportation distances.

Recommendation

- Member States should consider permitting onshore storage of CO_2. This would result in significant cost savings, compared to only offshore storage and would result in significantly lower demand for onshore pipelines.
  Actor: Member States
  Timeline: 2015-2020

CO_2 hub functions need to be further elaborated

Rotterdam and German harbours are in an unique position to i) demonstrate the CO_2 hub concept, ii) promote the advantages of cross-border planning, iii) demonstrate the advantages of combined shipping and pipeline transportation, iv) develop both the concept of storage only and storage/reuse of CO_2 for EOR and other means, and v) provide a growth path from phase one projects to large scale infrastructure.

As seen in both the Rotterdam (D4.1.1.) and the Ruhr-Rhine-Hamburg case study (D4.2.2), liquid CO_2 shipping should be part of the transport infrastructure as its flexibility in routing can be an enabler for demonstration projects and early injection in large mature oilfields to assess CO_2-EOR suitability.

Recommendation

- In the selection and management of CCS project funding, the value of important integrated business elements such as CO_2 hubs should also be considered to ensure timely maturity of integrated elements to support the necessary rapid development of CCS infrastructures from 2020.
  Actor: EU, Member States
  Timeline: 2015-2020

Composition of the CO_2 stream

Another area of regulation that needs further evaluation before development of a CO_2 transportation networks is a uniform specification for the composition of the CO_2 stream. Different types of capture technologies will produce CO_2 streams with varying compositions, and the synergistic effects of multiple CO_2 streams are not well documented. 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.

Recommendations

- Provide additional guidelines on minimum standards for the design and construction, including CO_2 quality, of new CO_2 network infrastructure (based primarily on CCS demonstration project learning), to ensure network reliability when used to convey CO_2 from a variety of capture technologies. These guidelines should be based on an understanding of the impact of impurities and quality on the behaviour of the CO_2 stream, and taking account of a techno-economic optimisation for the total CCS system following experience from the early CCS demonstration projects. The guidelines should help facilitate and not impede the development of a CCS infrastructure.
  Actor: European Commission and International Standards Organisations
  Timeline: 2015 - 2020

- Create agreements and standards for technical and regulatory/commercial interoperability. A successful transport and storage network will depend on the agreed standards and requirements being implemented and adhered to under the auspices of a competent and confident authority. In addition, it is important to learn from previous issues experienced when integrating the EU countries' individual gas transmission networks.
  Actor: International Standards Organisations, Member States
  Timeline: Recommended practices by 2015 – 2020, standards & firm regulations by 2020 - 2030

Liability for transported and stored CO_2

A key issue that should be regulated before more complex CCS networks arise is the liability for transported, as well as for stored CO_2. The EU Storage Directive stipulates that the storage operator will be liable for leakage over a significant period after injection. In addition, the liability is against future emission allowance prices, rendering the risk unknown and potentially large. In a one-on-one network, the financial backing for such a risk might be available. In a more complex network, with multiple suppliers and more than one storage provider, as well as in international networks, the liability issue poses a threat to their development and will need to be resolved beforehand.

Recommendation

- The liability for stored CO_2 must be regulated within (for national CO_2 storage projects) and among Member States (for international projects).
  Actor: Member State governments
  Timeline: 2015 – 2020

Ship transport

There is currently no dedicated EU legislation that covers 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[6] (hereafter referred to as the CCS Directive). With relevance to CO_2 transportation, the primary regulatory alteration brought about by the CCS Directive, is the declassification of CO_2 (captured for the purpose of geological storage) as a waste under the EU Waste Framework Directive[7]. The CCS Directive also includes concrete requirements for Member States to extend their environmental impact assessment (EIA) legislation to cover CO_2 pipelines, and also touches on aspects of third-party access and transboundary issues.

In June 2010, the European Commission released an amendment to the EU ETS Monitoring and Reporting Guidelines (MRGs) for the EU ETS released in 2007. The amendment,[8] 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[9], permitted under the CCS Directive.

Shipping is an alternative transport modality for CO_2 transportation that has been described in D4.2.2, D4.1.1, D4.3.1 and D4.3.2. Transport of liquefied CO_2 via ships is more cost-effective than transport via pipeline for low throughputs (< 4 million ton CO_2/year) and large distances between sources and sinks (more than a few hundred km). Another advantage of shipping is its flexibility of routing which enables injection and storage of CO_2 in different fields serviced with one ship. This flexibility is especially important for CO_2-EOR where huge investments (order of magnitude 1 billion euro per field) may be needed to establish all facilities for CO_2 conditioning, CO_2 injection, CO_2-oil separation and CO_2 recompression. Large scale trials in fields with CO_2-EOR using CO_2 shipped to the injection location will show whether large scale CO_2-EOR (requiring subsequent future large scale CO_2 transport per pipeline) is performing as expected. Shipping in this case can lower investment risks and can thus be seen as an enabler of CO_2-EOR and as a catalyst for building the larger transportation network.

Shipping capacity grows more or less linearly in steps with CAPEX by contrast to pipelines as a higher throughput requires more ships. The risk profile of the investment is also different as the residual value of a ship is higher than offshore pipelines because it can start a second life in the LPG trade after having serviced several storage locations. Ideally, the timing for such alternative use of ships should coincide with a phased transition to higher throughput pipelines for the large-scale network.

In spite of the regulatory provisions for the transportation of CO_2 and the development of CO_2 transportation infrastructure touched upon in the above legislation, there remains a number of regulatory gaps which need to be resolved in order to develop the

[6] Directive 2009/31/EC
[7] Directive 2006/12/EC
[8] Decision 2010/345/EU
[9] see Annex XVII of Decision 2010/345/EU

European-wide network. There are for example no activity-specific guidelines for transporting CO_2 via shipping, although this activity could be opted into the EU-ETS pursuant to Article 24 of the EU Emissions Trading Directive. The details of this, including corresponding monitoring and reporting obligations would be specified in the opt-in Decision[10].

Recommendation

- Clarify how the activity of shipping and subsequent account (monitoring and reporting) of the transported CO_2 will be taken into account in the whole chain.

  Actor: European Commission
  Timeline: 2015 – 2020

[10] From NER 300 Q&A

4.5 Shaping the financial environment

CO_2 transport over larger distances, often crossing country borders, will contribute in meeting CO_2 reduction goals by enabling CCS. Conclusions and recommendations regarding the financing of a pan-European network that could also ensure these goals in a cost effective manner in the post-CCS demonstration phase (e.g. 2020 – 2050) are presented below.

Long-term, stable regulatory framework for CCS financing mechanism
CCS is a low-carbon energy technology that is entirely climate change driven, which means development and deployment will not happen without policy intervention. Apart from regulations supporting the early demonstration projects, the mechanism that is currently foreseen to facilitate the deployment of a CCS industry is the European emission trading scheme for CO_2 (EU-ETS). However this framework is also currently a barrier to the development of large-scale projects beyond 2020.

The market price for CO_2 emissions, generated by the EU ETS, is supposed to finance CCS. However, these European emission allowance (EUA) prices will need to rise significantly to promote CCS deployment in the future. Besides the price of EUAs, there are also doubts whether the EU-ETS is the most appropriate mechanism to incentivize CCS (*Mulder, 2011*).

From interviews with finance specialists and potential users of CO_2 transport pipelines in the Netherlands, it can be said with confidence that without financial support from the public sector, significant[11] oversizing of pipelines, compression units and/or intermediary storage facilities (in the case of shipping CO_2) will not occur. Public finances are often used in large infrastructure projects that are considered to be in the interest of society as a whole. And it could be argued that public intervention through the co-financing in CO_2 transport infrastructure is justified on the basis that taking advantage of economies of scale can reduce the overall cost to society of reducing greenhouse gas emissions through CCS.

Recommendations

- Given expectations that the EUA price will not rise to the required level for CCS projects to be financed commercially in the medium term, EU and Member State government support in the form of additional funding should be announced in time for additional projects to be operating by 2020.
  Actor: European Commission
  Timeline: 2015-2020
- Beyond 2020, it is necessary to develop a stable, *long-term* regulatory and economic framework for CCS in the context of energy infrastructures. A robust

[11] Significant in this case is defined as over-sizing that goes beyond the foreseen requirements of a single project, and would allow multiple large emitters to co-utilize the infrastructure in the long term.

policy roadmap is essential for industry and society as a whole to give clarity on vision, burden sharing, regulations and business model to enable industry and financers to achieve the desired goals.
Actor: European Commission and Member States
Timeline: 2015-2025

Financial benchmarking gas and power transport companies

To attract capital for financing pipeline investments one should also have benchmarks for comparison on capital returns in similar business sectors. High-pressure gas pipeline transport and high-voltage power transport offer two good analogies to CO_2 pipeline transportation in terms of EPC (engineering, procurement and construction), technology, permitting, contractual structures and project partners (typically large energy and industrial companies). Except for CO_2-EOR there is no commercial driver for large scale CCS based upon the current and expected low EU-ETS prices. This implies that investments in CO_2 transportation are associated with a higher political risk that is absent from the gas and power sectors.

Five-year averages of financial parameters like ROI (return on investment), ROE (return on equity), net profit margin and dividend yield of European gas- and power transport companies have been analysed (D4.2.2). These data show a high ROE, as well as a high net profit margin with good dividend payments to shareholders. The ROI is defined as the yearly return (net cashflow) divided by the capital investment. The ROE is defined as the yearly return divided by the equity investment (which is usually lower than the total capital investment). Consequently, ROE is higher than ROI. A potential CO_2 transport company with these financial data could potentially attract sufficient capital from shareholders and lenders in order to invest in its infrastructure projects, given the attractive returns that can be reached (above 15 % ROE and net profit margins between 20 and 30 %). Note however that during the 5 year period some listed companies were not yet unbundled and they were not all treated equally during this period in terms of regulation of return on capital.

The business model (section 4.3) does not require that CO2 transport is regulated or unregulated. In practice regulated transport businesses for gas and power are, until now, able to attract sufficient capital for their investments. Consortia like Britned (power transport between the UK and The Netherlands) and BBL (natural gas transport between the UK and The Netherlands) have been able to acquire certain exemptions from regulated tariffs. The prime criterion should be whether the business model and proposition is able to attract sufficient capital while charging acceptable tariffs to the transport system users.

The ROE suggests that with low risk these investments could successfully compete with many other energy related projects. However 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 higher ROE. It can be concluded that these transport companies are only able to realize a higher return on equity by financing a larger 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 provide such loans to a potential CO2 transport company if the political risk is covered by government guarantees as previously mentioned. In addition, the collateral for the loans need to be of high quality; thus long-term contracts with companies that have a high credit rating. The latter will usually be the case for energy companies. It can be concluded that the gas- and power infrastructure 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 volumes of CO_2 from the main industrial clusters in Europe to regions with suitable onshore and/or offshore storage locations. These CO_2 transportation company could have a similar structure as consortia for cross-border transport of high pressure gas (BBL) or high voltage power (Britned). However, a crucial difference is the political risk that is associated with CO2 transport and that warrants government guarantees in order to attract capital.

Recommendation

- Develop guidelines into an EU-directive that allows EU coverage of financial guarantees by member states for CO_2 transport infrastructure investments. EIB should be tasked with lending for such projects complemented by commercial banks. It should be investigated that such guidelines are compatible with rules on state subsidisation and competition.
  Actor: DG-Energy
  Timeline: 2012 – 2015

Alignment of commercial planning in overall CO_2 development

The organisational issue of separate entities within the overall CCS chain, whose planning is not aligned is obviously also a key commercial problem. A coordination task of the EU DG Energy in the organisational development of CCS also requires a detailed implementation in its commercial aspects. The CCS chain requires organization (D2.3.1, D3.3.1). Contracts and related investment conditions for capture, transport and storage need to be coupled back-to-back (D3.3.1, D4.1.1). Investment planning for transport, storage, CO_2-EOR and capture plants needs to be harmonized in time (D2.2.1, D2.3.1, D3.3.1).

Potential incremental tax revenues from EOR may need to be earmarked for government guarantees in transport infrastructure that is needed to supply the CO_2 to the oil fields. (D3.3.1) Early investment and optimal dimensioning of large-capacity pipeline networks potentially reduces total investments considerably (D3.1.1, D4.1.1). Opportunities to optimise pipeline size to allow for greater future CO_2 transport demand on a regional basis could, firstly, minimize the overall costs to electricity customers, and secondly, reduce the risk to industrial users who emit CO_2 and who in the future, as the cost of carbon increases, consider CCS to be the most viable alternative to reduce CO_2 emissions (D2.3.1, D3.3.1, D4.1.1). Sizing pipelines appropriately, where the development of clusters is likely, offers an opportunity to deliver a more cost-effective CCS infrastructure (D3.1.1, D4.1.1, D4.2.1).

However, currently financers are not able to invest in future capacity without financial government support (D3.3.1, D4.1.1, D4.2.1, D4.3.1, D4.4.1). Clear political commitment and regulations with respect to the business model is required. Over-dimensioning of pipelines for the intention of sharing capacity between different parties will require commitments by users or governments for utilisation of such overcapacity in the future (D3.3.1). Therefore mechanisms for promoting early investment needs to be investigated in more detail, also taking into account rapidly growing costs of infrastructure construction (labour and materials), the integral aspects of infrastructure (re)design and the indirect costs of economic disruption due to large-scale infrastructure works (D3.1.1, D3.2.1, D3.3.1).

Offshore EOR requires high investments by oil field operators that necessitate timely design and construction of a larger CO_2 trunk lines from large-scale onshore hubs and out to the oilfields (D2.1.1, D3.1.1, D4.1.1, D4.3.1, NERA, 2009).

Recommendation

- Governments must work with the private sector to develop a finance model that will initially enable pipelines to be built with overcapacity in regions with the potential for extensive CCS deployment and in anticipation of the phased construction of capture plants.
  Actor: DG-Energy
  Timeline: 2012- 2015

4.6 Commercial options for CCS: CO_2–EOR

Financial value of CO_2 transport and CCS

In Nord-Rhein Westphalia (NRW, Germany) various energy plants need to be renewed or replaced in the coming 10 years. German legislation prescribes that these energy plants have to be "capture ready" when there is a reasonable expectation that a CO_2 transport infrastructure will be available in the coming 10 years. The amount of CO_2 that could be captured from these plants in NRW would exceed 20 Mt/yr already between 2020 and 2025. Required CO_2 amounts for EOR in the southern Norwegian field cluster grow to 25 Mt/yr already before 2025, continuing approximately for 25 years. D4.1.1 cost estimates show that pipeline transport and compression for these emissions, between NRW and the Norwegian fields, would result in costs per ton CO_2 significantly lower than current ETS tariffs. But business planning cycles of the electricity companies and the oil companies are not aligned. Currently, NRW-based energy companies claim that no transport infrastructure can be expected. Oil companies claim they cannot start EOR because of insufficient available CO_2. As a result, a attractive business opportunity could well be neglected. An early infrastructure as described would mean a giant step in the build-up of the CCS infrastructure for the whole of NW Europe, enabling commercial tariffs for other emission clusters in Belgium and the Netherlands as well.

Most studies that analyse CCS financially address the costs. There are, however, also benefits and potential revenues associated with CO_2 transport that can be categorised in 3 topic areas:

1) The value of CCS as a method to realize cost-effective CO_2 reduction (IEA Blue map scenario);
2) The value of CO_2 transport as an enabler for commercial CO_2 applications, such as EOR;
3) The value of CCS as an enabler for the revenues from the fossil value chain (important but not quantified in this report).

The second topic has been addressed in D4.1.1 in cooperation with the European project ECCO. The drivers for CCS (society/political interest to reach CO_2 reduction goals in the EU) and CO_2-EOR (oil company interest to increase oil production) are different. There is however alignment of interest in two areas:

- Using a common infrastructure leads to more customers and hence cost sharing and lower risks
- Increasing oil production from existing fields in the North Sea is in line with EU goals on energy security

The ECCO assessment of CO_2 demand for commercial CO_2-EOR purposes in the North Sea for a period from 2019 till 2042 is estimated to be more than 60 million tonnes CO_2/year. This is significantly greater than the scenario for CO_2 throughput based on transport from Rotterdam (30 million ton CO_2/year including import from Belgium and

Germany). Hence the potential EOR ambitions can only be realized if additional major ports around the North Sea capture, compress and transport CO_2 to the chosen oil fields.

Recommendation

- CO_2 based EOR know-how and field data for the North Sea oil fields needs to be updated and aggregated and aligned with CCS goals and EU energy policy and the foreseen CO2 transport network (D4.1.1), with current and potential stakeholders as power industry, governments and EP operators
  Actor: North Sea Basin Task Force
  Timeline: 2015-2020

- Develop a policy in to an EU-directive that stimulates the coordinated development of CCS and CO_2-EOR in Europe specifically in The North Sea and in line with the planning of infrastructure.
  Actor: European Commission/DG-Energy with NSBTF stakeholders
  Timeline: 2012-2015

Tax and revenue burden sharing in CO_2-EOR projects

Commercial CO_2 prices for CO_2-EOR have historically ranged from 10 euro up to 20 euro/ton CO_2 in West Texas. Using these prices for the North Sea will create an additional revenue stream that facilitates financing of transport but is yet insufficient to pay for all CCS costs. However, offshore taxation applied to oil revenues generates additional income for the countries that host the oil fields that benefit from EOR. The financing of a large transport infrastructure that is also able to supply enough CO_2 for the EOR could therefore be enabled if the government guarantees were also linked to the increased tax revenues. A recent study estimated the potential for CO_2 demand for CO_2-EOR in The North Sea to be around 7.3 billion barrels of oil (Tzimas et al., 2005). It can be concluded that the resulting tax revenues based on CO_2-EOR enabled oil production is more than enough as guarantee to cover the capital investments in transportation infrastructure. Therefore the financial synergy between CCS and CO_2-EOR in the North Sea should be utilized. The situation for onshore CO_2-EOR might be very different. The investment costs for onshore CO2-EOR will be much lower than for offshore CO2-EOR and this will have a decreasing effect on the CO2 price an EP operator is willing to pay to the emitter.

Recommendation

- Develop a consistent tax treaty enabling revenue and burden sharing agreements for enable all CCS-CO_2-EOR related investments by EP operators, power companies and transport companies into the North Sea Basin.
  Actor: North Sea member states (NSBTF)
  Timeline: 2012-2015

4.7 Safety and risk management

Transportation of CO_2 – like with any other gas – potentially poses additional health and safety risks. Under certain conditions, leakage or rupture of a pipeline can result in the release of CO_2 with the potential to affect humans and the environment. A significant part of the trunk lines will be located onshore, traversing densely populated areas. It is noted that this is quite different from the situation in the US, where the pipelines traverse remote areas. In addition, as shown in above sections, the total length of trunk lines, expected by 2050, is much larger (>20.000 km) than in the US (about 5800 km).. A number of issues were found that require action for a timely development of the onshore part of the transport infrastructure.

Harmonisation of risk assessment methods
The methodologies and methods to assess the safety (or broader: Health, Safety and Environmental, HSE) risks of CO_2 transport are well established by use of such methods in other industrial activities (e.g. as used in oil, gas, chemical and nuclear industry) or pipeline infrastructures (e.g. transport of natural gas). However an analysis of the methods used across Europe revealed differences between Member States. The harmonisation of risk assessment methods over Europe will therefore support the development of cross-border projects.

Recommendation

- CO2Europipe recommends the use of formal Quantitative Risk Assessment (QRA) methods, as used for instance in the natural gas transportation industry, to determine the HSE risks of CO_2 pipeline transport. This probabilistic approach can adequately deal with uncertainties associated with risks.
  Actor: European Commission and Member States
  Timeline: 2011-2015

Knowledge gaps
A number of areas were found where additional knowledge needs to be developed in order to fully understand the behaviour of $CO_{2.}$

a. *Physical outflow of CO_2 in case of a leak or rupture in a pipeline*.
   Due to the specific physical nature of CO_2 the physical outflow behaviour in case of a leak or rupture in a pipeline is not fully understood. The numerical models predicting the behaviour of the escaping gas are not yet fully validated with full-scale experiments; model predictions may therefore not lead to adequate estimates of the external safety of CO_2 pipelines.
b. *Limited experience on pipeline failure frequencies*.
   Compared to natural gas pipelines, there is only limited experience on CO_2 pipeline failure frequencies. The current experience is mainly related to CO_2 transport used for Enhanced Oil Recovery in the U.S. Once CCS projects and pipeline infrastructures start to develop, the experience base will grow and can be taken into account in adjusting the failure frequencies.
c. *Dose-effect relationships*.

Available Environmental Impact Assessments indicate the use of different dose-effect relationships to determine the fatality risk as a result of too high a concentration of CO_2. Until now there is no official generally accepted relationship across Europe. For example, TNO, Tebodin and the UK Health & Safety Executive (HSE) use different relationships leading to different estimates of fatality. This will result in different perception regarding calculated risks.

Safety risk policies showing compliance with quantitative risk criteria differ in the various EU Member States. Current external risk and industrial safety policies in the various EU Member States and Norway differ. Some Member States require a quantitative (probabilistic) risk analysis to be conducted. The risks calculated have to be compared to clearly defined risk criteria.

Recommendations

- CO2Europipe recommends a harmonization and eventual standardization (of best practices) to enable the development of a pan-European CO_2 pipeline infrastructure. Recommended standards and practices include those developed by DNV (DNV, 2010) and ISO3100 on Risk Management.
  Actor: European Commission and Member States
  Timeline: 2020 – 2050 (ongoing process)
- Validation of numerical simulation tools for the behaviour of gas flowing out of transport pipelines.
  Actor: CCS demonstration projects, R&D institutes
  Timeline: 2012 - 2015
- Establishment of a CO_2 database to record failure frequencies and experiences, e.g. a database set up in line with IGU report, A Guideline, "Using or creating Incident Databases for Natural Gas Transmission Pipelines."
  Actor: European Commission, Member States and Industries
  Timeline: 2012 – 2015

The results of other ongoing projects can help in validating the risk assessment models and to reduce the uncertainties in risk assessment. Projects to be mentioned are: CO_2PipeHaz[12], CO_2PipeTrans (a Joint Industry Project), and the EU CCS Network, which has already reported its first year's lessons (CCS Network EU, 2011). Also national CCS research programmes (like CATO-2 in the Netherlands) [13] will provide additional insights. More specifically, the Environmental Impact Assessments (EIAs) now in preparation to support the first large demonstration CCS projects will add to the knowledge base and may provide information that reduces the uncertainties.[14]

[12] www.co2pipehaz.eu
[13] http://www.co2-cato.nl/
[14] The EIA of the ROAD project, one of the CCS demos financed by the EERP is expected to be available for public consultation in the autumn of this year. An intermediate check by the NCEA was published May of this year (NCEA, 2011).

The various stakeholders in CO_2 infrastructure[15] should incorporate new lessons from other ongoing research and demonstration projects. These lessons can confirm the findings of the CO2Europipe risk work and, more importantly, knowledge gaps identified here can be narrowed down. Once detailed design for the CCS demos and resulting QRAs have been completed, the levels of safety risk estimated from QRAs can be used to judge whether these risks comply with national rules and regulations.

HSE risks are a key factor in public acceptance of CO_2 transport (and storage). Therefore, risk assessment, risk management and proper risk communication are key activities that can aid in public awareness and acceptance. *If not properly communicated, the HSE risks as perceived by the public may be a barrier to the development of CCS.* Other projects than CO2Europipe provide more lessons to deal with the issue of public acceptance of CCS, and timely public engagement. One relevant and nearly completed FP7 project in this respect is NearCO2[16].

[15] Stakeholders here: large emitters (e.g. power companies), gas network companies, pipeline construction and compressor companies, storage operators, regulatory and inspection bodies, R&D institutes.
[16] http://www.communicationnearco2.eu/documents-and-materials/

4.8 Technical issues

Both pipeline and ship transport is technically feasible methods for large-scale CO_2 transportation from sources to sinks. For example the petroleum industry has developed a mature industry for transportation systems, e.g. for natural gas, which, to a large extent can also be the basis for designing CO_2 transportation systems. All transportation systems, transporting CO_2, natural gas or petroleum products, need similar technical requirements to ensure a high degree of integrity of the system, i.e. need to withstand operating conditions (typically defined as pressure, temperature and flow conditions), both during normal operation and during unforeseen situations. Laws, regulations, standards and codes need to be honoured to secure safe and reliable operation.

Transport of CO_2 through onshore pipelines has taken place for more than 35 years in the US, and since 2007 an offshore pipeline for transport of CO_2 over a length of more than 140 km has been operated by Statoil in the northern part of Norway. The latter transports CO_2 captured from natural gas at the LNG plant at Melkøya to an offshore geological formation. Ship transport of food grade CO_2 from port to port has been performed for almost 20 years and although at a smaller scale compared to the anticipated volumes handled in the CO2EuroPipe study, the technology for such transport is to a large degree well known.

Some technological areas do need further development, of which none are expected to jeopardize the technical feasibility of constructing CO_2 transportation systems based on current knowledge (D3.1.1). Further development and increased knowledge will result in more optimised design and lower unit costs.

Pipeline transport

The CO2EuroPipe work concludes that most of the capacity for transportation of CO_2 from source to sink will be based on new installations in addition to some possible re-use of existing pipelines currently deployed for transport of natural gas or other petroleum products (D2.1.1). To the extent that existing gas or oil pipelines become redundant for its original purpose, a requalification to CO_2 transport is assumed feasible. Both cases are discussed in the CO2EuroPipe study (D2.1.1).

Presence of impurities in the CO2 stream

If free water is present in the CO_2 stream, serious corrosion may occur in carbon steel equipment and pipeline systems. Using corrosion resistant steel material is not regarded economically feasible for long pipeline systems. Hence, the CO_2 fluid must be dehydrated and thus non-corrosive. Effects and cross-effects of impurities still need to be more fully understood for dense phase CO_2 transport. Too stringent quality requirements may result in significant cost increases, because of investments (in cleaning facilities), operational costs and increased downtime. Inadequate quality requirements, however, may impact operations, maintenance and, most important, safety of the pipeline system and the public.

Recommendations:

- R&D activity needs to be performed to understand the behaviour of impurities in the CO_2 stream (with a strong focus on water), and, if required for future interoperability between CO_2 transport systems, to set acceptable levels of such impurities. Results from the R&D activities are ideally available as input to the CCS demonstration phase, and should be validated as part of such work. Several relevant R&D projects have been initiated to accomplish this, among which are CATO2 (in The Netherlands) and CO_2Pipetrans; new EU-funded research is being defined.
  Actor: Existing CCS research consortia, research companies, universities
  Timeline: 2012-2015

Development of accurate simulation tools

Simulation tools have been developed to analyse both the behaviour of the CO_2 in the pipeline, as well as dispersion of CO_2 from a planned and unplanned release. There are, however, limited data available from operations and testing which can be used to calibrate these simulation tools. Although the results from such tools currently are considered sufficiently suitable for their purpose, availability of data from actual practice would add further comfort to the results obtained by analyses performed during design and operation of CO_2 systems. Until such data are available, a conservative approach is used to establish safety requirements and capacities.

Simulation tools are also used to develop leak detection models. For large transport systems, leakages that may cause significant risk to health or the environment may be small compared to the total volume inside the pipeline system. More accurate leak detection models may be required for early detection of problems.

Recommendations:

- Experimental data, both from laboratory conditions and from full-scale testing, should be collected in time to validate existing simulation tools for the behaviour of CO_2 within a pipeline, as well as improve dispersion modelling.
  Actor: CCS demonstration projects, research companies, universities
  Timeline: 2015-2020

Soft materials

Under pressurised conditions, CO_2 may be absorbed by elastomers and other soft materials that are regularly deployed as seals and gaskets. During rapid decompression, the expanding CO_2 may not be escape quickly enough from these materials, causing blisters and other damage to the material. Usually, soft materials used in existing CO_2 systems have been tested on a case by case basis for each purpose, material and system. Hence, no general standards have been developed for such materials for pressurised CO_2 service. This probably does not represent a major challenge for pipeline based CO_2 transport, but particular attention should be given to testing materials and providing general specifications that cover operating conditions for typical projects.

Recommendations:

- Standards for qualification of soft materials suitable for use in CO2 transport systems should be developed in order to gain experience with a wide range of possible materials
  Actor: Suppliers, R&D organisations
  Timeline: 2012 - 2015

Noise during depressurisation

If there is a need for depressurizing the pipeline, e.g. as a result of an accident or incident causing a threat to the pipeline system or health/environment, a vent stack needs to be installed. Release of high pressure dense phase CO_2 into the atmosphere will result in high noise levels, typically higher than the noise from a full size jet engine at full throttle. A 200 km offshore pipeline system transporting 3 Mt CO_2 per year would need 1-2 weeks to depressurize. This would imply either the need for an extensive safety zone around the vent stack, or construction of a “silencer” around the nozzle of the vent stack. If such a “silencer” is to be installed, the design needs to ensure that sufficient dispersion of the CO_2 cloud is still possible, i.e. so that the design does not interfere with the flow pattern of the release in an unacceptable way. Initial design of such a “silencer” at the Kårstø full scale CO_2 project in Norway showed that a 60 meter wide concrete construction with a height of 20 meters would reduce the noise to acceptable levels. It is, however, assumed that further testing of design alternatives for such a “silencer” could significantly reduce the significant costs for such a structure.
While the above applies to all CO_2 pipelines, the case for onshore pipelines is different in the sense that onshore pipelines are sectionalised at a predetermined spacing. This greatly limits the volumes released when depressurising.

Recommendations:

- Methodologies for depressurisation of CO_2 transport systems should be evaluated. This should include concepts for high pressure, high velocity release, as well as concepts for low pressure release (pressure is reduced in a closed system before entering the atmosphere). Such methods should be physically tested (either in full or reduced scale) prior to a CCS demonstration phase, and validated as part of the demonstration phase.
  Actor: Existing CCS research consortia, demonstration project operators, research companies, universities
  Timeline: 2012 - 2015

Propagating longitudinal fractures

Preventing the propagation of longitudinal fractures is achieved through good design, choice of material properties and also, when required, inclusion of crack arrestors. For CO_2 pipelines this may represent a challenge compared to gas pipelines where the phenomenon is well documented. If a longitudinal fracture is induced, the length of the crack is determined by the strength in the pipeline material over the relevant section, as well as the relationship between pressure release on the CO_2 medium in the zone around the tip of the propagating crack. If the tip of the crack moves faster than the pressure reduction in the CO_2 medium, the crack may theoretically develop along the entire length of the pipeline section. To prevent this crack arrestors (small sections of pipeline

having higher material strength than the pipeline in general) have been installed at regular intervals (typically every half-mile). The mechanism of propagation needs to be better understood by extended R&D including physical testing. Until such knowledge is available, a conservative approach should be used in calculations of the pipeline's ability to withstand such cracks, as well as evaluating fracture mitigation techniques such as material specification and installation of fracture arrestors along the pipeline.
It is noted that this issue plays an important role when considering re-use of existing pipelines. The properties of CO_2 being quite different from that of natural gas, existing lines must be evaluated in detail regarding the above issue.

Recommendations:

- Physical testing needs to be performed in order to validate existing assumptions related to fracture mechanisms. This should be performed prior to designing pipelines planned for the CCS demonstration phase. Testing is currently underway as part of the CO2Pipetrans Joint Industry Project.
  Actor: Existing CCS research consortia (CO2Pipetrans), research companies, universities
  Timeline: 2012-2015

Internal inspection of pipelines

Internal inspections of natural gas pipeline systems are performed regularly (typically each 4 to 10 years, depending on characteristics of the pipeline and/or relevant regulations), using specialised internal inspection tools. The tools (termed 'pigs') are cylindrically shaped structures, containing technology for inspecting the condition of the pipeline material, following the internal stream of the pipeline, in this case the CO_2 stream. Although such inspection (termed 'pigging') has been performed for sections of existing CO_2 pipeline systems, tools needs to be qualified and tested for future long pipeline systems that may have a length extending even to 500 km. Physical wear and abrasion, as well as the effect on soft materials mounted as parts of the inspection tool need to be evaluated.

Recommendations:

- Technology qualification programs should be performed by vendors of pipeline inspection tools to demonstrate that qualified tools are available prior to starting the CCS demonstration phase.
  Actor: Vendors of pipeline inspection tools
  Timeline: 2012-2015

Re-use of existing infrastructure

Although it is expected that many future CO_2 pipeline systems will need to be new-build, re-use of existing pipelines (typically for oil and gas) may become appropriate in certain cases. Steel materials used in such pipelines will be as relevant as for CO_2 pipelines, so in general, it will be the original design premises that will determine whether an existing pipeline is suitable for CO_2 transport or not. For example, many onshore gas pipelines are designed for a maximum operating pressure of approximately 80 bar. CO_2 is transported in dense/liquid phase, but will, if the pressure is reduced or the temperature increased sufficiently, start to evaporate, entering gas phase. At 20 ºC, the bubbling pressure is just below 60 bar, implying that the liquid CO_2 will start to boil if the pressure is reduced. Requiring an operational safety margin could indicate that a minimum operating pressure is set around ~70 bar. Then, keeping the pressure along a pipeline route between the narrow pressure span of 70 to 80 bar would require many compressor stations and would not be feasible in practice. Alternatively, pipelines with limited operating pressures can be used to transport CO_2 in the gaseous phase, e.g. as proposed for the CO_2 transport infrastructure concept presented by National Grid Carbon as part of the Longannet CCS demonstration project.

Offshore pipelines are normally designed for a much higher operating pressure – up to typically 250 bar. The maximum temperature in subsea environments is also much lower, implying that the operational pressure span for such pipelines could be between 60 and 250 bar. Then, it could be sufficient to compress the CO_2 at the inlet, avoiding the need for compressor stations along the pipeline route.

For any pipeline that should be re-used for a different purpose than its original use, an evaluation of the integrity of the pipeline needs to be performed. In particular two issues needs to be emphasised if the new purpose of the pipeline is CO_2 transport.

- first, if the pipeline is coated internally (often done to reduce internal friction and/or to reduce risk of corrosion during/after installation) the coating material needs to be evaluated to ensure that it is not dissolved by the CO_2 fluids, and that the blistering effect described above does not occur.
- second, the risk of propagating longitudinal fractures needs to be carefully examined.

DNV's recommended Practice document for, "Design and Operation of CO_2 Pipelines provides a proposal for requalification of existing pipelines for CO_2 use.

Ship transport

Current regulations (IGCC, IMO, industry and class regulations) allow for the safe and regulated transportation of (food grade) CO_2. No major hurdles on the regulatory track to allow for large scale CO_2 transportation are expected. Port to port ship transport has been performed for almost 20 years, and the technology related to ship design and relevant onshore handling systems is well understood.

Offshore injection from ship

Injection of CO_2 directly from a ship to offshore underground storage is one of the concepts that are relevant for future CCS transport chains. Systems for such injection have not yet been installed, but alternative designs have been evaluated in early phase projects, and it is expected that robust solutions can be achieved. A key concern in this respect is injection directly from the ship into a depleted gas field. The combination of the high rates necessary, the temperature of the CO_2 and the pressure in the (depleted) gas field may require heating. An alternative approach could be to install local, temporary storage. There is significant economic cost associated with this design solution, but the technical aspects are well understood.

Recommendations:

- Technology qualification programs for offshore offloading systems from ship should be performed to demonstrate even further the technical (and economical) feasibility of such systems, prior to a CCS demonstration phase.
  Actor: Existing CCS research consortia, demonstration project operators, research companies, universities
  Timeline: 2011-2015

Re-use of existing vessels may also be feasible. In this context, existing LPG/ethylene ships may be used for CO_2 transport, with minor modifications in the event that port to port transportation will occur and adequate tank design pressure exists. If the vessel is to operate on a stand alone basis offshore for injection, re-use of existing LPG vessel is highly unlikely due to necessary CO_2 conditioning and dynamic positioning equipment that will need to be installed.

5 ROADMAP FOR CCS INFRASTRUCTURE DEVELOPMENT

The previous section formulated conclusions at different levels, along with recommendations for actions for the EU, Member State governments and industry. An indication of when these actions should be taken was given. The table below summarises these actions and lists them in chronological order. The table can be seen as a roadmap for the national and European governments for the development of an environment, in terms of policy, regulations, etcetera, that is most favourable for CCS.

The table shows that most of the recommended actions should be completed by 2020. This reflects the findings, explained in section 3, that 2020 can be seen as the start of the large-scale efforts in developing CCS in Europe. By that time, the environment, at the various levels described in section 4, must be in place to ensure an optimum development from mostly single-user systems (one capture plant, one transport pipeline or ship, one storage location) to more complex, multi-user systems. Preparing the regulatory framework for this transition is the background for most recommendations.

After 2020, EU and Member State governments will be required to continue their support, by creating a stable political environment that provides the necessary long-term certainty for private and commercial stakeholders.

During the entire period considered here, 2020 – 2050, the key players in Europe will be required to demonstrate leadership in the deployment of the CCS transport and storage infrastructure.

Table 5-1 Chronological list of actions for national and European governments as part of promoting the development of CCS.

Action	**Actor**	**Comment**
Period 2015 – 2050		
Key players in Europe to take the lead in developing CCS	Member States	Continued leadership is required
Period 2012 – 2015		
Support characterisation and qualification of storage capacity	Member States	Support development of CCS infrastructure during early phase

Harmonisation and standardisation of storage qualification method	Independent standards organisation	Decrease time needed for site qualification
Develop a master plan for large-scale transport and storage, optimised for cost and return on investments including storage qualification	DG Energy, Member States, industry stakeholders	Display vision to industry stakeholders
Set up international, open database of storage options	DG Energy, Member States	Support storage qualification process
R&D on behaviour of CO_2 with impurities	Existing CCS research consortia, research companies, universities	Establish validated modelling of CO_2 with expected levels of impurities eg MATTRANS project
Validate existing simulation tools	CCS demonstration projects; R&D institutes	Validated simulation tools are essential for startup of demonstration projects
Set up expert authority to coordinate cross-border transport and storage infrastructure investment plans	North Sea Member States	Ensure optimum infrastructure utilisation
Develop guidelines into EU directive to allow EU coverage for Member State financial guarantees using the unbundled fixed return common carrier model	DG Energy	Decrease financial risk for CCS infrastructure investments
Governments to work with industry to develop finance model that supports oversizing of infrastructure	EU, Member States	Support the optimisation of new projects for future demands
Develop tax treaty and revenue / burden sharing agreement for CCS and CO_2-EOR	North Sea Member States	Support cross-fertilisation between CCS and CO_2-EOR

Develop policy to stimulate coordination of CCS and CO_2-EOR	DT Energy, with NSBTF stakeholders	Support cross-fertilisation between CCS and CO_2-EOR
Establish database of pipeline failure frequencies and experiences	EU, Member States, industry	Support knowledge sharing
Develop standards for qualification of soft materials suitable for CO_2 transport systems	International standards organisations, member states, EU	Supports design and development of infrastructure
Concepts for depressurisation of CO_2 transport systems should be evaluated	Existing CCS research consortia, demonstration project operators, research companies, universities	Concepts for high pressure, high velocity release, as well as for low pressure release should be evaluated and physically tested, followed by a validation of the results during the demonstration phase
Physical testing needs to be performed in order to validate existing assumptions related to fracture mechanisms	Existing CCS research consortia (CO2Pipetrans), research companies, universities	Eg.testing is currently underway in the CO2Pipetrans and MATTRANS projects
Technology qualification programs should be performed by vendors of pipeline inspection tools	Vendors of pipeline inspection tools	In this way it can be demonstrated that qualified tools are available before the CCS demonstration phase
Perform technology qualification programs for offshore offloading systems from ship	Existing CCS research consortia, demonstration project operators, research companies, universities	Injection of CO_2 directly from a ship to offshore underground storage is one of the concepts that are relevant for future CCS chains
Support usage of QRA methods for risk analysis of onshore CO_2 pipelines	EU, Member States	Harmonisation, to remove hurdles in cross-border projects

Period 2015 – 2020		
Develop stable long-term regulatory and economic frameworks for CCS	EU and MS Governments	Improve long-term certainty for CCS investors
Develop regulatory and economic framework for CCS in the context of energy infrastructures	EU, Member States	Define the coupling between CCS and the energy policy in Europe
Provide support for new projects after 2020, in addition to the EUA price	EU	Improve financial basis for new CCS project
Provide guidelines on minimum standards for the design, construction and CO2 quality for pipelines in CO_2 networks	EU, MS Governments	Ensure compatibility between CCS projects, with minimum regulatory hurdles
Implement third-party access on a European scale; also on bi- or multilateral level	EU, Member States	Increase regulatory clarity
Update study of potential of CO_2-EOR and required investment needs	NSBTF	Optimise role CO2-EOR in relation to CCS
Ratify amendment for CO_2 to London Protocol	Member States	Enable offshore, cross-border transport and storage
Reach agreements between Member States on tariffs for third-party access	Member States	Increase regulatory clarity
Support the inclusion of intergrating elements in new CCS projects, such as hubs	EU, Member States	Support the development towards optimised, multi-user transport systems
Create agreements and standards for technical and regulatory, commercial interoperability	International Standards organisations, Member States	Ensure optimum contribution of individual projects to long-term, multi-user networks
Resolve liability issues for transport and storage	Member States	Remove this hurdle for cross-border networks

Clarify how the activity of shipping is taken into account in the CCS chain	EU	Support development of ship transport
Period 2020 – 2030		
Develop standards and regulations from earlier recommendations and best practices	International standards organisations, Member States	Eliminate barriers to growth from issues of interoperability

6 CONCLUSION

One overarching conclusion that can be drawn from the work in the present project, as well as from the multitude of CCS-related reports that have been published recently, is that although there is work to be done to create the right environment (on levels such as technical, regulatory and perhaps most importantly, political), *CO_2 transportation is feasible today.*

The technical expertise is present, with the largest challenge being the actual development and execution of a CCS project under the European CCS Directive, both on a demonstration scale, as well as on a full (commercial) scale. Although elements of the transportation processes require testing and demonstration; the equipment required for the level of transport that is foreseen to develop between 2020 and 2050 is expected to be developed in time.

Companies that together or on their own can implement and manage transport and storage activities exist. Examples of this are available through on-going CO_2-EOR projects in the United States. *The development of a regulatory and policy environment that is nurtures growth of a European CCS industry is a pre-requisite next step. Member State regulations, policy and master plans on CCS must be transparent, internationally consistent and geared towards cross-border cooperation for transport and storage.* The liability issues that presently are considered by many to form a major barrier will have to be solved among the Member States, because CCS is invariably a European and not just a national issue.

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8 CO2EUROPIPE PUBLICATIONS

The CO2Europipe project has published the following reports. The reports are available at www.co2europipe.eu. The deliverable numbers refer to work packages in the project.

[D1.1.1] CO2Europipe, *Developing a European CO_2 transport infrastructure - conclusions*, CO2Europipe consortium, September 2011.
The present report.

[D2.1.1] CO2Europipe, *Existing infrastructure for the transport of CO_2,* CO2Europipe consortium, May 2011.
This report investigates existing infrastructure and standards, regulations and modes of practice to ascertain to what extent CO_2 transport can benefit from them. The report discusses (the optional re-use of) platforms, pipelines, gas carriers (ships), etc. The experience with CO_2 transportion in the United States and Canada is discussed, with respect to current codes of practice.

[D2.2.1] CO2Europipe, *Development of a large-scale CO2 transport infrastructure in Europe: matching captured volumes and storage availability*, CO2Europipe consortium, April 2011.
The development of a large-scale CO2 transport infrastructure in north-west and central Europe is described, starting from the expected growth in captured volumes and the availability of storage locations, in the period 2020 – 2050. Growing from a limited volume in 2020, a strong increase in capture, transport and storage effort is foreseen in the following decades, to reach a volume of around 1 Gt annually by 2050. Conclusions are drawn regarding the construction effort involved and the distribution of that effort over the different EU Member States. The long-term, large-scale infrastructure is used in the CO2Europipe project as the goal, when deriving the requirements for optimum CCS infrastructure development.

[D2.3.1] CO2Europipe, *Development of a large-scale CO_2 transport infrastructure in Europe: a stakeholders' view*, CO2Europipe consortium, April 2011.
This report presents the current view of stakeholders on organisational requirements concerning the development of a large-scale CO_2 transport network. Special attention is paid to the transition from single source-to-sink infrastructure to more complex networks, in order to also provide insight into changes in stakeholder interests and requirements.

[D3.1.1] CO2Europipe, *Transport network design and CO_2 management*, CO2Europipe consortium, September 2011.
This report describes technical challenges in the design, construction and operation of a large-scale pan-European CO_2 transmission network. Additional elements of a CO_2 transport network are discussed, including compression, shipping, injection.

[D3.1.2] CO2Europipe, *Standards for CO_2*, CO2Europipe consortium, September 2011.
The central issue tackled in this report is the required composition of CO_2 for safe, reliable and cost-efficient carbon capture, transport and storage. The composition of the CO_2 affects the design of each of the components in the CCS chain, and vice versa. The report describes the effect of impurities on the storage reservoir and also discusses the implication of water concentration in the CO_2 stream.

[D3.2.1] CO2Europipe, *CO_2 transport through pipelines: risk characterisation and management*, CO2Europipe consortium, September 2011.
This report addresses the risks, related to CO_2 transport through pipelines, for society and the local environment. The characterisation and mitigation of pipeline transport risk is discussed and a literature survey of frameworks for risk assessment is given. The report lists current knowledge gaps related to the analysis of risks associated with CO_2 transportion through pipelines.

[D3.3.1] CO2Europipe, *Legal, financial and organizational aspects of CO2 pipeline infrastructures*, CO2Europipe consortium, May 2011.
This report covers the legal aspects of CO_2 transport and infrastructure development, presents cost-estimates for pipelines, compression and shipping from industrial partners, and reviews current literature regarding organizational issues of CO_2 transportation networks.

[D4.1.1] CO2Europipe, *Development of large-scale CCS in the North Sea via Rotterdam as a CO_2 hub*, CO2Europipe consortium, September 2011.
Scenarios for future captured CO_2 emissions for industry and power sector have been investigated together with models for CO_2 storage planning in the North Sea and scenarios for enhanced oil recovery using CO_2. These scenarios and models have been applied to develop a set of measures and a transport network in the North sea that best serves the objectives of society (large cost-effective CO_2 reductions) and industry/investors (competitive return on capital with acceptable risk profile).

[D4.2.1] CO2Europipe, *Report on the existing pipeline infrastructure in the WP4.2-area and on the reuse of existing pipelines for CO_2 transport*, CO2Europipe consortium, April 2011.
This report describes today's starting point, at the level of existing infrastructure and current regulations, for the development of CCS in the Rhine-Ruhr area in Germany. Sources of CO_2 as well as potential sinks in this area 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/yr might be reached within the test case area, 2.5 Mt/yr in 2025, 10 Mt/yr in 2032, and 20 Mt/yr in 2040 and 2050. The results from this report are used in D4.2.2.

[D4.2.2] CO2Europipe, *Making CO_2 transport feasible: the German case – Rhine/Ruhr area (D) – Hamburg (D) – North Sea (D, DK, NL)*, CO2Europipe consortium, August 2011.
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 volumes 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 volumes in a future CCS infrastructure.

[D4.3.1] CO2Europipe, *Kårstø offshore CO_2 pipeline design*, CO2Europipe consortium, July 2011.
This report describes a case study of transport of 1, 3 and 5 Mt/yr CO_2 from Kårstø to offshore storage in the Utsira saline formation on the Norwegian Continental Shelf. Both pipeline and ship transport is analysed. Description of technical solutions and cost estimates are provided.

[D4.3.2] CO2Europipe, *Kårstø CO_2 Pipeline Project: Extension to a European Case*, CO2Europipe consortium, July 2011.

This report describes a case study where the “point to point” system in the Kårstø case study described in deliverable 4.3.1 is extended to a small network consisting of additional CO_2 pipelines from Rotterdam (the Netherlands) and Teesside (UK) entering the same storage location in the Utsira formation on the Norwegian Continental Shelf. In addition, a ship transport chain is described as part of the sources for CO_2 at Teesside, i.e. that CO_2 is transported from a different location to Teesside by ship, for injection into the pipeline system to Utsira. In addition to the technical description, cost estimates are given for the transport system.

[D4.4.1] CO2Europipe, *Environmental impact and risks of CO_2 storage facilities in Poland*, CO2Europipe consortium, July 2011.
The environmental impact assessment presented in this report shows that there are grounds for issuing of a decision on the environmental constraints of implementation of a demonstration plant for CO_2 capture, fully integrated with the new 858 MW power unit at PGE Bełchatów Power Plant (synchronized for the first time with the national power grid), taking into account the recommendations included in the environmental impact report for the investment. Environmental decisions related to the storage place and to CO_2 transport systems can only be issued after more specific geological recognition of the CO_2 storage locations, and also after ensuring compliance of the said investments with the relevant local land use plans.

[D4.4.2] CO2Europipe, *Belchatow power plant – test case*, CO2Europipe consortium, July 2011.
This case study gives an overview of the CCS Project currently being evaluated for Bełchatów- the biggest lignite-fired power plant in Poland. The project consists of three phases: CO_2 capturing, transportation and storage in aquifers located within a range of 100 km from Bełchatów. The report describes how the capturing plant will be introduced into the whole electricity generation process. The report discusses the options for storage and gives basic assumptions of sinks’ capacities, as well as possible transport methods with associated risks. The last part of the report presents some economic facts connected with investments and operations of the capturing plant in different time horizons.

[D4.4.3] CO2Europipe, *CEZ CO_2 transport case*, CO2Europipe consortium, July 2011.
This deliverable describes a possible development of CO_2 transport infrastructure in the Czech Republic for a model unit, consisting of CO_2 source with lignite fuel and post-combustion capture; pipeline transportation facility and domestic or foreign CO_2 storage. Basic construction and operational aspects of the model unit are described; technical, legal, environmental and societal aspects are also taken into account as much as possible. Scenarios, defined in this deliverable, represent possible limits to the domestic CO_2 transportation network development. Several recommendations are formulated: evaluate CCS in comparison with alternative CO_2 abatement options in domestic conditions, to devise a state CCS development strategy, to promote research and development in CO_2 abatement technologies and to increase awareness on CO_2 abatement technologies.