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EXECUTIVE SUMMARY

The storage of captured CO_2 in geological reservoirs is currently seen as part of a portfolio of measures to reduce greenhouse gas emissions. Because of the need to bridge the geographical distance between the capture and storage site, transportation forms an important part of the CO_2 capture, transport and storage (CCS) chain. In the past, knowledge on transportation of a wide range of gases has been developed. Parts of this knowledge can be used for the development of the transportation network for CO_2. Still, new circumstances require new knowledge. However, technical and chemical characteristics of the captured CO_2 and the requirements at the storage site, as well as the limitations posed by the methods used for CO_2 capture and storage will be of influence on the transportation possibilities and need to be researched.

Currently, the development of a larger-scale CO_2 transport network in the future can only be drawn in outline. Existing sources and potential sinks influence the future CO_2 transport infrastructure, as well as other technical, economical, social, environmental and political factors. The challenge for a large-scale CO_2 transport network in the European Union lies in creating the environment in which the transition from small-scale to large-scale CCS occurs smoothly and without hindrance, leading to efficient CO_2 transport and storage.

This report aims to present the current view of stakeholders on 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 give more insight into changes in stakeholder interests and requirements. To this purpose, first an overview of different roles of stakeholders between three infrastructure topologies are described, i.e. small scale one-on-one infrastructure developing into a national infrastructure network, and a national network developing into an international infrastructure network. These transport topologies apply to transport by pipeline or ship. Size and complexity in these transitions increase significantly, due to increasing numbers of stakeholders: from one or several stakeholders towards multiple national and/or international stakeholders, changing requirements considerably.

For this report, stakeholders in the CCS chain were questioned to obtain their view on the requirements for the development of a large-scale CO_2 transport network. Views on their role in the development of the CO_2 transportation network are discussed, as well as the requirements they envisage in order to cooperate in the network. The latter touches on different factors influencing the future CO_2 transport infrastructure, i.e. technical, economical, social, environmental and political factors. Although the opinions were mainly based on the short-term developments (of small-scale CO_2 infrastructure), an effort was made to discuss the transition towards national and international CO_2 transportation as well.

The stakeholder discussion resulted in requirements defined per transport topology.

- In a small-scale infrastructure network, long-term contracts between emitter, transport and storage operators will be important, with agreements on, for example, CO_2 quality standards and liability issues. The national government regulates through safety requirements. The involvement of the public is limited and requirements include safety and economic aspects.

- In national grid scenarios other requirements become more important, such as open access to existing infrastructure, regulations to prevent increasing costs when the first, low costs projects have been exhausted and to regulate monopolies, liability issues, central planning and coordination.
- The international dimension adds cross-border requirements, e.g. interconnectivity with respect to composition (pressure, temperature, percentage CO_2), international safety regulations, liability issues, etc.

Furthermore, an overview is presented on existing modes of operation of natural gas and/or CO_2 infrastructure in several EU countries, including the Netherlands, Norway, United Kingdom, France and Germany. As a result of this overview different modes can be distinguished, each with different requirements. In case of international transport infrastructure these different models will have to be interconnected. In order to reduce interconnectivity problems the development of national CO_2 transport network must take into account, at an early stage, future international developments of infrastructure networks.

Cost aspects of the development of a large-scale CO_2 transport network need to be resolved before large scale CCS will 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. Also, cost differences may arise between CCS projects, due to picking of 'low hanging fruit' in early stages, so mechanisms need to be in place to prevent cost escalation. A price balancing regime may be appropriate. 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.

Finally, barriers that affect the development of a large-scale CO_2 infrastructure network need to be removed. These include existing technical, economic, social, environmental and political barriers. Specifically, the current lack of recognition of CCS being an approved and desirable means to reduce CO_2 emissions on a Member State level is an important barrier to deployment. Also, coordination is important between the multiple stakeholders, in order to reduce complexity and uncertainty and induce economy of scale. When suppliers of industry (plants, components) and power generators are convinced that a market is present, and when governments provide the proper regulatory environment, CCS projects will evolve and will result in demand for expert knowledge. The latter also induces recognition by the public. However, for CCS to be implemented, government incentives to make projects economic are the most essential precondition for CCS to be deployed.

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PROJECT SUMMARY

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

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

Project partners

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

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1 INTRODUCTION

While knowledge about CO_2 capture and storage technologies is rapidly growing, the transport of CO_2 is often regarded as the part of the chain in which knowledge is assumed to be widely available. However, transport not only needs to bridge the geographical distance between capture and storage sites, it also needs to bridge technical and chemical characteristics of captured and stored CO_2, and has to overcome all the limitations posed by methods used for CO_2 capture and storage.

The core idea of CO2Europipe is that future, large-scale CCS transport and storage networks in Northern, Western and Central parts of the European Union will evolve through coalescence of the infrastructure constructed by early, small-scale CCS projects. The challenge lies in creating the environment in which this transition from small to large-scale CCS occurs smoothly and without hindrance leading to efficient CO_2 transport and storage. The aim of CO2Europipe is to define the requirements for this transition, which can lie at a variety of levels, such as technical, societal and environmental.

There are several decisions that need to be taken concerning this transition. In the first place the most feasible transport medium per region and time frame that will be used, either via pipelines or transportation by ship, must be decided on as well as the network architecture and resulting network topology.

It is however unclear how the evolvement of the CO_2 transport network in the EU will work and what environment needs to be created so that large-scale CCS occurs smoothly, expediently and efficiently based on the infrastructure constructed by early projects.

An important question to answer is: can we expect that there will be a need for national and/or international large-scale transport of CO_2 in future? If the answer to this question is yes, how can the initial investments (installations) be made most effective, also for to the longer-term CO_2 transport network? Moreover, the suitability of aquifers for storage will be an important deciding factor because it will significantly increase the number of theoretically available storage sites. Besides technical suitability there are also other influencing factors, e.g. social and environmental requirements.

Neele et al. [2010] demonstrated that when looking at quantitative requirements from existing sources and currently verified suitable sinks it is very likely that larger-scale CO_2 transport will be needed in the future. From WP 2.2 it also becomes evident that it is not just the capacity of the suitable sinks that will be the prime bottleneck for decisions concerning requirements for a large-scale CO_2 transport network. As important will be the timing schedule indicating when storage capacity will become available. Furthermore, the injection capacity per year of the storage site and the economic and social feasibility of the site will all influence the storage potential.

There are also other factors, next to existing sources and potential sinks, which may influence the future CO_2 transport infrastructure. Technical, economical, social, environmental and political factors will be decisive.

It is recognised that it will not be necessary to develop a completely new design, construction, permitting and safety regime for the transport and storage of CO_2. Existing knowledge on transportation of gas can to some extent be used for the development of a CO_2 transportation network [*Coleman, 2009*]. Still, this knowledge needs to be adjusted towards transportation of CO_2 and gaps in technical knowledge need to be analysed and remedied.

Also, cost development is an important aspect of the development of large-scale CO_2 infrastructure. There are indications that the early CO_2 storage sites are the ones which can be developed the easiest and at the lowest costs, leading to the idea that with time the cost for CO_2 storage will increase, as the low hanging fruit will gradually be gone. Economies of scale and increasing experience might offset such increase. A trans-European network will take place only in case in which significant economical gains are to be expected.

The main driver or show stopper of CCS is legislation. If the public legislators wish CCS to happen as a carbon reduction measure, the legal framework should offer the necessary incentives in order that CCS projects are viable to go ahead. As the EU-ETS might not be able to deliver the necessary drivers in a suitable timescale, extra incentives might be needed (e.g. tax instruments, depreciation rules, EIB credits, etc.).

Moreover, the stakeholders concerned with the development of a CO_2 transport network will have a large influence in this development. Therefore, next to a quantitative analysis, it is important to provide an analysis of these factors, to identify pitfalls and bottlenecks in the realisation of the desired CO_2 transport.

In this report stakeholder requirements concerning the development of a large-scale CO_2 transport network are presented. Special attention is paid to the transition of one type of CCS project or infrastructure layout to more complex networks. These transitions are key to understanding the changes in stakeholder interests and requirements.

Section 2 discusses several network layouts (topologies) that can be expected to arise, either in different stages of the development of a CO_2 transport infrastructure, or side by side, in different regions in Europe. Differences are discussed between topologies, in terms of the stakeholders involved and their roles in the CCS chain.

Section 3 discusses the role and interests of stakeholders with the aim of highlighting differences in stakeholder requirements and the required knowledge to create the desired future based on economical, social, environmental and political influences.

Section 4 describes the approach to set up CCS as chosen in a number of countries. This will lead to different organisational models for the first CCS projects. When, on the longer term, cross border transport becomes reality, these organisational models will need to be linked.

Sections 5 lists a number of barriers that are to be removed as soon as possible, to ensure that stakeholders in the CCS chain will initiate activities, and also that different CCS networks can be connected.

2 TRANSPORT TOPOLOGIES

2.1 General

A network topology usually results as a mixture between the known capacity requirements for transport at a specific time and the given geographical situation and existing infrastructure. Current transport network topologies have mostly evolved in this way, for example the development of the transport network for consumer goods. Thousands of years ago production of goods and populations were locally oriented. The limited transport needs were based on this orientation. The transport infrastructure was extended when interesting goods were discovered further away and long-distance routes were added on top of the local transport infrastructure. Existing roads were extended, in size and capacity, and became part of a more national or even international transport infrastructure. The majority of the local infrastructure was used as distribution or collection network. In the evolution of both telecommunication networks and networks for natural gas similar steps can be distinguished.

This stepwise evolution of the transport infrastructure is also foreseen for the transport of CO_2. A CO_2 pipeline network may be as extensive as the current natural gas pipeline network, there will however be differences, e.g. no need for small pipelines as used for natural gas delivery in households.

In this section examples are given of the possible CO_2 transport infrastructures foreseen for Europe as well as examples of infrastructure models currently available or under discussion in several member states of the European Union.

2.2 Possible CO_2 transport topologies in Europe

CO_2 capture, transport and storage may develop from pilot and demonstration scale projects to full-size industrial projects on a regional and (inter)national scale. Based on this development as well as the evolution of existing transport infrastructures, three possible CO_2 transport topologies can be defined, which constitute natural milestones and a natural growth scenario for CCS on a European scale.

(1) In early projects infrastructure connects the capture location with one or several storage locations. In case the demand for storage capacity rises when capture capacity expands, new storage locations will be developed and the early transport infrastructure will be extended.
(2) This will lead to more complex, national transport and storage infrastructures. Over time the transport networks could coalesce into
(3) international transport networks. For countries that have limited availability of onshore and/or offshore storage capacity, trans-border transport of CO_2 may arise relatively soon. Different topologies are shown in Figure 2.1.

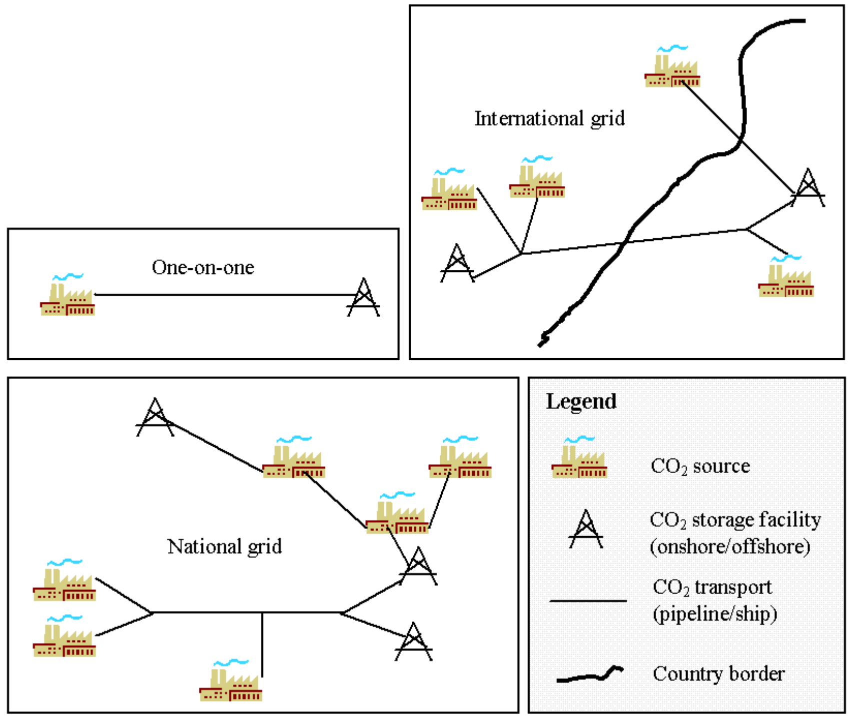

Figure 2.1 – Possible CO_2 transport network topologies.

It is also possible that large-scale CO_2 transport infrastructure is preferred from the start of CCS projects when clear and ambitious long-term reduction targets are set with a large CCS contribution [*Damen et al., 2009*]. However, due to uncertain future decisions concerning reduction targets and concomitant political instruments, it is more realistically assumed that dedicated pipelines will be developed first and a large-scale network will evolve largely based on these dedicated pipelines, i.e. routes and extensions.

An important role in these decisions will be played by the stakeholders concerned with the development of CO_2 transportation networks. Stakeholders have a direct influence on the requirements for transporting CO_2. Therefore, the most important goal is that all stakeholders work together to develop the most cost-effective CO_2 transport network based on present knowledge developments [*Coleman, 2009*]. The main stakeholders involved in the development of CO_2 transportation networks are:

- The emitter (or an industrial cluster),
- The storage operator,
- The transport (pipeline / shipping) owners
- The transport (pipeline / shipping) operators
- Other industrial players
- National/regional regulating authority,
- Civil society organisations/NGOs,
- The public.

It is essential that the public is seen as an important stakeholder in any grid development. In any development decision for CO_2 capture, transport and storage the public must be involved from an early stage on in order to induce participation in development and to identify and reduce existing concerns. Besides safety aspects, costs aspects will be important for them, while the costs for CCS will ultimately be paid for by the consumer.

The roles played by each stakeholder are different in the different topologies. In the following sections the different topologies are presented as well as the roles of each stakeholder involved.

2.2.1 One-on-one transport infrastructure

The one-on-one grids that will be the typical setup of early projects, and that will also be part of the later, more complex and extensive transport grid, will have a relatively simple organisation, with few stakeholders. They include one capture location (or a small group of collocated capture locations), one target storage location and a single transport solution (pipeline / shipping) that connects the capture location(s) and the storage location(s).

In this topology the stakeholder dynamics are limited. The requirements for the CO_2 mixture and other technical transport specifications will be based on the current capturing methods, the transport and storage requirements as well as legal requirements set by authorities in terms of safety and security. Moreover, the local legislation is expected to set the conditions for CO_2 ownership during transport and storage.

A transport company can limit the overall risks of the emitters by providing a transport service according to the independent transport model (analogous to natural gas transport market model in the Netherlands). In this situation, the transport company will own the transport infrastructure assets while the emitter is the owner of the CO_2. Costs of the transport services will have to be paid for by the emitters.

The public requires that the external safety issues of CCS is guaranteed.

Additionally, authorities can finance extra capital costs for over-dimensioning of the one-on-one infrastructure to enable cost effective future expansion of the one-on-one infrastructures to a network. Besides overall higher cost effectiveness of a network in the end phase compared to multiple one-on-one projects, the network also provides improved transport reliability.

2.2.2 National CO_2 transport network

National grids, which are projected to be the dominant type of transport networks when CCS is deployed on an industrial scale, in multiple locations within a country, can be compared to national transport grids for natural gas. Due to the expansion and/or merging of several one-on-one networks, the need for a more complex organisation arises. New types of players/stakeholders will enter the CCS field.

In this stage of the CO_2 transport network development the group of stakeholders differs considerably from the one-on-one networks. There is more than one of each type of stakeholders involved. As a result of this different cooperation model, i.e. several stakeholders per stakeholder type, two new types of industrial stakeholders could possibly arise:

- The regional distribution network operator could be involved in order to optimise the collection of captured CO_2 from several sources. The economical drive to optimise collection fits the company profile of current regional natural gas or electricity distribution network operators; the skills and economic models to do this are all in place, the local network operator has a strong relation with the local environment and is sensitive to local social preferences.
- The national or regional gas transportation company could be involved by interconnecting local CO_2 distribution networks to a more long-distance transportation grid, based on their knowledge of the transport and distribution of natural gas.

Regulations and standards are needed in order to force an optimisation of the technical specifications of CO_2 transport and the interconnectivity of different existing grids..

Ownership and responsibility for transported and stored CO_2 will remain an issue, especially while many stakeholders are involved. A market model that mirrors the natural gas market model in the Netherlands could be an example for the roles and responsibilities of all stakeholders involved in a transportation network.

Moreover, the regulatory authority will in the end have the tasks of facilitating open access to infrastructure, regulating natural monopolies and ensuring safe and at the same time lowest-cost solutions. Therefore national regulating authorities have a broader role than the regulating authority in the one-on-one case, because the regulator has to guard that every project sooner or later can be integrated in the overall architecture, that individual project solutions are compatible and that the transport tariffs are fair.

The public as a stakeholder requires safety throughout the CCS chain, as well as lowest cost solutions.

Due to the many different stakeholders involved, the investment decision for CCS might be a shared investment decision, depending on how the owner and user regimes are regulated.

While in a one-on-one network the bookkeeping for emission credits is relatively simple, this becomes a complicated task in a network with multiple sources and multiple sinks. Once CO_2 is pumped into the network, it can not be traced back to its source. Emissions (leakages) from the transport system or from the storage sites must somehow be divided over the active sources of CO_2. This requires central registration of captured and stored volumes.

2.2.3 International CO_2 transport network

After some time into the development of CCS in Europe, cross-border transport will take place. Although this does not necessarily imply the connection of national transport grids of the type described in the previous section (some European countries without geological storage will need to transport captured CO_2 to neighbouring countries immediately after the start of capture), in due time, during the development of European CCS national grids these may need to be connected. This will add another layer of complexity to CO_2 transport.

The stakeholder model for international transport and storage of CO_2 is similar to that of a national CCS infrastructure, including a European regulating authority. The stakeholder dynamics now also include companies emitting in multiple countries. This model addresses the market trends of international transport and storage.

The power of international energy players is presumably the most important factor that needs to be considered for any CCS solution, since the basic idea remains that the emitter pays. Without tying in the international dynamics of leading European energy companies, any national or regional regulation runs the risk of stimulating movement of production locations towards countries with a more favourable regulatory model. As an example: in the last few years, various European energy companies have decided to build new energy plants not in their home country but in the Netherlands, because of its economical conditions and its location and active positioning in the international grid. Differences in the CCS regulation between EU countries could lead to increased energy production growth in the countries with the easiest CCS regulation, then triggering a competition for the laxest CCS norms between countries that in the end might undermine levels of regulation necessary in order to fulfil public expectations and levels of confidence in CCS.

National CO_2 transporting grids operating under different rules and regulations might reduce interconnectivity (e.g. due to differing CO_2 composition, pipeline diameter, pressure) between the different countries, which will induce higher costs. In the national scenario, interests are represented by the national government. Now the interest of fair play between the different EU countries becomes more important and is governed by a shared responsibility for the “dark spots” on the EU CO_2 map and a shared “profit” from the achieved know-how and experience from the earlier projects.

The question about ownership and responsibility for transported and stored CO_2 becomes more complex. In current discussions and EU regulation national governments will take over some of the responsibilities concerned with long-term storage.

International capture, transport and storage within Europe should become an EU responsibility. Connecting national infrastructure on an international scale results in the need for an international (pan-European) regulatory authority.

The centralised bookkeeping of captured and stored volumes mentioned in the previous section takes on a larger complexity in international networks. The liability for transport and storage leakage must be clear for all CO_2 suppliers and storage operators in the network.

3 STAKEHOLDER REQUIREMENTS

A stakeholder analysis was conducted within the project team with an individual assessment. Using Pestle[1]-requirement overviews every company stated its individual requirements in terms of political, economical, social, technical, legal and environmental criteria. At first, these requirements proved to be largely based on the assumption of the present point-to-point infrastructure topology. As soon as more advanced topologies were introduced, the stakeholder dynamics changed significantly. New stakeholder perspectives and drivers became apparent.

The descriptions of possible transport network topologies in the previous section already described some of the roles played by the stakeholders. To advance the development of CO_2 transport infrastructure, the foreseen requirements by these stakeholders must be investigated. This has been done for the three topologies. For each, the stakeholders are listed and their requirements are discussed.

3.1 One – on – one grids scenario

Stakeholders.

- Emitter / owner capture installation.
  The capture operator requires the transport network and the storage location(s) to handle the amount of CO_2 captured, during the lifetime of the capture installation. It is likely that the capture operator requires long-term contracts with transport and storage operators to be in place. In a one-on-one grid, the transport and storage operator may be one party, or the transport may be a joint operation organised by the capture and storage owners. The contract will also cover quality standards for the CO_2. In an initial phase, there should be room for the development of a techno-economical optimization.
  As stated above, for the capture (and storage) operator to start a CCS project, economic uncertainties arising from unknown behaviour of the EU-ETS prices must be managed to an acceptable level of risk.
- Storage operator.
  The storage operator will also seek to have in place long-term contacts with the CO_2 delivering party.
  Liability issues regarding the ownership of CO_2, both during and after injection need to be resolved. This applies to the period during and after injection, but before handing over the site to the relevant authorities.
- Transport company.
  The transport company will also seek to have long-term contracts with the CO_2 delivering party to be in place. CO_2 quality monitoring is crucial for guarantee of reliable and safe CO_2 transport.
- Regulating authority.

[1] PESTLE stands for Political, Economic, Social, Technological, Legal, Environmental analysis.

The requirements from the point of view of the authorities will be that capture, transport and storage are done safely, that measurement, monitoring and verification (MMV) is in place to confirm that storage is secure and that all environmental conditions are met.

- Public.
  The requirements, from the public perspective may be limited. If the project is (partly) financed by the national government, the project must demonstrate its sustainability. In addition, the project must be conducted safely, be cost-effective and have minimum environmental impact.

3.2 National grids scenario

Stakeholders.

- Emitters.
  In addition to the requirement stated above for one-on-one networks, capture operators need to have open access to existing infrastructure, provided they meet the (national) standards on CO_2 quality and composition, again with room for techno-economical optimization.
- Storage operators.
  As the infrastructure expands and new storage locations are developed, regulations must be in place to prevent increasing costs with time from slowing down infrastructure development. When the first, low-cost options have been exhausted, developing new sites is likely to become more expensive. Measures need to be in place to offer incentives for new storage operators.
- Transport operators.
  Transport operators aim to provide transport on a fee for service arrangement, i.e., transporting the CO_2, without ownership of the CO_2 molecules but with ownership of the infrastructure assets (according to independent transport market model, mirroring the current natural gas market model in the Netherlands).
- Regulating authority.
  In the case of a larger-scale CCS infrastructure, open access for new entrants must be ensured. When merging early projects into larger-scale, national CCS networks, natural monopolies must be regulated and operated in a transparent way. This should ensure cost-effective deployment of the network and open access to the network to create a level playing field for emitters.
  In order to meet long-term emission reduction requirements, the development of CCS infrastructure must meet the increasing supply of CO_2. In case of possible increases in cost with time, due to more expensive storage sites being developed, there is a probable need for increasing levels of incentives for transport and storage operators.
- Public.
  The public will, as noted above, always require an efficient, safe and cost-effective solution. This will require central planning and coordination of the larger-scale infrastructure to drive lowest cost solutions (e.g. towards CO_2 hubs with concentrated CO_2 sources located close to storage sites).

3.3 International grids scenario

At the international level, the requirements are the same as those listed in the previous section, for national grids. The added dimension is the international one, which introduces additional levels of complexity.

Stakeholders.

- The requirements of emitters, storage operators, transport operators, and national regulating authorities are not different from those in a national network.
- Regulating authority, international.
  The aim of the international (European) authority is that the development of the CCS infrastructure keeps pace with the required capture activity, which in turn is to keep pace with the required European emission reduction targets.
- Public.
  The requirements of the public are the same as those listed in the previous section. In addition, on a Member state (MS) level, there is a requirement of fairness, from the point of view of the distribution of storage options. Those MS that have limited options for storing their CO_2 need to make use of transport infrastructure and storage capacity of neighbouring countries. Open access (guaranteed through the EU Storage Directive), connectivity across borders and fair and reasonable transport and storage fees are required. Ultimately, the CCS costs will be paid by the consumer via the electricity price.

4 NATIONAL MODELS FOR CCS

Important pilot or demonstration projects for CCS are ongoing on a national scale and serve as examples for the stakeholder roles and interests to be explored. These evolving “national systems” are laying the foundations now. These may (or at least should) be at the basis of a “trans-national” system may arise in the future. This chapter presents an overview of the current transport models in Norway, UK, Germany, France and the Netherlands.

4.1 The Dutch model

The Dutch government has high ambitions in relation to CO_2 capture, transport and storage. In the Netherlands two large-scale CO_2 capture, transport and storage projects are anticipated in the year 2015. For this development and in order to stimulate investments the Dutch government is currently identifying the preconditions. The organisation of the CO_2 infrastructure and storage is one of the main conditions that are being discussed.

In June 2009 the Dutch government issued a policy letter [*MEA, 2009*], explaining its view on this topic. The Dutch government recognises that it needs to build a CO_2 transport and storage strategy for the long(er) term in order to stimulate a well-timed realisation of the transport and storage facilities as well as the most optimal use of the subsurface. Therefore, two public bodies (Gasunie and EBN) have been asked to deliver the fundamentals, e.g. initial planning of available gas fields for large-scale CO_2 storage, for long-term CO_2 transport, as well as the distribution of tasks and possible roles of the different stakeholders. These two bodies also have the opportunity to initiate (Gasunie) and direct (EBN) the development and exploitation of (parts of) the transport and storage network. Moreover, the government states in its policy letter that private stakeholders should also have the opportunity to contribute.

Based on the building blocks concerning the possible long-term transport and storage strategy defined by Gasunie and EBN the Dutch government will define the conditions needed for maintaining the potential storage locations and the present infrastructure. The defined conditions will be recommended in the proposal to amend the Mijnbouw-wet, the Dutch law concerned with mining operations. This recommendation was proposed in the second half of 2010 [*EBN – Gasunie, 2010*].

The Dutch government also takes into account the possibility that in the long term large amounts of CO_2 will be transported and stored. The option is to over-dimension the infrastructure in the demonstration phase in relation to smaller amounts of CO_2 transport and storage that will be transported in that phase. Public and private companies will not be prepared to over-dimension the transport infrastructure due to higher costs, which is the reason why the government in that case will provide additional financing. EBN and Gasunie were also assigned to explore this possible business case.

The building blocks for the long-term strategy for CO_2 transport and storage will be delivered in the short term by EBN and Gasunie. Moreover, the Dutch government will, in the first half of 2010, decide regarding the additional funding for construction of the transport and storage infrastructure.

Current initiatives

Currently, there are several initiatives in the Netherlands. One of the important regions developing CCS in the Netherlands is the Rotterdam area. In 2007, RCI (Rotterdam Climate Initiative) began pursuing its strategy to develop and implement CCS in Rotterdam. Currently, the status of several CCS projects now indicates that CCS has entered the realisation phase (demonstration projects). Examples of these projects are mentioned here, as well as plans for further development [*RCI, 2009*]:

- The OCAP transport network delivers CO_2 from the Shell refinery in Pernis to greenhouses nearby. The network continues to grow and more CO_2 is delivered to the greenhouses. In the near future, OCAP will contract CO_2 from more than just the Shell refinery alone. Detailed studies have been conducted to extend the transport network to the North Sea to store CO_2 in a near-offshore depleted gas field.
- E.ON and Electrabel submitted a joint proposal for the European Economic Package for Recovery in July 2009. The project is designed to capture 1.2 Mt/yr of CO_2 at the new E.ON power plant and store it in depleted gas fields in the North Sea. Part of this E.ON/Electrabel project is the realisation of sufficient transport capacity to accommodate CO_2 from additional capture projects up to a transport capacity of 5 Mt annually.
- The Shell refinery is working on its project to store CO_2 from the refinery in the depleted gas fields near Barendrecht. For this project, a comprehensive environmental impact assessment was conducted and discussed with the local community. Currently, even though the Dutch government is in favour of this project, the general public is concerned about safety issues. Learning from this small-scale storage demonstration project in Barendrecht is key to the large-scale demonstration phase. This concerns largely an effective communication strategy with the general public.
- The Port of Rotterdam Authority, together with a consortium of business partners (Gaz de France Suez, EBN, TAQA, Gasunie, OCAP, Wintershall and Stedin), developed a business case for a transport and storage network based on the common carrier principle for the Port of Rotterdam area. This network might grow from 2 Mt annually in 2013 to 20 Mt by 2020.
- Anthony Veder, together with Gasunie, Gaz de France Suez and VOPAK, developed a 'CO_2 Liquid Logistics Shipping Concept'.
- Nine companies have signed Letters of Cooperation with RCI. These companies agreed to deliver data for possible capture projects. These data have been externally validated by Foster Wheeler.
- Climate Change Capital assisted RCI on the 'Deployment of a CCS network in Rotterdam', which involved a comprehensive financial analysis of the network in Rotterdam.

These projects all serve as important and useful stepping stones for future large-scale implementation of CCS.

In 2007, RCI presented its strategy for CCS by developing a CO_2 cluster approach for the Port of Rotterdam area. Various sources will be connected to multiple storage sites, depleted gas fields in the North Sea in particular. This integrated cluster approach will reduce the costs for capture, transport and storage compared to individual CCS chains. At that time (2007), a policy framework for CCS was not available and the drivers for a CCS market were expected to come primarily from the CO_2 market created by the European Emission Trading Scheme (EU-ETS) and from the application of CO_2 for enhanced gas and oil recovery.

In 2008, this cluster approach was further elaborated into a four-phase model. CCS starts with sources that emit pure CO_2 that can be used commercially in greenhouses (from 2010). During the second phase, experience will be gained with large-scale CO_2 capture demonstration projects at newly built power plants (from 2015). The CO_2 captured will be stored in the Dutch continental shelf. During the third phase newly built power plants will be expected to implement full-scale capture. During the fourth phase existing industrial sources will be retrofitted. As a result, the total amount of CO_2 captured and stored annually will increase to 20 Mt. This four phase model towards large-scale CO_2 storage in the North Sea is presented in Figure 4.1.

Figure 4.1 – CO_2 cluster approach for the Port of Rotterdam area - four-phase model [RCI. 2009].

Currently Gasunie and EBN are discussing the business model for CO_2 capture, transport and storage. It is expected that the example of the business model as shown in Figure 2.1 one source connected to one sink, could form the basis for the development of a Dutch CO_2 network. However stakeholders find it difficult to look beyond the demonstration phase and to give a prognosis for the development of a large-scale CO_2 network with multiple connected sources and sinks along with expected flows. The business model with basic requirements for the Dutch government will be based on the connection of one source with one sink, with flows and capacities based on supply of the source and the capacity and injectivity of the sink as well as economical parameters. Further development will concern an expansion of this network to more sinks when the supply of CO_2 will be larger than the capacity of the sink. As was previously mentioned, the Dutch government gave their opinion on the development of CO_2 transport and storage in 2010, including the roles of each stakeholder as well as the (financial) contribution of the government [*EBN – Gasunie, 2010*].

4.2 The Norwegian model

As discussed earlier in this document, it could be argued that the preference with respect to monopolies is that they should be avoided. However, for some systems, it is not possible to avoid monopolies, due to the magnitude of investments needed, and the magnitude of synergies and upsides with respect to CAPEX associated with developing one optimized system, compared to two or more parallel systems. Pipeline based transport systems for CO_2 may be one such case.

Potential negative effects from monopolies may be reduced or avoided in total by regulating the activities associated with such monopolies. The objective is that other users than the owner or operator of monopolistic systems should not suffer unreasonable disadvantages related to access to, and use of, relevant systems.

The model developed for transport of gas on the Norwegian Continental Shelf (NCS) is one such monopoly, where benefits for all players with need for transport of natural gas (shippers) are secured through a set of regulations and through the way the activities are organized.

The operator of the systems (Gassco) is an independent system operator (ISO) and has no commercial interests in the production and marketing of petroleum and has no equity interest in the transportation system. The pipeline elements in the pipeline infrastructure are merged into one integrated network, meaning that the shippers can relate to only one system for their total transportation need.

Having a totally neutral and independent ISO for an integrated transport infrastructure ensures enquiries from users of the system to be handled in a fair, transparent and coordinated manner.

Access to the transport infrastructure is regulated based on each shipper with a qualified need for transport. The qualification implies that each shipper must document the maturity of its gas resources, i.e. how far the development of exploitation of the gas fields or aquifers has come.

Transportation rights are then distributed between the shippers with qualified need according to specific rules. These rules take into consideration both investor rights and rights of shippers not being investors, but still having the transportation need on a transparent non-discriminatory and fair basis. Transportation costs (tariffs) for the shippers are based on a regulated rate of return for the investors/owners of the transportation systems.

Infrastructure development, such as eliminating system bottlenecks or extensions in the network, are performed based on analyses performed by the ISO as well as based on requests from the users of the system. Such development may then be financed by the original owners of the system, or by other investors. If the additional infrastructure implies use by more than one party, the ISO is normally appointed as operator also of this infrastructure, and it could also be an alternative to merge it into the overall transport infrastructure. In either case, rights related to use of the additional network parts are regulated based on the above principles.

The essential parts of this model are thus:

- A neutral and independent operator having no commercial or equity interest in the transportation system
- Qualification of the transportation needs
- Regulated access rules, ensuring access for 3rd party users
- Regulated transport tariffs
- Possibility for network extensions or modifications based on needs from users

Such a model may also be used for transportation systems for CO_2 if the nature of the systems for all practical purposes implying the need for monopolies for such services, having the following characteristics:

- Defining transportation rights based on transparent and fair rules for all users, both investors and 3rd party users. This could be based on prognoses related to captured emissions from each user.
- Appointing a neutral and independent system operator, ensuring fair treatment of both investors and 3rd party users.
- Transport tariffs based on regulated rate of return of investments and operating costs.
- Development and extensions of the CO_2 transport infrastructure based on analyses performed by the ISO and qualified needs from users.

4.3 The UK model

The UK Government is looking to set out arrangements that will facilitate the considerable investment in transport and storage that is needed and its integration into a network over time. In the Department for Energy and Climate Change's (DECC), A Framework for the Development of Clean Coal (DECC, 2009) it states that, "developers of new infrastructure will be required to consider the opportunity for joint investments prior to seeking Government approval for construction." It also plans to put in place measures that will facilitate the expansion of efficient utilisation of existing infrastructure, while ensuring the integrity of the system and the interests of the original investors.

Co-location of projects in the UK Government's Demonstration Programme (supporting between 1200-1600MW of CCS capacity) is encouraged and will be considered as part of the project assessments, however the Government has concluded that it will leave the selection of project location open to bidders who are best placed to assess costs against benefits (UK Government, 2010).

Whilst the basic legislative requirements are in place for CO_2 transport, the UK Government is yet to take a final view on the appropriate framework which will govern its economic regulation. At the demonstration stage of CCS, the Government intends to introduce a market-based regulatory model, based on that which currently governs investment in the offshore oil and gas industry (UK Government, 2010). Reforms to this regulation are proposed that will promote network integration and over sizing where it is efficient to do so.

The UK Government's approach to authorize new CO_2 pipelines and storage sites, to implement the requirements of the EU CCS directive's requirements for third party access and to ensure the efficient development of infrastructure are set out in detail in Appendix B of "Clean Coal: An Industrial Strategy for the Development of Carbon Capture and Storage Across the UK (UK Government, 2010)".

In summary, a market-based approach will be used with

- obligations on pipeline developers to invite joint ventures through open season arrangements
- obligations on pipeline owners to provide for interconnection
- obligations on pipeline owners to allow third parties to access excess capacity where it is possible to do so
- encouragement of private sector investment in additional CO_2 capacity at marginal cost
- retention of the option to move to a more regulated asset-based system.

This approach will be kept under review to ensure it is leading to timely and efficient investment in CCS infrastructure, and that it continues to be commensurate with the level of CCS deployment.

As a first step to implement its CCS strategy, the UK Government has established the Office of Carbon Capture and Storage whose aim is to

- set the strategic path for CCS technology in the near and longer term
- support security of supply by enabling fossil fuels to remain part of the UK's energy mix as a low carbon source of energy
- provide leadership in the development and deployment of CCS technology, including the delivery of four commercial scale demonstration projects
- create the policy and arrangements to stimulate private sector investment in CCS, and maximize the domestic and global opportunities for UK businesses and the economy to benefit from CCS opportunities
- work with stakeholders to remove barriers to investment and development in CCS in the UK and globally.

Although capacities for storage of CO2 are still uncertain, studies have suggested that the storage capacity within the UK continental shelf may be more than sufficient to cover UK requirements. The UK Government has indicated that there may be scope for storage services to be offered to other European Countries under commercial terms (UK Government, 2010). Further work on understanding UK storage capacities is currently being undertaken, for example, by the Energy Technologies Institute (ETI), the Scottish Executive and the North Sea Basin Task Force.

4.4 The German model

Germany has considerable storage capacities. EOR, EGR, DGF and DSF[2] all add to the capacities. Conservative recent estimates of BGR (April 2010) see a capacity of 9.3 Gt for DSF onshore alone, assuming a storage efficiency factor of 5 %.

However, from a large-scale source-sink matching procedure in the current project (*CO2Europipe, 2010*) it becomes evident that it is not just the capacity of the suitable sinks that will define the likelihood of CCS projects being realized. In Germany, factors affecting the requirements for a large-scale CO_2 transport network include the timing of storage capacity availability, the injection capacity per year of the storage sites, as well as the economic and social feasibility of the sites.

So far, it has been stated by German politics that they plan to have a national CCS law in place by the end of 2010. In this law, rights and duties of CCS shareholders and rights of stakeholders like public and authorities shall be defined. Until that time, it is unknown whether the German CCS law will incorporate the spirit of "making CCS possible" or if the outcome will be the opposite. A draft law that has been published by the two concerned Ministries (Environment and Economy) in September 2010 suggests allowing only a small number of demonstration projects with a limited amount of CO_2

[2] EOR: enhanced oil recovery, through injection of CO_2 in oil fields; EGR: enhanced gas recovery, through CO_2 injection in gas fields; DGF: depleted gas fields; DSF: deep saline formations (i.e., non-hydrocarbon bearing formations).

to be stored per year and to reconsider the law in 2017. This draft, however, has been in wide discussion with stakeholders during the last months and is likely to incorporate further changes once it is brought forward to the cabinet. It is still unclear when the draft will be introduced to the cabinet and how fast the process will move on from there.

Most advanced by now is the Vattenfall CCS project in Brandenburg, consisting of a 300 MW capture plant and two potential storage sites for the CO_2 that have been identified. The process of permitting Vattenfall to explore potential storage sites is ongoing. So far there is no detailed transport concept. In May 2010, the public bidding process has been started for a contract to perform the land use planning for a CO_2 pipeline in Brandenburg. This transport network could be in place by 2015/16.

The political and legal framework of a transport network in Germany will most likely be arranged in the above mentioned German CCS law. It seems that transport by ship, train or truck can be carried out by privately owned companies. There are however ideas to conduct pipeline transport partly in public ownership or in public-private partnerships. Ministries consider installing independent system operators (ISO), who might belong to consortia which are at least to 50 % owned by public bodies.

A model for ISO discussed recently includes these aspects:

- The operator of the transport network shall be neutral and independent. Best option is a (partially) public ownership, to guarantee absence of commercial interests.
- Qualification of the needs of transportation.
- Regulated transport tariffs.
- Regulated access rules, ensuring access for 3rd party users.
- Possibility for network extensions or modifications based on customers needs.

The precise arrangements of regulations for CO_2 transport networks will be defined in a German CCS law.

4.5 The French model

Reduction in Greenhouse gas (GHG) emissions in France is driven by two ambitious and independent (yet consistent) goals:

- Full adoption of the 20-20-20 European Union vision for 2020
- "Factor 4" strategy for a division by 4 of France GHG emissions by 2050 (28 million tons per year of carbon, vs. current emissions of 140 Mt/y C).

The "factor 4" strategy was announced in 2003 by the Prime Minister and set into law in 2005, and is driven by a the need for worldwide per-capita carbon emissions to stabilize at 0.6 t/y C in 40 years (and that in turn to limit CO_2 atmospheric concentrations at 450 ppm.

Given the low incidence of fossil fuel electricity generation in France (less than 10%, with 78% coming from nuclear power plants), CCS will mostly be applied to industrial sources and should contribute between 33% and 54% of the reduction in 2050.

The main strategic French goal in the CCS sector is to support development and deployment of French technology and expertise in the capture, transportation and storage of CO_2 – both at a European and global scale and by private companies as well as public research institutes.

Currently (June 2010) a roadmap for CCS development in France is under preparation at ministerial level, with support from the "Club CO_2" (an organization grouping private and public players in the CCS domain). The document will detail national CCS goals, scenarios and suggest a number or technical and regulatory actions to help meet goals for 2020 and 2050.
France has two potential (overlying) storage formations on its territory, the Dogger and Triassic aquifers, both carbonatic. The formations in the Paris basin (the North-East of the country) could potentially play a role as a European storage hub.
However, it must be stressed that the only ongoing pilot project in France (the Total Rousse field) uses a small depleted gas field in the Pyrenees. Depleting (Depleted?) gas fields (as well as offshore storage) may only contribute marginally to French storage potential.

Two demonstration projects are planned in France:

- Florange, which should be one of the European demonstrators, and will capture 1.5 Mt/y CO_2 from a steel mill;
- France Nord, which will start by investigating the feasibility of storage and will be partly financed by the French government (through the research demonstration fund).

Both demonstrators will need to assess the technical and social feasibility of storing in the Paris Basin (below a rich and densely populated part of France), while at the same time deploying less risky capture technologies. In light of the opposition Total had to face with the Rousse project and the geological uncertainty of the storage horizons themselves, it is not excluded that the captured CO_2 will need to be exported, to the Netherlands or the UK for storage in the North Sea.

More specifically, whereas the development and deployment of CCS is considered a strategic priority, large-scale, commercial storage of CO_2 within France is still being debated.

A consistent strategic approach to the CCS market (regulation, financing, structure) still needs to take shape, but from early discussions preference seems to go to "natural monopolies" for transport and storage, possibly in the hands of state-owned operators or consortia. It is sometimes feared that relying on market forces and private companies will not deliver economies of scale, learning-curve cost reductions and the longer-term financing required by large-scale industrial projects.

Given that there is some pressure for a public-body (or a public-private monopoly consortium) solution for transport and storage, but on the other hand that it is unlikely that there will be storage in France, the real question to be raised is: if storage doesn't develop in France, and CO_2 must be piped abroad, who will manage the French leg of the pipeline? One of the possibilities would be that private pipeline operator(s), possibly with a national concession, will handle the connection.

5 BARRIERS TO CCS DEPLOYMENT

5.1 Technical barriers to capture

Most of the components of the three main types of power plant configurations for capture – post-combustion, pre-combustion and oxy-combustion – can be considered proven to the extent that no completely new knowledge is required. However, the cost of commercialization (i.e. improving efficiency, reducing costs, scaling-up, integrating process designs and optimising systems integration) should not be underestimated.

Although cost-estimates vary, a commercial size demonstration coal-fired power plant with an installed CO_2 capture costs some €2500/kW, compared to an equivalent conventional plant at €1000/kW for coal and less for Natural Gas Combined Cycle (NGCC) power plants with 400 - 500 MWe capacity. For a demonstration plant, this difference represents a total extra construction cost of €250 - 750 million. Thus the scale of investment alone constitutes a barrier. Furthermore, plant efficiency is reduced by about 10 percentile resulting in a major increase in operating expenses throughout plant life.

For the emerging technologies, however, the situation is different. Most of these depend on supporting developments such as new gas separation technologies.

A structured analysis has been conducted of newer thermodynamic processes for both oxy-combustion and pre-combustion CO_2 capture in which a large number of different designs were analysed.

In ENCAP (FP6), seventeen of these processes were selected for further analysis, all with promising thermal performance. Of these, all but two contained key components considered to have "red light" properties, meaning "completely new development needed or considered a very high cost component".

This implies that there are major technical obstacles to finding processes more suitable than the three currently well-known technologies. If these obstacles are to be overcome, research has to start now, since it can take up to 20 years to develop and commercialise completely new core components for the power generation industry. Already the selection process has been started to identify those processes which have a reasonable chance of developing.

5.2 Infrastructural barriers

Concerning the infrastructure necessary for plants and capture technology, barriers are related to the new plants' supply and size, but also to a kind of institutional infrastructure.

A future system of power plants and storage sites must be considered as one where there are multiple producers CO_2. This is fed to a main trunkline pipeline system which then distributes the CO_2 to multiple storage sites. It must be assumed that there will be industries handling transport and underground storage, which provide services to CO_2 producers. Thus the new technologies for CCS need - in addition to traditional plant requirements of fuel, water supply and electricity - connection to a CO_2 transport system and space for the extra equipment.

Another barrier, yet to be clarified, relates to the CO_2 specifications. There is a trade-off between the purity of the CO_2 the process produces and the cost of the technology required. What constitutes reasonable CO_2 quality will probably be agreed between the producers, transporters and storage owners during the technology development period.

However it is important that the regulators oversee this process so that some stakeholders do not concur on too stringent requirements that might unnecessarily burden a specific process design with higher costs compared to another process.

Finally, the potentially increasing volume of CO_2 being transported each year - and the necessity for expansion to an ever larger infrastructure - may constitute another barrier. Material, rights of way, operations and management will all play a part.

5.3 Regulatory barriers

As with all current plants, a structured and systematic process for approval must be developed. This already exists, with standards for other types of emissions, safety, handling of substances etc, which must now be adapted to include several new constituents. The barrier is therefore the drive of the authorities – from the highest international level, down to local communities – for which training and education is required.

5.4 Maximising international collaboration

From the R&D initiatives that have already taken place, it is clear that many technical aspects of large-scale CO_2 storage are suitable for international co-operation (although issues such as intellectual property rights on CO_2 capture are more complex).

We should therefore include opportunities for international collaborative projects within the EU research frameworks. This would not only ensure continuity in the collaboration already initiated (e.g. with China), but pave the way for further co-operation with other major industrial countries, as well as emerging economies. The EU is already a member of the global Carbon Sequestration Leadership Forum (CLSF).

5.5 Cost aspects

5.5.1 Incentives for the early movers

One thing is clear: without major capital investment, new generation technologies like CCS will never take off. Indeed, the economic aspects of technology development management should not be underestimated: *without clarity on the financial risks and rewards - including a stable regulatory framework - investors will not have the long-term certainty they need to commit their funds.*

Short-term incentives

Certainly, at current trading levels (\$10-15/tCO_2, price level April 2010), it does not look like emissions trading will provide sufficient financial support even to cover the costs for CCS at this stage. The CCS value chain therefore needs to be kick-started with the implementation of specific incentives, either at Member State or EU level. They must be:

- Clearly articulated in State Aid Guidelines on CCS implementation, whilst being elaborated and deployed at Member State Level. This should include funding by governments of transport infrastructure, i.e. pipelines.
- Compatible with the EU ETS in its current/future forms and not significantly distort the carbon trading market, or its ability to minimise CO_2 reduction costs will be undermined.

Long-term incentives

However, long-term incentives are also essential in order to create a stable environment for investors who may be deterred by fears that they could be changed, e.g. as a result of political changes. They also need to be of sufficient value to overcome any vagaries in the greenhouse gas (GHG) market.

It is also recommended to establish a *Clean Power Generation Act for Europe* which stipulates that a certain percentage of energy production should be clean energy – either by CCS, nuclear or renewables. This should be in line with the RES Directive.

Making the most of the EU ETS

Emission trading is a powerful tool for reducing GHG emissions at the lowest cost to society and CCS technology is a key element in fulfilling this objective. Indeed, the avoidance of emissions to the atmosphere through long-term geological storage should be treated as equivalent to emissions reduction at the source, receiving similar incentive treatment as renewable energy sources and energy efficiency programmes.

It is therefore essential that CO_2 used for CCS projects is fully accredited under EU ETS, as well as the Clean Development Mechanism (CDM).

This can be achieved by adopting a methodical approach to monitoring and reporting which would put CCS projects on a par with natural gas storage, EOR and deep underground disposal of acid gas. It also means taking a mass balance approach to calculating fugitive emissions across the CO_2 capture, transport and injection chain. However, longer-term regulations must to be in place to govern the EU ETS beyond 2012.

Another incentive scheme is *volume allowances*. Here, petroleum companies using CO_2 for EOR or EGR receive tax reduction on the additional oil/gas extracted in order to compensate for the enormous capital expenditure and risks these tertiary projects involve – be they onshore or offshore. It is estimated that a volume allowance of approximately $5.00 per barrel could entice an oil and gas company to invest in such a proposition.

Implementation of the CO_2 infrastructure can also be facilitated by changing the taxation system, e.g. by introducing a carbon tax or passing on the cost of CCS to electricity consumers. In some cases, there could also be publicly owned subsidiaries for investing in Zero Emission Power plants, although these might be time limited. ‘Carbon contract’ incentive schemes are another option, being readily compatible with the EU ETS.

One main driver in any NPV calculation for large projects is interest rate. To build an IGCC plant with CCS could in the long run even be cheaper than current plants, except for the high initial investment and long depreciation intervals. If for such projects a low long-term interest rate could be offered (e.g. via EIB, etc.), those projects would be much more profitable, break-even would happen at a much lower carbon-price. The phase-out of old power plants would happen much more quickly.

Another taxpayer-friendly lever that could be very effective as an incentive might be a modification of depreciation rules.

5.5.2 Costs for CO_2 transport network development

The costs concerned with CO_2 transport depend on methods (pipeline, ship, trucks), amount of CO_2 transported and distances (large distance means higher costs). Costs of (using) the infrastructure and the storage of CO_2 in geological reservoirs will have to be paid for by the emitters. As the current plan to finance CCS relies on the mechanism of EU ETS the CO_2 price of these emission allowances or credits is an important driver. Investment decisions of emitters will be based on the revenues from emission allowances versus the costs for capture, transport and storage of CO_2. The CO_2 price, and therefore costs or revenues, cannot be controlled or influenced by the emitter. This induces uncertainty on the financial viability of planned CCS projects. At present, uncertainty about the future emission credits costs is a major cause for delay in the development of CCS plans. If the ETS is to be the only mechanism for CCS development, additional measures need to be put in place to alleviate the risk arising from EUA price levels becoming too low to allow commercial deployment of CCS.

As one possible outcome could be that later CCS project might face higher costs, this suggests that mechanisms need to be put in place to prevent cost-escalation once the 'low hanging fruit' has been picked. Moreover, while costs in general may differ substantially between projects, e.g. due to differing distances, a price balancing regime (or common tariff) may be appropriate to induce fairness by the regulator. On the other hand there is a risk that there are too much regulations, adding up a number of marginal effects that complicate investment decisions.

While such reasoning can be applied on a regional or national scale, it also applies on an international scale. Any map of CO_2 emission and CO_2 storage options [*Neele et al., 2010*] demonstrates their uneven distribution over Europe. Current plans for CCS projects are mainly located in north-west Europe, where sources are relatively close to storage locations. Conditions are less favourable in other parts of Europe and distances between CO_2 sources and sinks in e.g. the North Sea Basin will result in huge costs. Again, to prevent such factors from impeding the development of CCS throughout Europe, measures must be taken to support EU regions that have a less favourable setting for CCS.

Another aspect to consider is the translation of CCS costs into the price of the emitter's products. Several European countries have strong coal-based electricity production. CCS for these production sites is of eminent importance to achieve the overall emission reduction targets for the EU. When these countries need to build up CCS nationally, they would need to raise their product costs substantially, transferring the economic burden onto their customers, thus resulting in a competitive disadvantage. The cheapest, best fitting storage locations will already have been reserved.

Of course this factor could be compensated for by increased experience and scale-effects. Especially a larger-scale network only makes sense when there are clear economic advantages.

If a “cost-penalty” for later CCS storage solutions persists, it would need to be compensated for by EU wide subsidy schemes. Otherwise companies would gradually move their facilities to those countries with the most efficient CO_2 regime.

It is therefore important to avoid the situation where multiple countries reinvent the wheel, resulting in differences in efficiency, and with still a substantial risk that scalability issues will arise later that require cross-border interconnection anyway.

5.5.3 Return on Investment

Science, government and industry need to work together to avoid unnecessary costs, because in the end, all costs of large-scale CCS in the EU will be a societal cost paid for by the European citizens and its industry.

Current economic and regulatory models render the emitters responsible for the realisation of CCS, albeit supported by initial subsidy from each country or the EU.

The limited stakeholder setup of point-to-point projects will result in sub-optimisation, limited to the small group of directly involved stakeholders. It will not result in the necessary standardization, the necessary overall planning and the future re-usability needed to become an efficient pan-European CCS topology.

The Return of Investment (ROI) of point-to-point solutions will prove to be more attractive when calculated for the short term, but will prevent addressing the longer term and wider-scale challenges. The results will address “low hanging fruit”. The investments from emitters in this partial success scenario will lead to extra resistance from these same emitters, when in a later stage the broader community challenge becomes visible.

The ROI calculations for a larger-scale, commonly usable CO_2 collection and transport infrastructure need to be considered, in order to avoid an increased societal cost in the future. Certainly, the investments in this type of larger scale, commonly usable CO_2 infrastructure can not be made by the industry on its own. It needs overall European public planning and public financial support. Besides that, a strong CO_2 tax incentive (like EU-ETS) is necessary for economic viable business cases.

5.5.4 The costs of interconnection

The cost of interconnection of separate, independently optimised CCS infrastructures needs to be investigated. To what extend these topologies will need to be implemented will differ per case, and will change over time.

Past examples of transport infrastructures provide good learning material. In order for gas networks to interconnect, both the gas itself and the transport technology must be aligned. Otherwise, an intelligent interface is needed to bridge these gaps. For CCS the case is different, since knowledge is still rapidly growing. Various countries and even various regions within countries now have knowledgeable teams working on the standardization of CCS. Section 2.1 explains the major points of discussion and the differences of opinion. Networks based on different CO_2 phases, on substantially different pressure standards and other impurity values will be difficult to merge later. The upgrading of pipeline systems is also problematic. Interfaces between different network architectures will create their own problems that cannot be solved without limiting the functionality of the separate networks.

In that context it is important to emphasize the potential of transport by ship. Ship based transport is attractive, when the planning timeline is shorter, since it is more flexible than pipeline transportation. Investments can easily be reused. Hence, ship transport might be an option in an intermediate phase, while developing pipeline systems.

Interconnection of incompatible systems can only be realised by redesigning and often rebuilding. Next to the material costs and construction costs related to rebuilding, the costs of disruption of the involved local communities, economies and environment will also increase, as with growing density of the usage of public space these costs may increase significantly over time.

It is therefore important to consider more than one project when designing elements of a CCS transport infrastructure. Projected developments in the local transport requirements for both space (CO_2 delivered from other areas, possible for further transport along the route being designed) and time (future increases in CO_2 capture capacity in the area) should be considered.

5.6 Creating a level playing field

The present legislative system was not written with CCS in mind and is currently being revised, as any successful implementation will depend on consistent and long-term laws and treaties. In fact, an ongoing movement has put in place a legal framework for permitting CCS as soon as possible, initiated by the EC itself (via a DG Environment taskforce). The London Convention[3] and OSPAR[4] have already accepted a proposal that sub-sea CO_2 storage should be permitted.

Such permitting creates a level playing field for all industrial actors, with a common legislative framework wherever possible. Indeed, the larger the system, the more stable it will be and the higher the chances are it will extend worldwide. The framework must also have a long lifetime - for at least an investment period (around 30 years). The EU and member countries therefore have a key role to play in:

[3] The London Convention sets out rules to prevent marine pollution by the dumping of waste worldwide and has over 77 member countries.
[4] OSPAR was set up in 1992 to prevent and eliminate pollution in the marine environment of the North-East Atlantic and entered into force in 1998. Its members include Denmark, the EC Commission, France, Germany, the Netherlands, Norway, Spain and the UK.

- Aligning the (their?) legislative frameworks in order to enable CO_2 capture technologies to develop in Europe,
- Creating a coordinated action, so that research programmes at EU level are coordinated with national programmes,
- Acting on behalf of all participants in Europe to create a level playing field internationally and contribute to create a market worldwide.

Many international, regional and EU legal frameworks are relevant to zero emission power activities and many definitions and prohibitions within these frameworks are sufficiently broad to encompass and regulate various power generation, CO_2 capture and geological storage activities. However, only a few (UNFCCC, Kyoto Protocol and the EU's Monitoring and Reporting Guidelines) explicitly address zero emission power activities and either include or exclude them from their scope.

Clear and appropriate inclusion in, or exclusion from, legal frameworks will increase transparency, provide regulatory certainty and facilitate zero emission power activities and methodologies that are agreed to be consistent with international, regional and EU frameworks.

5.7 Crossing the borders

Laws and treaties regulating the economics involved when CO_2 crosses country borders must be consistent and compatible within all countries taking part in a CO_2 infrastructure. Each country therefore needs to implement laws and regulations for CO_2 that are acceptable and compatible with other countries involved in the infrastructure. These laws and regulations have to address all legal issues related to CO_2 capture, transport and storage, including the potential for single or multiple CO_2 sources to be transported through one or more countries to the final storage site.

5.8 Contract considerations

Commercial contracts will need to be developed which address the concerns of all stakeholders, as CO_2 source locations, transport routes and CO_2 storage location all have different economic needs. Alignment is key and contracts will give both parties the confidence to build their share of the infrastructure in parallel, so that (for example) when CO_2 needs to be stored, the site will be operational; or the EOR/EGR project will be expecting to receive it. The independent market model is a market model that is able to facilitate this alignment.

Who is liable?

Liability is a key issue that must be addressed to clarify the ownership of CO_2 during transport and storage – who is responsible, industry or government? It will also have a significant impact on our ability to reassure the public. With rigorous risk monitoring systems, CO_2 leakage should be identified and immediately corrected. However, in the unlikely event of damage caused by leakage, a proper liability scheme must be in place, based on the principles of the Environmental Liability Directive.

CCS liability issues are actually very similar to those of other industrial activities and gases. Indeed, CO_2 capture plants and transport already have well-established directives and national legal frameworks; whilst storage facilities can adapt current mining and petroleum laws, whereby the state assumes liability after a law- regulated abandonment process. The use of insurance or related financial mechanisms should also be explored, including the possibility for specific funds - financed by storage site operators - to cover liability of the storage site, during both operation and after its transfer to the state.

5.9 Public support

Gaining public – and political – support is vital if CCS is to receive the funding, incentives and State Aid guidelines it now urgently requires. Understanding public concerns and attitudes towards climate change and CCS is therefore key to its successful implementation. It is essential that high-quality research continues the work of social studies regarding the public perception of CCS.

How do experts, stakeholders and the public perceive CCS?
It means understanding the:

- Perception of risk from CCS, with reference to previous research on the social perception of technologies and their contribution to climate change
- Perceived benefits of the technology
- Existing level of knowledge
- Role of media in framing public perceptions
- Differences between public, stakeholder and expert perceptions. Understanding those of experts, politicians, media and NGOs may offer a broader understanding of the social perception of CCS. Particular attention should be paid to possible regulator(s), as their role it is not yet clearly defined.
- Differences in perception across European countries using a high quality measurement tool and time series analysis.
- Reactions to the location of onshore reservoirs. In many countries, the best CO_2 storage sites are onshore, which could generate concerns from local

communities. (Here, the attitude toward CCS of local citizens may differ from that of the general public.)

- Potential for CCS within the broader debate over energy and climate change policy at national and EU levels, particularly with respect to nuclear power and renewable energy.
- How opinion-leaders use information on public attitudes to shape their views and policies.
- CCS will also need to be attractive to major emerging economies, such as China and India, who will see much of the growth in greenhouse gas emissions over the coming century. It is therefore also important to understand how it might be perceived in these markets (as the case of Monsanto's efforts to introduce GMOs in India illustrates).

How can we build public trust?

Research needs to be undertaken to find out how best we can build trust, including understanding:

- The level of trust in institutions, environmental organisations, industry and the media, as well as amongst regulators and scientists, as reliable sources of information.
- The role of political debate and political representation. In the end it will always be a democratic decision process that will have to decide to adopt large-scale CCS or not to do it. The CCS Storage Directive actually provides for this option in its formulation.
- How successful organisations build trust - and how it can be lost
- The relationship between trustworthy sources and the formation of public opinions.
- How public support can be built up through dialogue, joint efforts and partnerships - and what forms of public engagement erode support.

Developing a risk communication strategy

Developing a risk communication strategy is key to stimulating a public debate about CCS, but is a delicate task, as emotional and ethical (and irrational!) elements are involved. Research questions include:

- How important is the background and reputation of the communicator?
- What tools have been used successfully to convey complex information?
- What mental models develop around CCS and how do views of climate change and other technologies influence them?

Adapting in-depth research tools

In order to gain a deeper understanding of the public perception of CCS, we need to research/develop quantitative and qualitative methodologies, including participatory approaches, by:

- Understanding how pseudo-opinions can be distinguished from more robust representations
- Distinguishing between the reliability of alternative survey instruments (open-ended versus closed-form questionnaires, internet, phone and face-to-face interviews)
- Investigating how framing can affect the way that information is presented and processed
- Drawing extensively from work being done in the study of public attitudes towards problems of science and technology, environment and risk.

5.10 High-level requirements

At a higher level, there are several barriers to deployment which must be overcome for CCS to fulfil its true potential. First and foremost, of course, we need the *recognition* of *all* international treaties and governments that CCS is both an approved and desirable means of reducing CO_2 emissions (Although some countries may not wish storage on their territory, as the Storage Directive acknowledges.) With so many different parties in the value chain, *coordination* is also essential, not only for establishing legal and regulatory policies, but benefiting from economies of scale.

One major prerequisite for reaching our target is that both the supplier industry for plants and components, and power generators are convinced that they have *a market* - especially in Europe, but also worldwide. This means that industrial-scale use of fossil energies for zero emission power generation will also have to be possible and desirable for a period of 40–50 years after 2020.

The commercial availability of *CO_2 storage facilities* is also essential. Should approval not be given for CCS, only efficiency-enhancement measures would be available. Increasing the efficiency of the energy conversion process is therefore always beneficial.

Another precondition is the continued availability of *expert knowledge* in universities and institutes, as well as industry. This requires recognition by the public - and by young people in particular - that CCS technology complements, not replaces, renewable energy, with fossil fuels a necessary part of the energy mix for a long time to come. This is key to attracting R&D funding and expertise.

To this end, there must be dedicated training and education for the next generation of professionals to continue the work (whether it is with industrial companies or regulators). Geo-science and engineering disciplines are currently dominant within CO_2 storage and these will need to be supplemented by a broader range of other professionals within biology, social sciences, communications, legal and financial issues etc. This means universities, in co-operation with research institutes and industry, (should?) offer the necessary range of competencies and ensure that funds are available. Developing existing and new CO_2 networks in Europe is also important (e.g. CO_2GeoNet, CO_2Net, CO_2Net East).

But all these issues can be resolved. There then remains one essential precondition to the development of CCS – *Government incentives* to make the projects economic. Without such incentives, even if today Zero Emission Power plants are built, it will be uneconomic to switch them on.

6 CONCLUSION

As previous transport networks evolved due to changing supply, demand and distances, current developing transport networks can built on this knowledge. In case of the current stage of the development of a CO_2 transport infrastructure the possibility is available to use previous knowledge to create an efficient and cost-effective infrastructure and take specific circumstances into account.

6.1 Transport topologies

It is expected that the CO_2 transport infrastructure, i.e. pipeline and/or ship transport, will start with a small-scale one-on-one infrastructure developing into a national transport network, and national networks joining into international transport networks. Specifically important in the development of a CO_2 transport infrastructure is the transition from one infrastructure topology to more complex networks. Size and complexity in these transitions increase significantly, due to increasing stakeholders per stakeholder type. i.e. from one or several stakeholders types towards multiple national and/or international stakeholder types, changing requirements considerably. Besides the gradual change of stakeholder interests and requirements during this transition, also previous choices made during the development will have an important effect on later stages of the development.

6.2 Stakeholders requirements

Current opinions are mainly based on development of a first small-scale CO_2 infrastructure while designing a large-scale CO_2 transport network is not straightforward. It appears that in a small-scale infrastructure network especially, long-term contracts seem important between emitter, transport and storage operators, containing agreements on CO_2 quality standards and liability issues. The involvement of national government and public is limited in the on-on one topology. National authorities and the public encourage safety requirements and economical aspects.

In national grid scenarios, requirements such as open access to existing infrastructure, regulations to prevent increasing costs when the first, low costs projects have been exhausted and to regulate monopolies, liability issues, central planning and coordination become more important.

The international dimension adds cross-border requirements, e.g. interconnectivity with respect to composition (pressure, temperature, percentage CO_2), international safety regulations, liability issues, etc.

6.3 National models for CCS

The development of a CO_2 transport network is largely compared with the evolvement of the national gas market. Still, differences in planning and design of the future CO_2 transport infrastructure in different countries of the EU are already visible based on current developments. Based on the review of infrastructural models in the Netherlands, Norway, United Kingdom, France and Germany differences can be distinguished. In case of large-scale international transport these different models will have to be interconnected. The main differences can be found in the regulatory requirements as well as the composition of the transported gas. In order to reduce interconnectivity problems the development of national CO_2 transport networks can (and should) take into account future international developments of infrastructure networks at an early stage.

6.4 International issues

Industry will invest in the projects, mainly dependent on a positive business case. Without a common, shared CO_2 transport infrastructure, the differences between various regions of the EU may lead to an imbalance, projects in regions with an attractive CCS regime on one hand and no projects in regions with less attractive regulation on the other hand. The goal of an EU-wide policy should be that projects are realised where they are most needed and effective.
Without a common, shared CO_2 transport and storage infrastructure, there is also a substantial risk that projects which start earlier will exclusively allocate resources (storage locations, pipeline routes etc..) than can not be used by other projects later, forcing the later projects into much more expensive solutions. This would not contribute to the overall EU objective to reach the target CO_2 emission reduction against the lowest cost. An infrastructure built to enable a common shared CO_2 transport and storage infrastructure, enables optimal reuse of this infrastructure also by the projects that start later and will therefore contribute to reach the EU objective.

6.5 Barriers to CCS deployment

Technical, economical, social, environmental and political barriers need to be removed in order for the implementation process to take place. Many of these barriers are of influence on the early phases of the CO_2 transport network. Capture technology currently needs improved efficiency, reduced costs, scaling-up, an integrated process design and optimized systems integration. New technologies for both oxy-combustion and pre-combustion CO_2 capture are currently researched in order to find processes more suitable than current possibilities. However, technology development can take up to 20 years to develop and commercialize and therefore the development has to start as soon as possible.

In the early phases it is also very important to raise the awareness of authorities, from international to local governments, by means of training and education. Furthermore, the current investment climate is not favourable for CCS projects. In order to stimulate early movers' clarity on the financial risks and rewards – including a stable regulatory framework – is needed to provide investors the long-term certainty they need to commit their funds.

A level playing field for all industrial partners induces investments. Therefore, legal frameworks need to increase transparency, provide regulatory certainty and facilitate zero emission power activities and methodologies that are agreed to be consistent with international, regional and EU frameworks strategies.

Barriers concerning large-scale deployment of CO_2 transport infrastructure relate to supply and size of new power plants, the purity of the CO_2 stream and the costs of the technology required. Besides, requirements set by national authorities also become requirements of the emitter, the transport operator and the storage operator concerning the composition of the CO_2 stream will be agreed upon. Moreover, material, rights of way, operations and management could pose barriers to the large-scale development of a CO_2 transport infrastructure. Especially when borders are crossed during CO_2 transport laws and treaties regulating the economics must be consistent and compatible with all neighbouring countries involved in CO_2 transport.

Probably the most important barrier to deployment of CCS concerns the perception of the general public. The first step in removing these barriers is understanding the perception of risk and benefits as experienced by this stakeholder as well as the existing level of knowledge and the role of media. It must be noted that a general method to reduce concerns within the public is not possible to develop. Differences in development, background and history of cultures are important parameters that can be different, even from region to region. Research to build public trust needs to be site or region specific. A risk communication strategy as well as gaining a deeper understanding of public perception of CCS by developing quantitative and qualitative methodologies, including participatory approaches, are important starting point.

6.6 Overcoming the barriers to CCS deployment

CCS needs to be recognized by all Member States as being an approved and desirable means to reduce CO_2 emissions internationally. Also, when multiple stakeholders are involved coordination is needed to reduce complexity and uncertainty and induce economies of scale. When suppliers of industry (plants, components) and power generators are convinced that a market is present, CCS projects will evolve and will result in demand for expert knowledge. The latter also induces recognition by the public. However, for CCS to be implemented, government incentives to make projects economically feasible are the most essential precondition for CCS to be deployed.

This implies that standardisation needs to be implemented from the start of the development of CCS, to avoid the costs of connecting systems with different technical solutions. On a national scale, this requires oversight by a national regulator, while on an international scale the regulating body needs to be at a European level. There is probably a need for a transition period for the development of both technology and regulatory systems.

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