Carbon Capture and Storage:

A reality check for the Netherlands

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Abbreviations

bcm	Billion cubic meters
CCS	Carbon capture and storage
CDM	Clean development mechanism
CER	Certified emission reductions
EU ETS	European emissions trading scheme
IGCC	Integrated gasification combined cycle
IOC	International oil corporation
LNG	Liquefied Natural Gas
Mt/a	Mega tonne per annum
NGT	Natural gas transport pipeline system (Noord Gas Tranport)
NOGAT	Northern offshore gas transport
PC	Pulverised coal
UGS	Underground gas storage
WGT	Natural gas transport pipeline system (West Gas Transport)

Executive Summary

A carbon capture and storage (CCS) reality check for the Netherlands has been conducted with two main goals; first, to gain an understanding of the role that CCS could play in the Netherlands; secondly, to find out what still needs to be done to move towards a large-scale CCS system by 2020. This study covers the entire CCS value chain, from the generation of CO_2 emissions to the long-term storage in the subsurface.

Physical potential
CO_2 storage in the Netherlands will have to rely on the portfolio of depleted gas fields. In a realistic case, the Dutch subsurface could technically store approximately 35-40 Mt/a of CO_2 for a period of 40 years (equal to the typical lifetime of a power station). This amount is significantly lower than what is theoretically available when looking at, for example, the accumulated volume of gas already produced from small fields. There are a number of limiting factors that can explain the difference between theoretical volumes and realistic volumes. In the first place, it will be unattractive to store CO_2 in very small fields (total volume < 1 bcm/ 2.5 Mt) or in places where the infrastructure has already been abandoned or is too remote. Furthermore, careful planning and coordination will be required to enable a match in time between the end of gas production and the start of CO_2 storage.

Taking into account the limited storage capacity, CCS could contribute to 20 to 25% of the long-term emission reduction targets set by the Dutch government, if the right economic and regulatory conditions are in place. When the storage locations in the Netherlands are filled, the CO_2 flows should be exported to storage locations abroad or CCS should be replaced by alternative reduction options. Coal-fired power stations are best qualified to be equipped with CCS. This is because of the high CO_2 emissions associated with coal, compared to gas. Nevertheless, for niche applications, some industrial processes will also offer attractive CCS opportunities. This is especially the case when the stream of CO_2 is relatively pure because the capture costs for these streams are lower than for less pure sources.

Economic potential
One of the most important factors that determines the future role of CCS is the economic viability of the technology. This viability depends on the total costs of carbon capture and storage and on the expected CO_2 price on the carbon market. Expected CCS costs vary substantially - between €30 and €120 per tonne of CO_2. CO_2 price forecasts for the period between 2013 and 2020 vary between €20 and €70 per tonne. It is therefore difficult to predict when commercial viability of CCS will be a reality. However still subject to uncertainty, it cannot be ruled out that somewhere between 2015 and 2025 CCS might become commercially attractive. This broad range does not yet provide a sufficient basis for making investment decisions. Besides that, further development of the technology will still take time and the exact outcome of this learning phase is inherently uncertain. A variety of demonstration projects with different technologies being tested can help to provide the required experience. Clear and predictable government incentives will therefore be needed to make CCS a viable technology that will be ready on time, i.e. shortly after 2020.

Role of the government
A number of issues should be addressed urgently, in order to avoid delay in the development of CCS: liability for the long-term storage of CO_2, coordination and public acceptance. After a certain period of time, the liability for safe storage should pass from the storage operator to the government. Therefore, criteria for demonstrating that secure long-term storage has been achieved should be agreed upon. As long as these terms and conditions are not clear, the liability issue will remain a hurdle for the further development of CCS. To date, it is unclear what government body could take care of the long-term storage and what such custodianship exactly implies.

Active coordination is crucial for timely availability and, where necessary, the integration of storage reservoirs, pipelines and large-scale CO_2 capture. Several dependencies between the different steps towards a full-scale CCS system exist. The government will have to take steps to pave the way for other actions. These steps include providing clarity about the liability for safe storage, setting clear

permitting procedures, providing incentives for private action with support schemes and, if needed, coordinating storage locations. Timing also depends partly on the envisaged market model. There is still time for further analysis and consideration, but not much. It would be wasteful, for example, if depleted gas fields were abandoned, while they may still have a possible role for CO_2 storage.

Public perception of CO_2 storage (especially on-shore) could become a major hurdle if not managed properly. If the licensing authority is convinced that safe storage is possible, the government should help to promote public acceptance of it.

1

1. Introduction

Energy and climate policy have become more and more interlinked and it is unlikely that the two will get separated again. There is increased awareness with nearly all stakeholders involved in energy that the current global energy system and the direction in which it is heading is unsustainable, posing a threat to society. Nevertheless, the enormous inertia of the system, due to the vast volumes and capital stock involved, makes changing it go at a snail's pace. There are several options available that can contribute to a more sustainable system, but none of these is a silver bullet and many studies show that we will most likely need all of them.[1]

One of the technologies that could potentially play an important role, and that takes the inertia and characteristics of the current energy system into account, is carbon capture and storage (CCS). Carbon capture and storage, in short, means preventing carbon from being emitted into the atmosphere by capturing it, transporting the captured CO_2 in pipelines to underground storage locations, injecting the CO_2 and storing it permanently. Estimates of the potential role of CCS as a mitigation option are typically between 15% and 33% of the achievable global CO_2 emission reductions by 2050.[2] There are several different ways of capturing CO_2: pre-combustion, post-combustion and oxyfuel. Also, many different possible storage locations exist such as depleted oil or gas fields, rock salt caverns, non-recoverable coal beds, aquifers or in the ocean.[3] For the Netherlands, the most suitable storage locations are depleted gas fields.

The Dutch government aims for accelerated development of CCS. Prime-Minister Balkenende announced in March 2007 that the Netherlands wants to become a front-runner in clean coal technologies and CO_2 storage. To make this ambition a reality, the government started a "CCS Project" in 2008 with the goal to get large-scale CCS demonstration projects running by 2015 and to have CCS commercially available by 2020.[4] In addition, the Dutch government, with its policy plan called "Schoon en Zuinig", set ambitious targets to reduce CO_2 emissions by 30% by 2020. To reach these targets, it is likely that CCS needs to play a role.[5] It seems useful, therefore, to link these ambitions to the current status of CCS and to assess what questions should be addressed to facilitate the process towards 2020 and beyond.

Many policy goals rely heavily on CCS, at regional (e.g., EU targets), national (e.g., "Schoon en Zuinig") and local scales (e.g., the Rotterdam Climate Initiative) to bridge the gap to other technologies. However, to date, there is no experience with the large-scale deployment of this technology and, in fact, many uncertainties remain unaddressed. The very ambitious policy proposals, therefore, require a reality check to find out whether the potential of this mitigation option matches with the high hopes and expectations uttered by politicians and industry. For a number of reasons, the

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[1] Pacala, S., Socolow, R. Stabilisation Wedges: Solving the Climate Problem for the Next 50 years with Current Technologies. *Science.* Vol. 305. www.sciencemag.org, 13 August 2004; National Petroleum Council, *Facing the hard truth about energy,* July 2007.

[2] IEA, *Energy Technology Perspectives 2008. Scenarios and Strategies to 2050.* Paris, OECD. 2008. IEA. *Legal Aspects of Storing CO_2: Update and Recommendations.* Paris, OECD. 2006; Stern, N. *The Economics of Climate Change. The Stern Review.* Cabinet Office HM Treasury. Cambridge University Press. 2007; Enkvist, P.A., Nauclér, T. & Rosander, J. A cost curve for greenhouse gas reduction. *The McKinsey Quarterly.* No.1. 2007.

[3] IEA. *Legal Aspects of Storing CO_2: Update and Recommendations.* Paris, OECD. 2006; IPCC, *Carbon Dioxide Capture and Storage,* 2005. New York: Cambridge University Press.

[4] Ministry of Economic Affairs. *Energierapport 2008.* (www.ez.nl). June 2008.

[5] Ministry of Environment. *Nieuwe energie voor het klimaat. Werkprogramma schoon en zuinig.* September 2007. www.vrom.nl/schoonenzuinig

Netherlands is in a favourable position for CCS. There are numerous depleted gas fields, onshore and offshore; there is a lot of relevant knowledge available from the gas industry; the seashore makes the Netherlands a good location for coal-fired power stations; and large sources of CO_2 are fairly concentrated in a small number of densely industrialised areas, like the Port of Rotterdam or the Eems region, where the newly planned coal power stations will be operational. This study will therefore conduct a reality check on the potential of CCS in the Netherlands. In order to improve the understanding of the potential role of CCS, this study focuses on four core questions.

1. Do the physical resources and their storage capacity underpin the storage of significant amounts (≥ 20Mt/year) of CO_2 in the Dutch underground, by when and for how long?

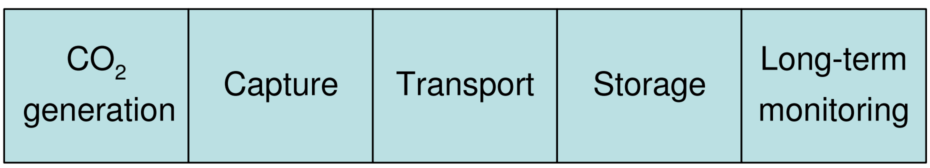
2. Are the required economic conditions and sufficient incentives for the industry in place to get CCS off the ground and, if not, what additional measures should be taken?

3. What are the main barriers/risks that can potentially block an accelerated development of CCS?

4. Is there a realistic path to get from a few pilot tests to an accessible and operational system for large-scale CCS and what timelines relate to this? Is there a need to set up a full-scale centralised system for large-scale CCS or should single initiatives be supported?

The aim of this reality check is to understand the outstanding issues that need to be addressed before CCS is able to fulfil its promise of contributing substantially to emission reductions. Large-scale CCS here means injection volumes of at least 20 mega tonne per year (Mt/a). The analysis will cover the whole value chain of CCS (Figure 1), which is important because CCS can only be implemented if every step of the chain works. This study concentrates on the CO_2 sources and sinks within the Netherlands, because it seems that these will be the most economically and rapidly available for CCS in the Netherlands. This assumption will be further substantiated throughout the paper.

Figure 1: Carbon capture and storage value chain



This report starts in Chapter 2 with an assessment of the CO_2 sources that can qualify for CCS to get an idea of what role it could play as an abatement option in the Netherlands should the right conditions be in place. The second part of Chapter 2 focuses on the CO_2 sinks to understand the storage and injection potential in the Netherlands and the potential storage issues that might come across when designing a large-scale integrated project. In Chapter 3, the economic conditions will be discussed by focussing on the issues related to the European emissions trading scheme and on the expected costs for CCS. Moreover, this chapter will briefly present some ways to bridge the possible CCS price gap. The fourth chapter deals with a number of key uncertainties, such as the long-term liability for storage and public acceptance that could hinder the development of CCS. Chapter 5 highlights the learning process, possible timing constraints, and possible models for a full-scale operational CCS system. The final chapter summarises the conclusions. Every chapter ends with a summary of the key messages.

2

2. CO_2 sources and storage capacity

This chapter will relate the different CO_2 sources to the storage capacity in the Netherlands. The first sections deal with the CO_2 sources that are suitable for CCS and the volumes that will have to be stored annually to comply with policy expectations. The second part of this chapter focuses on the geological reservoirs in which CO_2 can be injected and stored, and on planning uncertainties that need to be taken into account.

2.1. CO_2 Sources: power generation and industry

The carbon capture and storage chain start with the emissions of CO_2 at the different sources. Obviously, not all emitted CO_2 can be stored because capturing from small sources, like cars or small-scale residential heating units and streams with low concentrations of CO_2, would be overly expensive and therefore a very inefficient way of decreasing CO_2 emissions. So, only the so-called large point sources are suitable for CCS. Such sources can be found within large industries, including refineries, and, in particular, in the power generation sector.

In Europe the annual emissions of point sources (> 0.1 Mt/a) amount to 1500 Mt/a, of which two-thirds comes from power stations.[6] Also in the Netherlands, the power sector accounts for the largest share of emissions from point sources. Nevertheless, there are also opportunities to cut emissions from industries with CCS. A general drawback of these sources is that their total emission is lower, which means that more installations need to be attached to a network to significantly reduce emissions. This will go at the cost of economies of scale. Some industrial processes, however, have a relatively pure stream of CO_2 as a by-product, and applying CCS at these sources can drastically decrease capture costs. The total volume of these sources in the Netherlands is low, approximately 3 Mt/a.[7] Such an amount can be especially useful in decreasing the cost of the learning process towards a full-scale CCS system.[8]

The following table shows the CO_2 emissions from all sectors in the Netherlands. As can be seen in Table 1, the amount of CO_2 from large point sources (i.e. industry/power) was approximately 101 Mt in 2005. Further economic growth will, under business-as-usual (BAU) scenarios, lead to higher CO_2 emissions in 2020 than are evident today, rising from 176 Mt in 2005 to 211 Mt in 2020.[9] This growth comes from new industrial activity, power production and transport. The four newly planned coal-fired power stations, for example, would add approximately 21 Mt of emissions.[10]

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[6] Lysen, E.H., Jansen, D, Van Egmond, S. *Afvang en opslag van CO_2.* CATO Brochure. 2006.
[7] Damen, K.J. *Reforming Fossil Fuel Use. The Merits, Costs and Risks of Carbon Dioxide Capture and Storage.* Copernicus Institute, Utrecht University, The Netherlands. March 2007.
[8] IEA. *Prospects for CO2 capture and storage. Energy technology analysis.* Paris, OECD, 2004.
[9] Menkveld, M., Van den Wijngaart, R.A. *Verkenning potentieel en kosten van klimaat en energiemaatregelen voor Schoon en Zuinig.* Energieonderzoek Centrum Nederland, Milieu Natuur Planbureau. July 2007.
[10] Ploumen, P.J., Koetsier, H., Tulpin, F., Smeets, R.D. *Investigations to CO_2 storage; Strategy for CO_2 capture.* KEMA. Arnhem, The Netherlands. March 2007.

Table 1: The Netherlands CO_2 emissions per sector

Emissions in Mt[11]	**1990**	**2005**	**2020 (BAU)**	**2020 (Policy)**
Conurbations	30	29	26	15-20
Industry/power	93	101	131	70-75
Transport	30	39	47	30-34
Agriculture	9	7	7	5-6
Other greenhouse gases	54	36	35	25-27
Total CO_2	*161*	*176*	*211*	*120-135*
Total	**215**	**212**	**246**	**150**

2.1.1. Dutch policy targets: role of CCS as an abatement option

The Dutch government has formulated an ambitious CO_2 reduction target of cutting greenhouse gas emissions by 30% by 2020 and has committed itself to further reductions over the course of the century. The total emission reductions that have to be achieved by 2020, as formulated in the government's work plan *"New energy for the Climate"*, are 96 Mt/a in 2020.[12] This includes further growth of emissions that would occur due to increased economic activity. This report defines large-scale CCS in the Netherlands as the capture and storage of at least 20 Mt/a, which corresponds to a fifth of the mid-term reduction targets (2020).

Table 2 gives an overview of the volumes of CO_2 that should be stored under different scenarios for the reduction targets and roles of CCS therein. The reduction percentages (20%, 30%, 60% and 80%) and the call on CCS together show the annual volume of CO_2 that has to be captured and stored.

Table 2: Volumes of CO_2 (Mt/a) to be stored under different assumptions*

	Total CO_2 reduction**		**Call on CCS**		
			20%	**33.33%**	**50%**
2020	**20%**	70	15	25	35
2020/30	**30%**	90	20	30	45
2050	**60%**	140	30	45	70
2050	**80%**	175	35	60	90

** We assume that after 2020 the emissions will not grow further due to additional industrial activities (amongst others) due to efficiency improvements and clear policy aimed at emission reductions. So we have compared the 2020 BAU predictions with the 1990 levels to calculate the needed reductions.*
*** The numbers in Table 2 are rounded off and corrected for a more than average decrease of non-CO_2 greenhouse gases between 1990 and 2005. Two different reduction targets for 2050 are highlighted.*

The volumes presented in Table 2 are only based on the sources of CO_2 and do not yet assess which storage volumes would technically and economically be realistic.

Several other estimates of the role that CCS could play in future Dutch emission paths exist.[13] Damen et al. (2007) sketch a number of possible pathways for CCS in the Netherlands and find that in 2020 15 Mt/a could be avoided with CCS, climbing to a realistic maximum of 30 – 60 Mt/a over the course of the century. More ambitious targets would imply that CCS should be employed at nearly all potential capture opportunities and that CO_2 can be stored in mega-structures like the Groningen field,

[11] Ministry of Environment. *Nieuwe energie voor het klimaat. Werkprogramma schoon en zuinig.* September 2007. www.vrom.nl/schoonenzuinig
[12] Ministry of Environment. *Nieuwe energie voor het klimaat. Werkprogramma schoon en zuinig.* September 2007.
[13] In the "*Energy Technology Perspectives 2008. Scenarios and Strategies to 2050"* report, the IEA presents two scenarios / technology roadmaps (ACT and BLUE) in which the total global role of CCS accounts for 14% and 19%, respectively.

the Butser Sandstone formation or the Utsira (Sleipner) formation in the North Sea.[14] Van den Broek et al. (2008) present higher estimates for the potential of CCS in the electricity sector and state that CCS could contribute 29 Mt/a of emission reductions already by 2020 and 63 Mt/a by 2050.[15] The presented estimates are based on model simulations with a variety of assumptions.

Local initiatives

The Rotterdam Climate Initiative formulated its own CO_2 reduction target of 50% by 2025 for the Rijnmond area around the Port of Rotterdam (see Annex I). This means that Rotterdam wants to cut 32 Mt/a by 2025, of which 20 Mt/a should be realised through CCS.[16] Obviously, this target can only become a reality if CCS becomes available on a large scale in time. Also, the northern area of the Netherlands has set ambitious targets with respect to CCS. The two planned coal-fired power stations will be built in such a way that the plant can be equipped with CCS as soon as the technique becomes available. This means that annually 10 Mt of CO_2 could be captured and stored in that northern area (see Annex II for further details).

2.1.2. Power sector: window of opportunity for decarbonisation

The power sector offers the largest potential for a reduction of emissions through CCS. It is especially attractive to apply CCS at coal-fired power stations because coal emits roughly twice as much CO_2 as gas, which leads to lower unit costs. Retrofitting existing power stations is possible, but often not economical due to large efficiency penalties.[17]

The Dutch fuel mix has been dominated for a long time by natural gas, but coal has also played an important role and will continue to do so (almost 24% of power production is generated by coal). From a security of supply point of view, coal can be an important addition to the energy portfolio to lower the dependency on natural gas, for which imports will increase over the coming decades due to the depletion of domestic reserves. In addition, the Netherlands is an attractive location to build coal-fired power stations because of its large shore and ample availability of cooling water. Another advantage of a coal-fired power station is that it is relatively easy to co-fire biomass, which helps electricity companies increase their share of renewables in their generation portfolio. In all practicality, coal can only be combined with the climate policy targets when CCS becomes available.[18] In the global energy context, coal will continue to play an important role and its role is even expected to grow further over the coming decades, especially in the power sector.[19]

In Europe, 52% of the coal-fired power stations are older than 30 years and will reach the end of their life cycle within the coming 10 to 15 years. This implies that a lot of capacity will have to be replaced.[20] These replacements could offer opportunities to decarbonise the coal-fired power capacity, when new power stations are able to use CCS. The window of opportunity is small because CCS is still in the early phase of development and is not expected to be ready for large-scale deployment

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[14] Damen, K.J., Faaij, A., Turkenburg, W. *Pathways towards large-scale implementation of CO_2 capture and storage: A case study for the Netherlands.* PhD thesis. Copernicus Institute. Utrecht University. The Netherlands. March 2007.
[15] Van den Broek, M., Faaij, A., Turkenburg, W. Planning for an electricity sector with carbon capture and storage. Case of the Netherlands. *International Journal of Greenhouse Gas Control.* No. 2. pp. 105 – 129. 2008.
[16] This figure includes additional emissions that are caused by growth of energy use.
[17] Efficiency drops by about 9 percentage points for a PC plant and 7 percentage points for an IGCC plant. Older power stations generally have lower efficiencies than newer ones. Ecofys. *Making CCS Work Policy, Technology and Organisation. Large-scale carbon capture and storage in the Netherlands, an agenda for 2007-2020.* 2007.
[18] For more information on coal in the Netherlands see: Van den Heuvel, S.T.A., De Jong, J.J. *Putting Coal to the Test: Is Coal-fired Generation Clean, Competitive and Secure?* CIEP Briefing Paper. Clingendael Institute, The Hague. December 2007. http://www.clingendael.nl/publications/2007/20071200_ciep_briefingpaper_heuvel.pdf
[19] IEA, *Clean Coal Technologies. Accelerating Commercial and Policy Drivers for Deployment.* Coal Industry Advisory Board. Paris, OECD. 2008; Van den Heuvel, S.T.A. Metamorfose van de kolensector. Van vies naar schoon? *Internationale Spectator.* Clingendael Institute, The Hague, May 2008.
[20] World Energy Council. *Europe's Vulnerability to Energy Crises.* World Energy Council, London UK. 2008.

before 2020, whereas replacements are planned now.[21] The concept of power stations that are 'capture ready' should ensure that CCS will be implemented already for the current wave of replacements as soon as the technology becomes commercially available. This would avoid the unwanted situation that the carbon emissions of new power stations would be locked in for 40 years (the average lifetime of a power station). In the Netherlands most coal-fired capacity is not yet at the end of its life cycle, with the oldest stations having been built in the early 1980s. Nevertheless, there are opportunities for CCS in the Netherlands as well, since plans for new coal-fired power stations exist.

2.2. CO_2 storage and injection in the Dutch subsurface

A part of the CCS value chain that sometimes seems to be taken for granted in projections of the future potential for CCS is the subsurface storage capacity.[22] The remainder of this chapter will therefore pay attention to this often-neglected subject, with a special focus on the situation in the Netherlands.

Large point sources, like coal-fired power stations, will each deliver some 5 Mt per year over their life cycle of, on average, 40 years, thereby emitting approximately 200 Mt over their lifetime. Since it seems logical that a power station equipped with CCS will capture the emissions over its whole lifetime (and not, for example, only the first 20 years), it seems practical to assemble storage clusters of gas fields that together can take in on the order of 200 Mt.[23] So, when assessing the storage capacity in the Netherlands, the maximum annual storage level is the level that can be sustained for at least 40 years.

2.2.1. Geological storage options for the Netherlands

In the Netherlands, depleted gas fields present, by far, the best option for storage from a technical point of view and because of the relatively large volume of empty pore space. In general, the oil field storage potential is considered modest compared to that of gas fields. This is largely explained by the fact that during gas production 'void' pore space is created by pressure depletion, while in oil production the challenge is to maintain reservoir pressure, if needed, by artificial means such as water injection, so that no 'void' space is created. Aquifer traps may be a local alternative when depleted gas fields are not present or available, but exploration, development and the operation of aquifer storage will be more costly. A number of reasons explain the higher costs: aquifers in the Netherlands are widely dispersed geographically, generally a low effective storage volume, lack a proven cap rock (which makes retention less certain compared to gas fields) and can only handle low injection rates per well.

The technical advantages of gas fields over other options include:

- proven (natural) gas tight over the long-term
- well-known dynamic behaviour
- geographic spread
- high storage volume per unit surface area (= small footprint for monitoring)
- well-known storage capacity and injection capacity
- lowest cost and energy per Mton CO_2 sequestered
- limited number of well penetrations (= limited risk of leakage)
- transport infrastructure (re-usable?) / trajectories in place
- CO_2 can easily be produced back if necessary

[21] Wuppertal Institute for Climate Environment and Energy. *Ecological, Economic and Structural Comparison of Renewable Energy Technologies with Carbon Capture and Storage. An Integrated Approach.* Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Germany. April 2008.

[22] See for example: Van den Broek, M., Faaij, A., Turkenburg, W. Planning for an electricity sector with carbon capture and storage. Case of the Netherlands. *International Journal of Greenhouse Gas Control.* No. 2. pp. 105 – 129. 2008. Many other studies refer to an assessment done by the IPCC in 2005, whose estimates are, according to industry experts, highly optimistic.

[23] AMESCO. Generic Environmental Impact Study on CO_2-Storage Royal Haskoning (9S0742/R04/ETH/Gron) July 2007.

CO_2 storage outside the Dutch borders

CO_2 can, in addition to storage in the Dutch subsurface, be transported over long distances and stored abroad. An option often mentioned in this respect is storage in the Utsira aquifer in Norway. This would require a large trunk line through the North Sea. Another option is to transport CO_2 by ship to Algeria or the Middle East, for example, where it potentially can be used for enhanced oil recovery.

Although these options might prove very attractive beyond 2020, it seems unlikely that they will be more attractive than initial CO_2 storage in the Netherlands. Two main reasons can be given for this. In the first place, it is conceivable that other countries (with probably less storage opportunities than the Netherlands) will also look for storage opportunities abroad. This implies competition for CO_2 storage, which can have an upward effect on prices, since there are no unlimited storage and injection locations. Since the Netherlands itself is already well suited for CO_2 storage compared to many other countries in northwest Europe, it is likely that other countries in need of storage capacity will be able to pay a higher price for storage abroad than the Netherlands. Secondly, a country that has pore space available for CO_2 storage from other countries (which is mainly the case in Norway) will seek rent optimization and will, therefore, try to maximize its revenues from CO_2 storage. An advantage of storage in another country could be that public acceptance will be much less of a problem than with (onshore) storage in the Netherlands.

Because of the latter arguments and the many unknowns that are still related to CO_2 storage abroad (timing, availability and price), it seems risky to bet on storage abroad. Therefore, this study focuses on the storage potential in the Netherlands.

Enhanced recovery of hydrocarbons

Technically, CO_2 may be stored in conjunction with enhanced recovery of hydrocarbons, either from oil fields (enhanced oil recovery, EOR), gas fields (enhanced gas recovery, EGR) or coal beds (enhanced coal bed methane, ECBM). There may be local opportunities for these options, but the contribution to large-scale CCS is to be considered modest. The Netherlands seems to offer few opportunities for enhanced recovery. For gas, the recovery efficiency is already high and EGR may introduce more risks than rewards. EOR options in the Netherlands are equally limited, since oil reserves are very limited compared to Norway and the Middle East, for example. In addition, it remains to be seen whether EOR would count as carbon not emitted (and, hence, contribute to reaching the climate targets) since part of the CO_2 will be released back into the atmosphere during oil production.

2.2.2. Lifetime storage of CO_2 from point-source emissions: field clustering and cut-offs

As stated above, the storage clusters that have to accommodate the CO_2 streams would ideally have a capacity of approximately 200 Mt (the average life cycle emission of a coal-fired power plant). When defining logical clusters, it seems useful to have a look at the geographical distribution, the size and the availability of fields. Figure 2 shows the *geographical* distribution of storage volume in the Dutch gas fields (excluding Groningen).[24] From the map it is clear that the concentration of large storage volumes are in the northeastern part of the Netherlands (onshore) and in the central part of the Dutch North Sea (offshore). For all practical purposes, clusters of storage fields are to be projected for either of the two areas. Obviously, CO_2 point sources in the northern part of the Netherlands will prefer to store in that area. Point sources in the west coast area will have to transport CO_2 to the central offshore. Overall, the clustering of fields can be expected to reduce the unit cost of transportation and storage through sharing of infrastructure and operational costs.

[24] AMESCO. Generic Environmental Impact Study on CO_2-Storage Royal Haskoning (9S0742/R04/ETH/Gron) July 2007.

Figure 2: Geographic distribution of CO_2 storage capacity in depleted gas fields

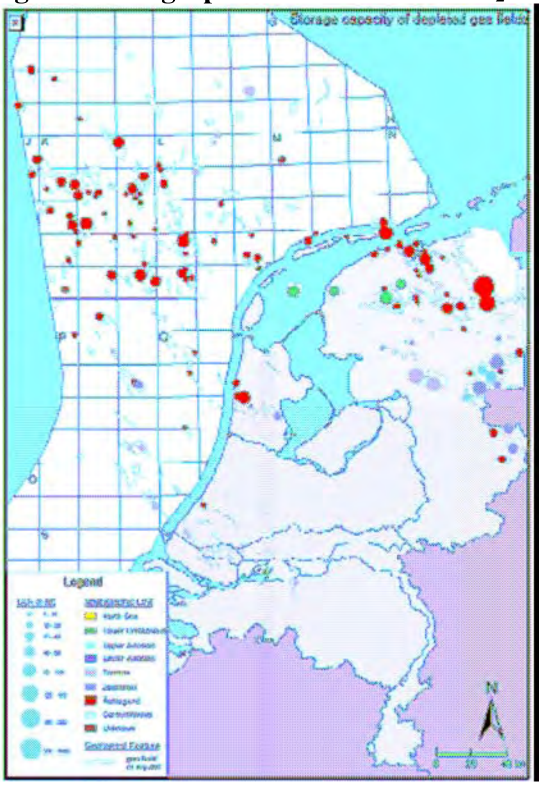
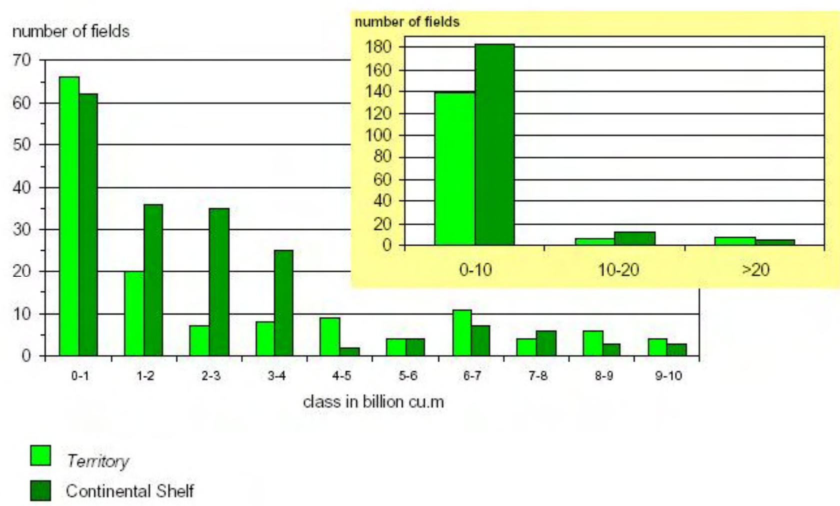


Figure 3 below shows the typical *size* distribution of Dutch gas fields (excluding Groningen).[25] In the size class >20 bcm (>50 Mt), there are seven onshore fields (excluding Groningen) and five offshore fields. These fields are likely to become the 'core' fields of storage clusters for large-scale CCS developments. A volume cut-off is set for gas fields with an ultimate recovery of 1 bcm, since they can only take some 2.5 Mt, meaning only half a year (or less) of the total CO_2 stream from a coal-fired power station can be stored.

Figure 3: Field-size distribution of Dutch gas fields



One option would be to cluster fields depending on the period in which they are expected to become depleted, e.g., 2010-2015, 2015-2020, etc. But, geographical clustering is probably more appropriate and cost effective than clustering in time.

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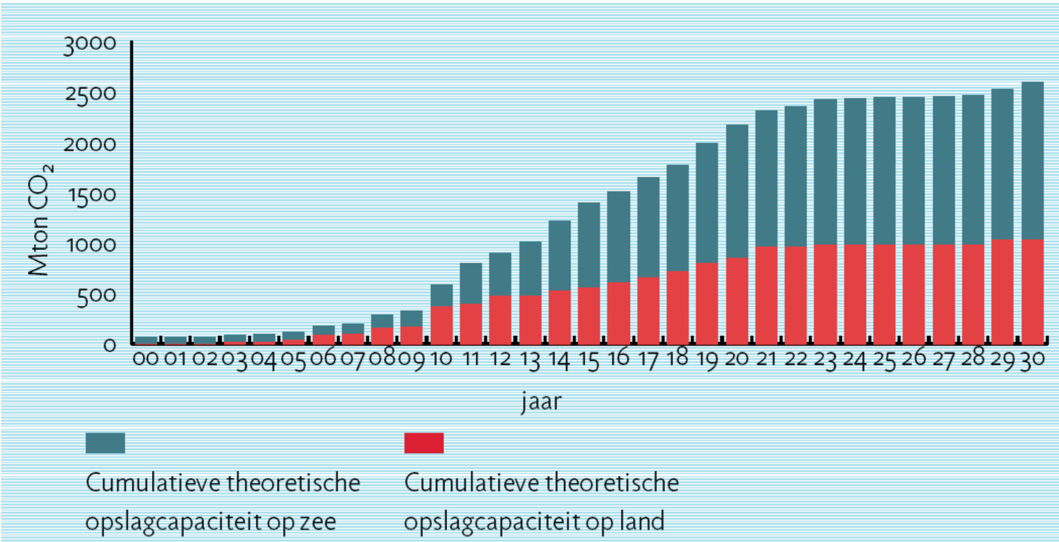
[25] Ministry of Economic Affairs. *Oil and Gas in the Netherlands: Exploration and Production.* (www.nlog.nl) 2003.

Timing and possible gaps between the end of production and the start of CCS

Figure 4 shows the curve of expected capacity to be released according to the present-day views of the operators in depleted Dutch gas fields (excluding Groningen).[26] It is clearly seen that, between now and 2020-2025, the vast majority of fields will become depleted. In fact, by 2020-2025 large-scale CCS is expected to take off in the Netherlands. It is stressed that the curve of availability represents the best knowledge of today, but is subject to uncertainty, like the curve for the demand for CO_2 storage capacity.

Figure 4: CO_2 storage capacity of released depleted gas fields[27]



Higher energy prices can alter the availability of gas fields in the sense that it remains economical for a longer period to produce small amounts of gas from nearly depleted fields, referred to as tail-end production. Tail-end production has the potential to impact timing or the value of storage capacity: depleted gas fields at the end of their economic life will typically have options for increasing recovery through low-cost operators, alternative production technology or a lower back pressure. Depending on government policy, this can have an upward effect on the cost of storage capacity (if an economic choice is made) or affect timing (if maximising recovery always takes priority, as is the current policy). Nevertheless, it seems unlikely that (all) nearly depleted gas fields will remain in operation for such a long time that it will hinder large-scale CCS, since the need for storage capacity is unlikely to become urgent before 2020. In fact, there may also be a downward effect on the cost of storage when possible synergies between tail-end gas production and CCS are carefully planned and exploited.[28]

Timing can be a crucial factor especially for offshore storage. This has to do with a possible time gap between the end of gas production and the start of CO_2 storage. If an operator ends production, a site gets abandoned and the infrastructure is removed (in line with existing legislation). Offshore storage requires that some infrastructure remain in place ('mothballed'), because otherwise it will prove very hard to re-use the wells, which would lead to much higher storage costs. To enable a match in timing and to avoid a loss of potential storage capacity, facilitation and coordination between the different parties is needed.

Offshore clustering is less dependent on existing pipeline patterns than onshore: offshore can more easily by-pass certain parts of existing infrastructure, if needed; onshore, licensing for new or extended infrastructure may be more difficult.

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[26] Ministry of Economic Affairs. *Energierapport 2008.* (www.ez.nl). June 2008.

[27] Dark blue shows cumulative capacity off-shore; red (below) shows cumulative theoretical capacity on-shore

[28] Ministry of Economic Affairs and NOGEPA. *Potential for CO_2 storage in depleted gas fields on the Dutch Continental shelf: Phase 1: Technical assessment.* September 2008.

2.2.3. Towards realistic storage volumes

The objective of the subsurface assessments is to understand what level of storage capacity will realistically become available in the Netherlands over the next decades. Until now the focus has been on the types of reservoirs suitable for CCS, the size and geographic distribution of fields, and the match between the start of CCS and the end of gas production. The next section will briefly discuss another important factor that determines the available storage volumes, i.e. the injection capacity of wells. After that, a classification scheme will be presented to fully explain what determines available capacity.

Injection capacity of wells

The 2007 AMESCO study, using desktop and reservoir simulation studies, mentions 0.2 – 0.5 Mt/a as a typical well injection capacity.[29] Indeed, high rate CO_2 injection in a depleted gas field has not been done so far. In principle, existing normal gas production wells will be re-used for CO_2 storage. Wells in gas storages like Grijpskerk and Norg are high capacity wells and are not representative of ‘ordinary’ production wells. Moreover, the maximum injection capacity of a well is not as important as the duration of injection on a certain ‘plateau’. So, although a typical gas well in the Netherlands may take 1 Mt/a or more for a start, the injection capacity will decrease over time. Technically, if CO_2 is injected in a dense (supercritical) phase, gravity helps to provide the energy for injection.

The injection capacity of a field could, in principle, be enhanced or extended by drilling additional new wells. Typically, one gas production well is used per every 2 bcm of gas recovery, i.e. 5 Mt CO_2 equivalent on pore volume basis. Larger storage sites will probably need more injection wells. As in ordinary gas production, this has to be optimised against other measures such as compression or even the early shift to other depleted fields, which may actually be more (cost) effective than drilling new wells. Taking the AMESCO 2007 well injection capacity of 0.2 – 0.5 Mt per year, it follows that a constant stream of 20 Mt/a is to be handled by 40 to 100 wells that inject simultaneously. Moreover, new injection wells have to be scheduled in, as no single field or well will be capable of injecting for 40 years. Therefore, also at the cluster level, the supply of CO_2 and the injection will have to be matched by the storage operator.

Classification of storage capacity

The Carbon Sequestration Leadership Forum (CSLF) proposed a classification scheme for CO_2 storage capacity that was derived from hydrocarbon resource classifications (see Figure 5).[30] It entails the following classes:

CSLF classification scheme

Theoretical capacity
In theoretical capacity only physical limits are taken into account, such as pore space in the reservoir and pressure constraints. Usually a direct link between gas produced in the past and future CO_2 storage volume is assumed here (where 2.5 – 3 Mt of CO_2 equals 1 bcm of gas produced in volume terms).

Effective capacity
With effective capacity, various factors at the reservoir level are considered that may affect the storage capacity. Such cut-offs may be applied on storage size and injectivity. The rationale here is that the portfolio of depleted gas fields will contain a subset that will not qualify for large-scale CCS on a stand-alone basis (e.g., small and remote reservoirs). In addition, the state of a gas field and/or its water content at the end of its production life will not be equal to its initial state. Part of these effects may give rise to an irreversible reduction of storage volume and injectivity.

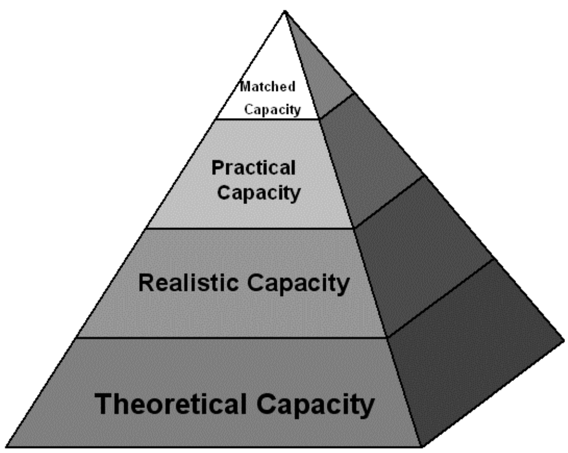
[29] AMESCO. *Generic Environmental Impact Study on CO_2-Storage.* Royal Haskoning July 2007.
[30] CSLF. *Estimation of CO_2 Storage Capacity in Geological Media – Phase 2* – Carbon Sequestration Leadership Forum (CSLF) June 2007.

Practical capacity
In addition to effective capacity, practical capacity takes various surface-related constraints on storage into consideration. These constraints have nothing to do with the reservoir itself, but with its accessibility in a technical, environmental or legal sense. Public acceptance is also to be considered here.

Matched capacity
The final goal is to have a match between sources and sinks in terms of injection rates and storage volume under reasonable demand-supply scenarios. Matched capacity is a subset of practical capacity referring to that which is available, taking into account economics and investment decisions (this is similar to reserves in the E&P arena). Projections of matched capacity, then, depend on projections of practical capacity and on actual investors' behaviour and CCS market expectations, which is similar to production forecasting for a portfolio of gas fields and prospects.

In the end, only the *matched capacity* category is relevant for analyzing the feasibility of future large-scale storage of CO_2 in the Netherlands. Since there is no market demand yet, nor any form of commitment between suppliers, transport and storage operators, the actual matched capacity now is equal to zero. The development of matched capacity can only be evaluated against assumptions about the development of the CCS market and the related legal and economic conditions.

Figure 5: CCS capacity classification scheme



Competition for gas storage
For decades, flexible production from the large Groningen field, as well as other fields, has provided flexible production for large parts of the European gas market, and in this way contributed to matching supply and demand. Many hundreds of gas fields and salt caverns around the world are being used for temporary storage of gas streams between sources and market. With domestic production volume and capacity declining in the near future, the EU will have to increasingly rely on import streams, both pipeline gas and LNG (Liquefied Natural Gas). Demand for storage capacity will grow accordingly. So in the future, there will also be an increased claim to accommodate working gas.

In the recent 2008 energy policy report by the Ministry of Economic Affairs, the concept of the Dutch gas roundabout ('Gasrotonde') is strongly advocated.[31] The goal is that the Netherlands will serve as a large-scale hub and buffer for the Northwest European gas market. To a certain extent, this merely implies extending the function that the Netherlands has had in the past, but with somewhat different means, in particular, using the small fields rather than Groningen for buffering.

[31] Ministry of Economic Affairs. *Energierapport 2008.* (www.ez.nl). June 2008.

Potential interference or competition between CCS and underground gas storage (UGS) has been investigated for the Dutch onshore storage.[32] It was concluded that the Netherlands offers excellent opportunities to make the most out of the natural gas assets portfolio, not only in terms of recovery but also in terms of value for re-use for CCS and UGS in particular, provided that the window of opportunity is carefully considered. This calls for some kind of master plan that oversees and preserves the options needed for both security of supply and CO_2 reduction.

From a technical point of view, UGS requires excellent field productivity characteristics (for high delivery and fast recycling) and a certain bandwidth of field size (for optimal work gas to cushion the gas ratio). From a commercial standpoint, gas production is more attractive than UGS, and UGS is more attractive than CCS. Therefore, there is an incentive for licensed operators to select and reserve their best fields for UGS. Conflicting use may emerge when a good UGS candidate field happens to be a strategic core field in a future CCS cluster. Careful planning is therefore needed. Competition between CCS and UGS might grow stronger when both markets grow in time. However, even with Dutch storage serving large parts of the NW European markets, these combined storage sites will probably need less than 10% of available depleted volumes. Yet, pending the future of UGS development (which is probably more attractive than CCS), the final decision on the use of a field may be delayed and in the meantime these fields will not be available for CCS.

2.3. Match between CO_2 sources and sinks

The previous paragraphs gave insight into the total CO_2 emissions in the Netherlands, the volumes that would need to be stored and the availability of storage capacity. Based on this information, one can make an estimate of the technical potential for CCS from a storage perspective. With the different cut-off levels and different storage constraints taken into account, a recent study by the Dutch Ministry of Economic Affairs (MEA) and the Dutch Association of Oil and gas Operators (NOGEPA) has concluded that the Dutch offshore offers an 'effective capacity' on the order of 800 Mt.[33] This capacity, if ever fully brought to the status of 'matched capacity', would allow for a CO_2 stream of 20 Mt/year to be injected in offshore depleted gas fields for a period of 40 years. Looking at the ratio between onshore and offshore 'theoretical capacity' in Figure 4, one may justify another 15 to 20 Mt/year of effective storage capacity onshore, bringing the total to 35 – 40 Mt/year. It should be stressed, however, that both onshore and offshore surface-related and economic factors will reduce the storage and injection capacities that can be realized.

If larger volumes are to be stored or if after this period the need for CCS persists, CO_2 could be exported to storage locations abroad. The latter implies that it will be unattractive to allocate storage capacity for CO_2 flows from other countries, since this would imply that in an earlier stage a shift must be made towards the (expectedly) more expensive storage options abroad. So, due to scarcity of storage capacity, CCS should be seen as a transition technology towards a low carbon energy system, rather than as an ultimate solution.

Key messages

- The largest share of emissions to be captured will come from the power sector. Applying CCS is especially attractive for coal-fired power stations, because the CO_2 emissions are high compared to other fuels leading to lower unit costs.
- If the planned new coal-fired power stations will actually be built, there will be no lack of point sources that are suitable for CO_2 capture in the Netherlands, making implementation of CCS mainly dependent on the economics of capturing, transporting and storing CO_2, and on the regulatory framework.
- Under different scenarios that combine CO_2 reduction targets and the role that CCS should play

[32] Breunese, J.N. *The Netherlands: a case of optimisation of recovery and opportunities for re-use of natural gas assets.* 23rd World Gas Conference, Amsterdam 2006.
[33] Ministry of Economic Affairs and NOGEPA. *Potential for CO_2 storage in depleted gas fields on the Dutch Continental shelf: Phase 1: Technical assessment.* September,2008.

therein, annual volumes of CO_2 to be stored vary between 15 and 90 Mt.

- There is a great need for new power stations and for replacements of old power stations by newer ones, both in Europe and in the Netherlands. This offers opportunities for CCS.[34] However, to make use of these opportunities, timing on all aspects (technical, economical, legal conditions) is crucial.
- The window of opportunity is small because CCS is still in its early phase and new plants and replacements are planned now. This time gap requires the attention of policy makers to ensure that newly built power stations will be expanded with CCS equipment as soon as the technology becomes available.
- Total storage capacity in the Netherlands could (technically) accommodate up to 35-40 Mt/a for a period of 40 years (typical lifetime of a power station). Half of this amount is onshore and half offshore. The numbers do not take vulnerable ecosystems or spatial planning into account, therefore the actual volume will likely be lower.
- For the planning of large-scale CCS implementation, the Netherlands has to rely on its portfolio of depleted gas fields. Other geological options, like aquifers, offer ‘niche’ opportunities, but currently seem to be too uncertain to be part of a firm upscaling strategy.
- The key is to establish a plan that provides a match between supply and demand for CO_2 storage. Such a plan should enable synergy between gas production and CCS by aligning the end of production and the start of CO_2 storage. This requires a strategic selection to conserve valuable and critical parts of the assets and infrastructure. The clustering of fields is a necessary step.
- The availability of existing gas infrastructures for large-scale CCS requires active coordination to enable optimal extraction of gas reserves, underground gas storage and CCS.
- Simultaneous injection of large streams of CO_2 will require several injection wells. Over time, new injection wells will have to be scheduled in, as no single field or well will be capable of injection for 40 years. Also at the cluster level, the supply and injection of CO_2 will have to be matched by the storage operator.

[34] In the Netherlands replacement is a less important driver, but four new plans for coal-fired power stations can also offer new opportunities for CCS.

3

3. Economics and Incentives

In general, CCS technologies will not be deployed when CO_2 has no price or when the (expected) CO_2 price will be persistently lower than the cost of CCS. This is because CCS will never add value to the end product (electricity) and there are few economically viable applications in which large amounts of CO_2 can be used. This chapter starts with a short discussion of the uncertainties related to the carbon price and shows the current price estimates. Next, different views on the (expected) costs of carbon capture and storage will be summarised. Finally, a number of incentives that can be put in place and measures that can be taken to bridge possible gaps are discussed.

3.1. CO_2 price: trends and uncertainties

A CO_2 price that can cover the costs of capturing, transporting and storing CO_2 would probably be the strongest incentive for CCS.[35] In fact, if the CO_2 price were lower than the costs of CCS, and there would be no expectation that this would change, companies would buy their credits on the carbon market instead of investing in the development of CCS. So, the (expected) CO_2 price is either high enough and market players will invest in the development of CCS, or the price is too low and, unless additional incentives are put in place, no CCS projects will appear. The total cap on emissions set by policy makers determines the level of the CO_2 price. A tighter cap will mean a higher price.

For the CO_2 price to be an incentive, it is necessary that the CO_2 that is captured and stored count under Europe's Emissions Trading scheme (EU ETS) as carbon not emitted. Another important aspect is the method of granting CO_2 credits. If the credits are auctioned (instead of allocated freely), the total costs will be higher for electricity companies and it might be harder to earn back previous investments with bad CO_2 records. For the development of CCS, auctioning might be beneficial because replacing an older, less efficient power station with a new state-of-the-art power station with CCS becomes attractive much sooner than would be the case with a free allocation of credits.

Another element that should be taken into account is the possibility of importing emission credits through the clean development mechanism (CDM) or through joint implementation (JI).[36] The credits from these systems, the so-called certified emission reductions (CERs), generally have a lower price than the CO_2 price on the carbon market. Prices for future contracts at the European Climate Exchange show that the EU ETS credits are between 35% and 50% more expensive than CDM/JI credits.[37] In the proposed legislation, there is a certain limit on the number of credits that may be imported into the European market system (a maximum of 10%). The risk that a larger number of CERs will still get into the European carbon market in another way needs to be addressed, since this would have an unwanted depressing effect on CO_2 prices.

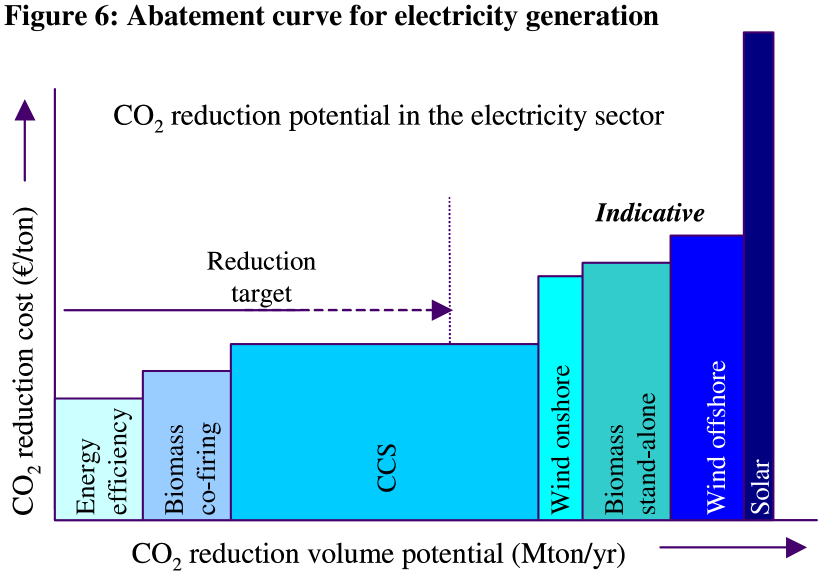
A more general uncertainty related to CO_2 price development can be found in the sphere of international climate politics. Until the end of 2009, when the final negotiations on a new global climate agreement will take place, there will not be much certainty about the future CO_2 price. A global agreement that would include an extended carbon trading system or allow a larger share of

[35] Rotterdam Climate Initiative, DCMR. *CO_2-afvang en –opslag in Rijnmond.*DCMR Milieudienst Rijnmond. 2007.
[36] CDM and JI are instruments accepted under the Kyoto Protocol that allow investments in carbon mitigation projects abroad and from which the credits can be added to national emission reductions. The advantage is that they allow low cost options to be employed before more expensive options. A drawback of these systems is that the risk exists that credits are taken from projects that also would have been executed without the CDM or JI.
[37] See www.europeanclimateexchange.com

CERs to be imported could have a depressing effect on EU ETS prices, as is shown with Fortis' price estimate in Table 3. At the same time, such an agreement could lead to a more efficient (i.e. cheaper) global abatement of CO_2 emissions. The oft-mentioned difficulty with CERs is that it is at times unclear whether the CDM or JI projects that receive credits would still be executed without the help of said credits.

European leaders already announced that irrespective of an international agreement, they would continue the emissions trading scheme after 2012. This announcement is seen as a necessary step to maintain trust in the carbon market. The European Commission proposed in the "Climate and Energy package" a number of adjustments to the post-2012 EU ETS that are expected to lead to higher price levels because it would bring more scarcity to the carbon market. The most important measures are (partial) auctioning of credits and an emissions cap that is in line with the reduction targets (i.e. 20% reduction in 2020).[38] So, in case CCS would be the marginal abatement option to reduce the emissions (which it will probably be as can be seen in Figure 6), it would *in theory* lead to CO_2 price levels high enough to enable CCS. The Commission's proposals still have to be approved by the heads of the different member-states, which is expected by the end of 2008.

Figure 6: Abatement curve for electricity generation



For the second EU ETS period that goes from 2008 – 2012, several market analysts expect that the European Commission will have done enough to create the needed scarcity.[39] For CCS, especially the price level around 2020 is important, because before that time no large-scale CCS will have been in place. Nevertheless, for confidence in the functioning of the carbon market and because credits can be transferred to future periods, the price level during EU ETS 2 will already be of great importance. In Table 3 the price estimates of different market analysts are given.

[38] European Commission. *20 20 by 2020. Europe's Climate Change opportunity.* COM (2008) 30. Brussels, 2008.
[39] Reuters 31 March 2008, *EU carbon market expects boost beyond 2007 data.*

Table 3: Estimates of future carbon price under ETS 2 and ETS 3[40]

Price estimate €/t	ETS 2 2008 – 2012	ETS 3 2013 - 2020	2020
Deutsche Bank	€40	n.a.	€65 – €70
Ecofys (2007)	€5 - €25	€15 – €35	€20 - €50
Fortis (March 2008)*	€48/t (a) €27/t (b)	Max. €100	
IDEAcarbon/ECON Global Carbon Report	€15 – €20	n.a.	n.a.
New Carbon Finance (2008)	€38	€35 - €55	n.a.
Point Carbon	€30	€30 - €70	n.a.
Societe Generale	€27 – €39	n.a.	n.a.
UBS	€30 - €35	€30 - €40	n.a.

* (a) Without a post-Kyoto agreement; (b) with 430m offset emission allowances

3.2. Carbon capture and storage cost estimates

The previous section dealt with CO_2 pricing and showed that expectations of future price levels vary considerably. The expected costs for CCS show a similar discrepancy. Current cost estimates are in the range between €20 - 70/tCO_2 (Table 4). This corresponds to €2-3ct/kWh for new coal-fired generation and could fall to €1-2ct/kWh by 2030.[41] Under current technological circumstances, the main share of the costs of CCS are capture costs, between 75% and 85%.[42] The remainder is for transportation and storage. Cost decreases that are needed to make the technology competitive into the future should therefore come mostly from capture. The next paragraphs describe how the costs of the different steps in the CCS chain are built up.

Table 5 shows that on average the estimated cost to capture, transport and store CO_2 is €45/t. The recent rise in energy prices and construction costs (such as steel prices and engineers' wages) might lead to higher CCS costs than showed in the table below. In addition, costs will be very site specific.

Table 5: Cost of carbon capture and storage per tonne

	Capture	*Transport*	*Storage*	**Total**
CERA (2008)	$60-75	$5 – 35		$65 - 110
RCI (2008)	€13 - 40	€7.5 - 10	€4.5 – 6.5	€25 - 57
European Commission (2008)				€35
Pöyry (2007)	€30 - 45			€45
World Coal Institute (2007)[43]	$15 – 75	$1-8	Injection: $0.5–8 Monitoring: $0.1–0.3	$40-90
Ecofys (2007)				€30 - 40
IPCC (2005)			Injection: $0.5 – $8	€20
Rubin et al. (2007)[44]	$23 - 63	Transport and storage cost: 4 – 10% of Cost of Electricity (COE)		$32 -72
MIT (2007)[45]			$20[46]	
E3G				€75 - 120

[40] Reuters, 6 September 2008, *EU carbon price forecast remains elusive;* Reuters, 14 November 2007, *UBS raises EUA price forecast to 35 euros.*; Rotterdam Climate Initiative, DCMR. *CO_2-afvang, -transport en –opslag in Rijnmond. Rapportage 2008.* DCMR Milieudienst Rijnmond. 2008.
[41] The lower range cost levels require that the CO_2 is used productively, e.g. for enhanced oil recovery. Ecofys. *Making CCS Work Policy, Technology and Organisation. Large-scale carbon capture and storage in the Netherlands, an agenda for 2007-2020.* 2007; IEA. *Legal Aspects of Storing CO_2. Update and Recommendations.* 2006. Paris, OECD. IEA uses a higher upper limit.
[42] MIT. *The Future of Coal,* 2007.
[43] World Coal Institute. *Coal Meeting the Climate Challenge. Technology to reduce greenhouse gas emissions.* September 2007.
[44] Rubin, E.S., Chen, C. Rao, A.B. Cost performance of fossil fuel power plants with CO_2 capture and storage. *Energy Policy.* 35, pp. 4444 – 4454. 2007.
[45] MIT. *The Future of Coal. An interdisciplinary MIT Study.* 2007.
[46] This counts for sources where CO_2 supply is already concentrated. Total costs would include compression costs, well count, reworking requirements, availability of key data sets and monitoring complement.

3.2.1. Capture costs

Several techniques for capturing CO_2 exist. With regard to power generation, three basic technologies include post-combustion capturing, pre-combustion capturing and oxyfuel combustion. For a comparison across these technologies see Annex III. All technologies offer advantages and disadvantages, depending on the type of fuel used and site/location characteristics. From a technology development point of view, it is safer to spread the development risks over a number of technologies to avoid the risk that one technology is a 'dead-end street'. Therefore, research, development and demonstration have to continue on the three technological tracks. Current capturing technologies capture about 85-95% of the CO_2, so in combination with the efficiency losses, CCS can avoid 80-90% of the emissions.[47]

Generally, the costs for CO_2 capture consist of capital requirements and operating costs (mainly additional energy use). Estimates for increased capital requirements vary between 20% and 50% of the total investment for a new coal-fired power station and depend on the technology used. The process of capturing CO_2 leads to additional energy use and thus reduces the efficiency of a power station. The efficiency drops by about 9 percentage points for a PC plant and 7 percentage points for an IGCC plant.[48] It is expected that, due to learning effects, the efficiency penalty can drop to 4-5%.[49]

Approximately 50% of the total capture cost is related to additional energy use and 50% is related to additional capital requirements (i.e. construction costs). Both price categories are subject to cost inflation. Energy prices (including coal) have risen tremendously over the last year. The same counts for the cost of equipment. Some projects are suffering from large cost overruns and some are being cancelled, postponed or scaled down to limit costs. Examples are the FutureGen project in the United States that was scaled down due to cost overruns and Nuon's decision in mid-September 2007 to first build a gas-fired plant that can later be expanded with a coal and biomass gasification unit.[50]

3.2.2. Transport costs

Transport costs can be split among investment costs (infrastructure), running costs and repair and maintenance costs. The running costs take the largest share, arising from the energy needed for compression to transport the CO_2 through pipelines or for the energy needed to liquefy CO_2 for transport per ship, depending on the means of transport. The other major part of the transport costs are the cost of building the infrastructure. Evidently, transport costs per unit depend on the cumulative volume, transport distances (between source and sink), utilisation rates, presence and re-usability of infrastructure, and the means of transport.

In some fields, it might be possible to use existing pipelines for the transport of CO_2. This will depend on the likelihood of competition with other uses for the pipeline (e.g., when in a central part of a cluster of depleted fields, some production is still going on) and on the state of the pipeline. Large-scale CCS will, however, inevitably require the construction of new pipelines. Such infrastructure can consist of a trunk pipeline that can be fed with CO_2 from different sources that are transported through smaller pipelines.

3.2.3. Storage costs

Storage costs vary for different storage locations. The IEA estimates that storage in depleted oil or gas reservoirs will cost between $1 and $40.[51] This very wide range shows that the costs of storage vary significantly per location, but it can also point to a large degree of uncertainty regarding the cost levels

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[47] IPCC. *Carbon Dioxide Capture and Storage,* 2005. New York, Cambridge University Press.
[48] Ecofys. *Making CCS Work Policy, Technology and Organisation. Large-scale carbon capture and storage in the Netherlands, an agenda for 2007-2020.* 2007.
[49] Lysen, E.H., Jansen, D., Van Egmond, S. *Afvang en opslag van CO_2.* CATO Brochure. 2006.
[50] Reuters, 30 January 2008. *US scraps plan for biggest clean-coal power plant*. Nuon press release: *Nuon faseert bouw multi-fuel centrale vanwege hoge bouwkosten*. 18 September 2007.
[51] IEA, *Energy Technology Perspectives 2008. Scenarios and Strategies to 2050.* Paris, OECD. 2008

to expect. The Rotterdam Climate Initiative calculates using costs between €4.5 and €6.5 /t, but these costs also seem difficult to generalise since storage costs are very site specific. To give some understanding of storage costs, the following presents the cost elements of CO_2 storage.[52]

Different cost elements of CO_2 storage are shown below:

Capital expenditures:

- Work over of the wells[53]
- Modifications of the facility
- Other modifications
- Pipeline inspection and modification

Operating expenditures:

- Costs for maintaining offshore infrastructure (mothballing = optional)
- Platform and terminal operations
- Well maintenance
- Pumping, compression and heating costs
- Monitoring

Work over of the wells will generally be the largest share of the investment costs for storage. When large volumes of CO_2 need to be injected, more wells will be needed because the injection capacity of a well is limited. This limited injection capacity is likely to limit economies of scale. Generally, a spare well is desirable to ensure that unforseen problems with another well will not interrupt CO_2 storage.

The storage-cost estimates in published literature do not generally include a cost for the use of the depleted field (opportunity costs). However, as stated earlier in this report, it is conceivable that an economic trade-off will be made between CCS and alternative options such as tail-end gas production. In that case, the value of the next best alternative (e.g., 'trapped gas') should be attributed to the CCS project. Another likely cost element is the storage operator's subsurface capability, including his or her understanding and monitoring of the geology and dynamic behaviour of the field. The latter would require that storage costs for the existing operator be lower than the costs for a new entrant. It is also not yet clear at what storage price it becomes attractive for field operators to invest in CO_2 storage. Generally, hydrocarbon production projects will be more attractive than CO_2 storage projects. So, in case there is competition between these projects, the storage price at which an operator will be prepared to allocate its resources to CO_2 storage will rise, leading to higher overall CCS costs.

CCS cost curve

The simplified and purely conceptual CCS cost curve in Figure 7 is intended to show that the costs of CCS vary sharply under different circumstances. Important variables that play a role in this are the market value of CO_2 in other applications (e.g., enhanced oil recovery abroad or usage in greenhouses or the soda industry), the purity of the CO_2 flow (which determines capture costs), the presence of an infrastructure and its re-usability, and the distance between the CO_2 source and sink. The first very small bar (A) shows the rare instances in which CCS could have a negative cost (i.e. a positive value); the following bars (B & C) show cases where capture and storage costs are relatively low, for example in specific industries. The large bar (D) shows that the majority of the capture potential will have to come from sources with relatively high costs (e.g., coal- and gas-fired power stations). The final bars (E & F) show cases where CCS is no longer attractive, like capturing from very small or non-stationary sources or storing in very small fields.

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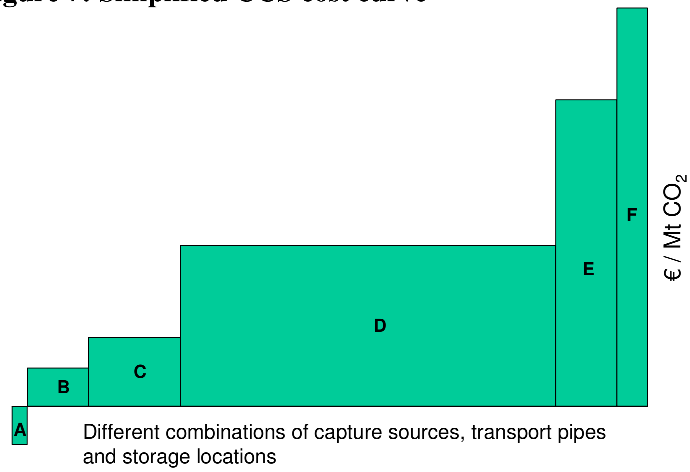
[52] Rotterdam Climate Initiative, DCMR. *CO_2-afvang, -transport en –opslag in Rijnmond. Rapportage 2008.* DCMR Milieudienst Rijnmond. 2008.

[53] Work over of wells entails the improvement of existing wells, which often requires drilling rigs.

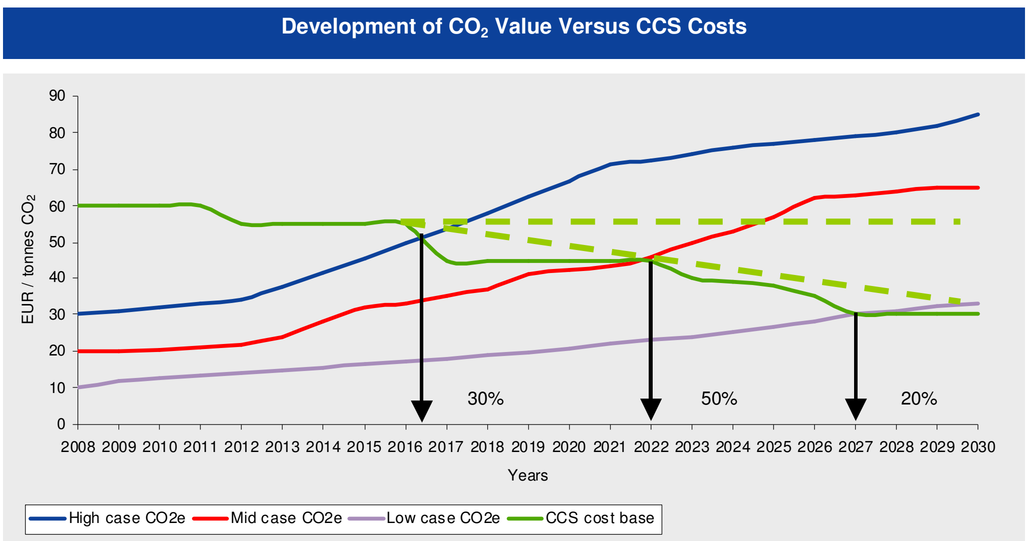
Figure 7: Simplified CCS cost curve



3.3. Gap between CO_2 price and costs of CCS

A principle that generally underpins CCS activities is that CCS is expected to be economical in the long-term carbon-abated power market.[54] Based on the data from the previous two sections, it can be concluded that this is not yet the case and that it remains uncertain at what point in time this will be the case. In fact, CCS costs more than doubled between 2004 and 2007, due to increases in energy costs, material costs and a lack of resources (e.g., drilling rigs and labour).[55] Technological learning and tighter CO_2 caps (leading to higher CO_2 prices) can, over time, close this gap. An illustrative path towards closing the gap is shown in Figure 8. The main elements that determine these paths are CO_2 price estimates and CCS cost estimates.

Figure 8: Possible development of CO_2 price and CCS costs



The most recent cost data for CCS come from the Rotterdam Climate Initiative (2008) and show a wide range of uncertainty in expected costs. Estimates vary between €25 and €57 per tonne. A more pessimistic estimate comes from E3G who point out that CCS is likely to require carbon prices of €75 –85/t to be competitive with unabated gas power and, if construction costs escalate further, this could

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[54] Zero Emission Fossil Fuel Power Plants (ZEP). *The EU Flagship Programme for CO_2 capture and storage (CCS). ZEP Recommendations: Implementation and Funding*. February 2008.

[55] IEA, *Energy Technology Perspectives 2008. Scenarios and Strategies to 2050.* Paris, OECD. 2008.

be between €100-120/t.[56] Obviously, this depends as well on the level of the gas and coal prices. Other sources, like the Deutsche Bank, point at the European cap on emissions that will be 20% lower in 2020 than in 1990 (in line with policy proposals), which could imply that CCS will, sooner rather than later, become the marginal abatement option; hence, the CO_2 price will converge with the costs of CCS.[57] The (expected) fuel prices are an important variable in this respect, because they will determine the level of fuel switching and the point at which CCS could become economical. As mentioned earlier, the final cost level will depend on specific circumstances. Because of these uncertainties, it is still difficult to assess what CO_2 price level will be needed for CCS. [58]

3.4. Ways to bridge the financial gap: incentives for CCS

The basic technologies behind CCS are known and have been employed for more than a decade. Upstream players may have either invested in transport and injection of CO_2 because it can help, in certain cases, to increase the output of the oil production (enhanced oil recovery). In other situations, upstream players may have invested in CO_2 separation because the CO_2 content of gas reserves was higher than the amount allowed by commercial specifications. Industrial companies (like refineries) that have invested in capture techniques have generally pure CO_2 streams that can be sold to other companies that need pure CO_2, like companies in the soda industry or greenhouses. Evidently these non-climate change-related reasons to use CCS have been very important for the development of the technological basis. Nevertheless, the viability of such projects has depended on revenues from oil and gas production or from the sale of pure CO_2. The viability of CCS merely depends on the CO_2 price, of which the value is currently still less reliable than that of oil or gas.

The EU proposal as outlined in the "Climate and Energy" package recognises CCS in the EU ETS in the sense that a tonne of CO_2 stored counts as a tonne not emitted. A well-functioning EU ETS, therefore, could provide a stable framework in which the price of emission credits is sufficiently high for alternatives to be developed. Assuming that the future price outlook remains high, this would provide a signal to invest in long-term commercial deployment of CCS.

3.4.1. Incentives for the industry

CO_2 is becoming an increasingly important part of the value chain of energy (intensive) industries. One of the key reasons for companies to invest in CCS is to offset their exposure to (possibly rising) CO_2 prices. Another important motivation can be that companies want to build coal-fired power stations to diversify their generation portfolio and need CCS, not only to hedge against further price increases, but also to make the investment in coal power more accepted. Finally, upstream companies might want to leverage their knowledge of (almost) depleted reservoirs in which they are concession holders.

3.4.2. Government incentives

In the ideal economic world, robust and rising carbon prices would drive the learning investments that are needed for CCS. In reality there is uncertainty about the future price level and government policies, which block investments in (the development of) new technologies. The urgency of immediate action to decarbonise the energy system requires commercially available CCS as soon as possible. So there seems to be enough ground for additional government support.[59] This support should reduce the risks and uncertainties of CCS and stimulate the learning process to enable the commercial scale to be reached within the desired timeframe (i.e. commercially available in 2020).[60]

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[56] Mabey, N. Taming King Coal – The EU's energy policy. *Carbon capture journal.* Issue 3. May - June 2008.
[57] Deutsche Bank. 2 June 2008. *Carbon prices must rise over 2008-20 to meet EU policy targets.* Press release.
[58] Reuters 11 March 2008, *EU carbon market lagging in climate fight: analysts.*
[59] IEA, *Clean Coal Technologies. Accelerating Commercial and Policy Drivers for Deployment.* Coal Industry Advisory Board. Paris, OECD. 2008.
[60] We assume CCS to be in the commercial scale when no other incentive than the carbon price is needed for economic deployment.

Although the debate on financing and incentives for CCS projects is attracting much political attention at both the national and EU levels, it remains to be seen whether the current EU ETS price for CO_2 and uncertainty regarding the final package provide sufficient incentives for the shorter-term demonstration projects. Certain EU governments already recognise that incentive structures will be needed to stimulate early CCS investments.[61]

From a company perspective, investments made to accelerate an immature technology like CCS carry additional risks and costs, also known as first-mover costs.[62] CCS is tied to considerable upfront capital investments that involve the risk of becoming obsolete when the right economic, technological and regulatory conditions are lacking. Industry is capable of carrying these risks, but (without additional incentives) will probably require more time to deal with the associated risks than is available to meet the policy targets. The following will briefly describe the most important measures and incentives that can be put in place to close the financial gap.[63]

Targeted investment support aims at lowering the upfront investment in a new (demonstration) installation. It can either take the form of a capital grant, a tax deduction or a loan guarantee. An advantage of this type of support for the investor is that it lowers the costs at the beginning of a project and, as such, positively affects the net present value.

Production subsidies provide a subsidy for every MWh of electricity produced or for every Mt of CO_2 stored underground. Production subsidies can either be granted as feed-in subsidies when counting the MWh of low carbon power produced or as cash payments per tonne of CO_2 stored.[64]

CO_2 price support is based on the emissions trading scheme and can either provide companies that apply CCS with a guaranteed CO_2 price or offer them double CO_2-allowances permits. Such CO_2 price support can be made more effective by granting a level of support that depends on the CO_2 price (where a higher CO_2 price means less support). This support should have a certain maximum, to lower government exposure to price changes. It is important that this type of support be phased out once the technology has entered the competitive phase.[65]

CCS obligations forbid (power) companies after a certain date to emit CO_2 emissions and make storage compulsory. This can start with CCS for newly built plants, followed by the obligation to retrofit existing plants. Obviously, this can only be done when the technology can be applied on a large scale and when enough storage capacity is available. Another risk involved with CCS obligations is that they might lead to the cancellation of investments and, hence, can hamper security of supply and economic development.

Key messages

- By 2020 the EU ETS could cover all costs of the CCS value chain in case of rapid cost reductions and a higher CO_2 price than today's.
- Expected CCS costs vary substantially, between €30 and €120. CO_2 price forecasts vary between €20 and €70. It is, therefore, difficult to predict when commercial viability of CCS will be a reality. However, still subject to uncertainty, there are projections that somewhere between 2015 and 2025 CCS can become commercially attractive.

[61] Energeia, 12 August 2008. *Europa naarstig op zoek naar financiering voor CCS-demonstraties.*
[62] Zero Emission Fossil Fuel Power Plants (ZEP). *The EU Flagship Programme for CO_2 capture and storage (CCS). ZEP Recommendations: Implementation and Funding.* February 2008.
[63] For more information on incentives see: ECN, Norton Rose, GiG, ERM, *Technical support for an enabling policy framework for carbon dioxide capture and geological storage. Task 3: Incentivising CO_2 capture and storage in the European Union*. 2007.
[64] The feed-in subsidies can be designed as a fixed tariff per MWh of electricity produced or as a fee that compensates (part of) the financial gap, e.g., dependent on the CO_2 price.
[65] Platform Nieuw Gas. Werkgroep CO_2- opslag / Schoon fossiel. *Beleidsrapportage Schoon Fossiel. Advies van de Werkgroep Schoon Fossiel.* June 2007.

- For CCS, auctioning might be beneficial because replacing an older, less efficient power station with a new state-of-the-art power station with CCS becomes attractive sooner than would be the case with a free allocation of credits.
- Uncertainties regarding the economic viability of CCS, the importance to have CCS as soon as possible commercially ready, and the fact that the CCS concept is still in the demonstration phase imply that additional government incentives are needed. These incentives should, in particular, decrease first-mover costs.
- Capture costs seem to account for the largest share of total CCS costs; thus, the main share of cost reduction should come from the capture side. There is a risk that cost reductions will be delayed due to higher operational costs (mainly energy) and inflation of construction costs. Unlike renewable energies like solar and wind, CCS does not benefit from higher energy prices.
- Storage costs are very site specific. This makes it hard to estimate an average cost level. In addition, it is uncertain at what storage price it becomes attractive for upstream companies (IOCs) to invest in CO_2 storage.

4

4. Barriers and risks: liability, regulation and public acceptance

The previous chapters focussed on the physical, technical and economic feasibility of large-scale CO_2 capture and storage. However, economically and technically feasible CCS is not enough to realise it in practice. Several other uncertainties, like regulation, laws and social considerations need to be taken into account. This chapter briefly discusses the different non-economic or technical barriers and uncertainties that could block the uptake of CCS.

Companies that want to engage in CCS generally face two types of uncertainties. In the first place, there is market uncertainty (discussed in Chapter 3) that relates to the CO_2 price and the price of electricity. Secondly, policy uncertainty influences the price path of CO_2 and the expectations about the future regulatory framework (e.g., CCS obligations or decisions regarding support schemes). Fuss et al. show that policy uncertainty has a greater negative impact on investments in low carbon technologies than market uncertainty.[66] Under market uncertainty, some market players might invest earlier in CCS than would be the case if they had perfect information (i.e. without policy uncertainty). Policy uncertainty can bring about two types of risks. First, there is the risk of investing too late and making losses because of high CO_2 prices. Secondly, there is the risk of investing too early and ending up with stranded capital. The energy industry is particularly vulnerable to policy uncertainty because of its capital-intensive nature. To avoid stranded investments, market players are likely to postpone investment decisions until the government's commitment becomes clear.

The main barriers for further uptake can be summarised in the following categories:

1. Unclear who is responsible for long-term liability issues
2. Lack of a functioning business model for CCS
3. Public acceptance due to concerns about safe storage

The first barrier mentioned is mainly a policy uncertainty. The second barrier is currently still a policy uncertainty that may evolve into a market uncertainty once a fit-for-purpose regulatory framework is in place. So, one of the current main challenges is to find a regulatory framework that addresses the key risks and uncertainties.

4.1. Liability issues and regulatory framework

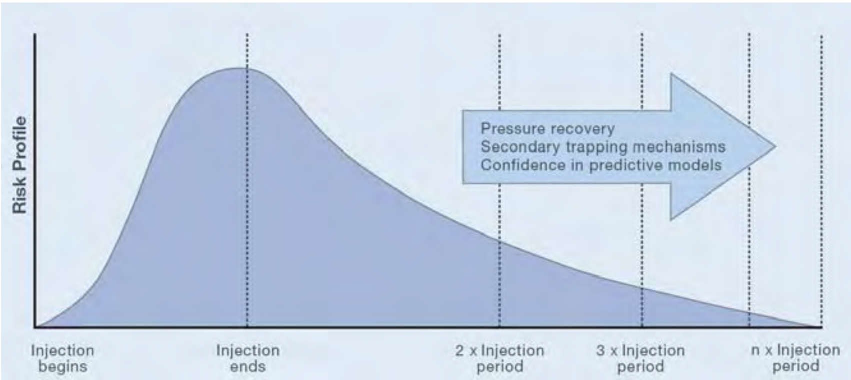
Responsibility for safe storage: long-term liability

If commercial players are to engage in a full-scale CCS industry, policy makers will have to address the liability issues associated with geological storage of CO_2. Currently, the scope of the long-term liabilities is not fully defined. For all practical purposes, the CO_2 will have to remain stored forever. A private company cannot be expected to take on responsibilities that last for centuries or more, but a state can. It seems reasonable to expect that the operator or developer of a storage field carries the responsibility for safe CO_2 storage during the operation of a project and during an agreed upon number of years thereafter (see Figure 9), as is the case with gas production.

[66] Fuss, S., Szolgayova, J., Obersteiner, M., Gusti, M. Investment under market and climate policy uncertainty. *Applied Energy.* Vol. 85. pp. 708 – 721. 2008.

This liability, however, cannot stretch further than the requirement that industry has done all that is technically possible to guarantee safe storage. To hand the responsibility over to the state, the criteria that should be met should be clearly defined, after which the operator and the government can agree that all that is technically possible has been done. Once these criteria have been met, private companies are likely to require full indemnification against any future claim by government and/or third parties.

Figure 9. Hypothetical CCS site leakage risk profile[67]



Regulatory framework

Currently, there is no regulatory framework designed to deal specifically with CCS. It seems likely that a variety of institutions, existing and new regulations, and industry best-practices will guide how initial projects are conducted. Existing standards and regulations are often not designed with CO_2 storage in mind and will, therefore, need to be adapted.[68]

On 23 January 2008, the European Commission presented a 'Climate and Energy' package that included a proposal for a directive on the storage of CO_2 for CCS projects. It sets out a common framework for *inter alia* site selection, exploration and storage permits, monitoring and reporting, operation, closure and post-closure obligations, third-party access, and the ultimate transfer of long-term responsibility to the state.[69]

The draft "CCS Directive" from the European Commission provides for long-term liability to pass from the site operator/developer to the state at the end of storage operations, but the earlier mentioned criteria for safe storage have not yet been defined. As long as these terms and conditions are not clear, they remain a hurdle for CCS investments.

Apart from creating the right framework for CCS business, a number of international conventions still classify CO_2 as a waste that cannot be stored in the sub-seabed, for example. Principal amongst these conventions are OSPAR and the London Convention. In November 2006, amendments to the 1996 Protocol of the London Convention were successfully passed, while in June 2007 the OSPAR contracting parties approved by consensus an amendment to "allow all forms of carbon capture and storage in sub-seabed geological formations". Efforts are now underway to amend Article 6 of the Protocol to the London Convention, as this prohibits the transboundary shipment of waste and therefore could effectively hinder the development of the pan-European CO_2 infrastructure. Meanwhile, the amendment to OSPAR will only come into effect once ratified by a minimum of seven contracting parties, an event which is not certain and which may take a number of years. Progress is being made, but the timing will remain a factor that influences short-term decisions on CCS investment.

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[67] Benson, S.A. *Geological Storage of CO_2: Analogues and Risk Management, presentation to Carbon Sequestration Leadership Forum.* Pittsburgh. 7 May 2007.

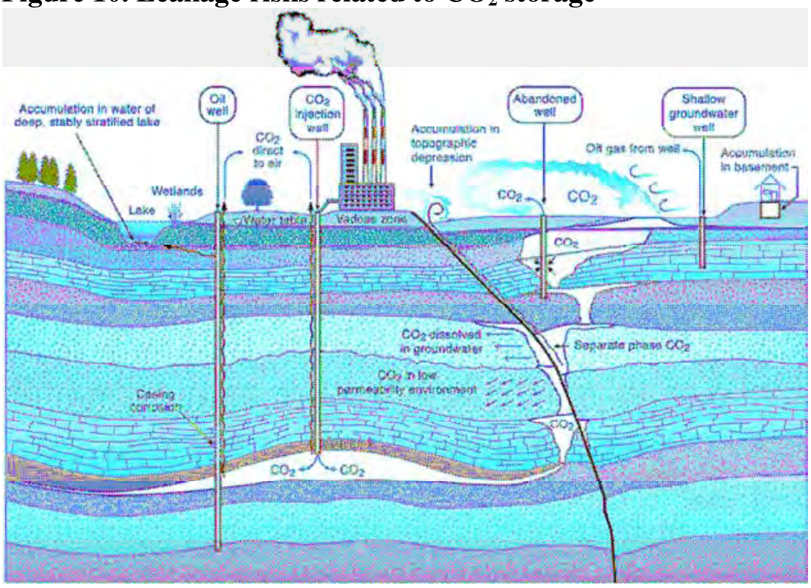
[68] World Resources Institute. *Capturing King Coal. Deploying Carbon Capture and Storage Systems in the U.S. at Scale.* Washington D.C. June 2008.

[69] European Commission. *Directive on the geological storage of carbon dioxide and amending Council Directives.* COM (2008) final. Brussels, 2008.

4.2. Permitting and leakage risks

There are still unknowns around the exact behaviour of CO_2 in underground formations. Experts believe that the risks will be manageable and not greater than the risks of other industrial activities.[70] However, when it comes to permitting, the licensing authority (and its advisors) will require maximum certainty that all risks involved are visible and manageable. Since CCS is a new activity, the licensing authority and related parties will need time to build up their knowledge of all possible risks related to CO_2 transport and storage. In depleted gas reservoirs, the risk of leakage mainly depends on the cap rock, faults, possible spill points and well integrity. With permitting, the main aim is generally to avoid any hazards through different kinds of "barriers" for example by monitoring underground and near possible spilling points. Should an undesired event occur, other barriers should be in place to avoid/mitigate dangerous consequences. What these barriers should be, exactly, still has to be determined.

Figure 10. Leakage risks related to CO_2 storage



Six different categories of unwanted consequences from leakage have been identified. These are not specific for depleted gas fields, but count for all different types of storage reservoirs:[71]

1. Groundwater contamination from leakage in drinking water or catalyzing other pollutants
2. Induced seismicity risk due to the pressure build-up of CO_2 in the underground
3. Risk to human health from leakage
4. Climate risk associated with potential releases of CO_2
5. Property damage risk to underground assets (like natural gas)
6. General environmental degradation

The potential for each of these risks occurring obviously depends on the type of storage formation. It is often stated that the risks associated with storage in depleted gas fields are limited, since these fields have already held natural gas for several hundred-thousand years. In any case, the risks will be subject to assessment by the licensing authority, in the Netherlands the Ministry of Economic Affairs is advised by the "State Supervision of Mines" and TNO. There is already extensive experience with such permitting procedures in the natural gas industry, but since CO_2 will probably behave differently in the subsurface than natural gas, it will take some time to build the right competencies that are needed for the permitting procedures.

[70] IPCC. *Carbon Dioxide Capture and Storage,* 2005. New York, Cambridge University Press.
[71] de Figueiredo, M. *The Liability of Carbon Dioxide Storage.* PhD Thesis. MIT. 2007.

4.3. Public acceptance and 'NUMBY'

Public acceptance represents a significant hurdle to the realisation of CCS. A fundamental concern that has to be overcome is the acceptability of CO_2 storage near one's home, school or office, the so-called 'not-under-my-backyard' (NUMBY) issue. Along with this, there is also the perception that the costs and risks will be borne by the local community while the benefits go to the larger global community.[72] A successful regulatory framework for CCS should, therefore, also address communication with the general public. Because this is a new type of development, it is important that the public be educated on the subject. Very few people seem to be aware of the option of CCS to mitigate climate change, let alone to be aware of the real risk level associated with it.

Just a bit of negative media attention can easily create the perception of a much higher risk profile than would be expected in reality. A proposed project for onshore storage that suffers from public fears is Shell's Barendrecht project, for example. Lack of public acceptance for onshore CO_2 storage holds the risk that onshore projects cannot materialise, which could lead to a loss of almost half of the total Dutch storage capacity. If the licensing authority (government) is convinced that safe CO_2 storage is possible at certain sites, it would be very helpful to the optimal development of CCS if the government would help to overcome public concern.

Key messages

- Three main non-economic or technical barriers for CCS are identified: unclear who is responsible for long-term liability, lack of a specific regulatory framework and public perception.
- Responsibility for storage and transport can be with the operator (if not a public party) during the operation phase and for some years thereafter. Long-term liability should be with the government, because no private party can carry that risk. Liability issues are mainly related to CO_2 transport and storage and not to the capture of CO_2.
- After a period of time, the liability for safe storage should go from the operator to the government. Therefore, criteria for demonstrating that secure long-term storage has been achieved should be agreed upon. As long as these terms and conditions are not clear, the liability issue will remain a hurdle for the further development of CCS.
- To date, it is unclear what government body could take care of the long-term storage and what such custodianship actually implies.
- Public perception of CO_2 storage, especially onshore, could become a major hurdle if not managed properly. If the licensing authority is convinced that safe storage is possible, the government should help to gain public acceptance.
- There still seems to be some uncertainty about how the permitting authorities will evaluate possible leakage risks related to CCS. In fact, the parties involved in licensing also have to undergo a learning curve and need time to build the right competencies and skills.

[72] World Resources Institute. *Capturing King Coal. Deploying Carbon Capture and Storage Systems in the U.S. at Scale.* Washington D.C. June 2008.

5

5. Learning, timing and upscaling

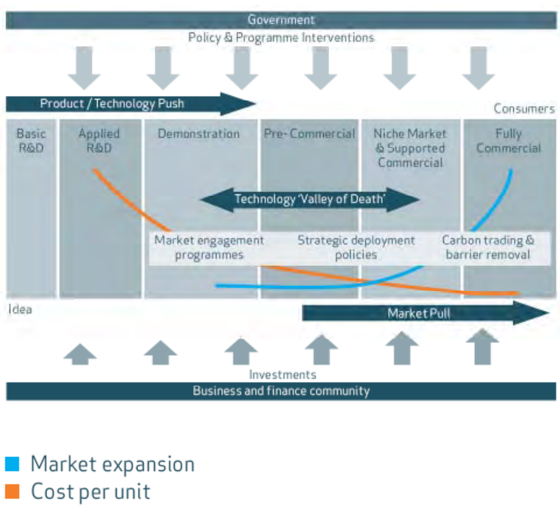
This chapter will focus on the discussion surrounding the elements that should be managed on the path towards a large-scale CCS system. Firstly, the cycle of technological developments; secondly, timing; and thirdly, models of upscaling.

5.1. The cycle of technological development

New products and technologies generally have to go through a number of stages before they become commercially available. Basically, this learning process starts with the research and development phase, followed by the demonstration phase, the upscaling/deployment phase and, finally, the commercialisation/diffusion phase. The different phases generally require different roles for the government. The early stages of development usually require the government's role as enabler and financier of R&D and as co-funder of demonstration projects, whereas in the later stages the government's role should be more focussed on setting the conditions that enable the market to embrace the new technology.

Figure 11 shows that in the first stages of the technological development cycle the role of the government should be focussed on lowering the costs per unit and pushing the technology forward. In the later stages of development, the role of government should be more focussed on enabling the market to adopt the technology by setting the right regulatory and economic conditions.

Figure 11: Cycle of technological development[73]



The division of roles between the government and companies is clearly illustrated by the following quotes:

"Industry is very good at developing the technology, but if you look at the major innovations that have occurred over the twentieth century, the initiation and the innovation in almost all cases comes from government research spending. Once the concepts are out there, then industry comes in and makes a buck out of it. But they are not good at starting the ball rolling."

[73] Grubb, M. Interaction of technology and carbon markets – a "full circle" journey around carbon policies. *BP Madrid Forum, 2008.*

"…The government should focus on creating the conditions for technological innovation, rather than assuming that technological advancement needed to achieve emissions reduction will happen spontaneously" [74]

5.1.1. Accelerating the learning process

A learning process is inherently uncertain and involves wasting options. It is therefore important for CCS that it be tested with a variety of different capture technologies and in different storage locations.[75] CCS is different from other technologies because it is not one technology that has to be further developed, but a chain of technologies. Therefore, this chain also has to be tested in integrated projects.

Industry and governments want to accelerate the learning process for CCS. This mainly has to do with the idea that CCS is one of the key elements in an abatement strategy. The European technology platform on zero emission fossil fuels (ZEP) stated in its February 2008 recommendations that *"any material delay not only risks, but ensures, that CCS technology will not be commercially available by 2020 and that the target for 2050 emissions will be gravely endangered"*.[76]

Accelerating the learning process too quickly holds the risk of ending up with a more expensive (immature) technology than would be the case for a technology that has had time to climb up the learning curve through trial and error. The best way to facilitate the CCS learning process at this time is to start with demonstration projects as soon as possible.

5.1.2. Testing the technologies in demonstration projects

CCS is currently at the start of the demonstration phase (i.e. the pilot phase), which means that the basic technologies are known, but that more experience is needed about how these technologies will work in practice and on a larger scale. So, the crucial next step for CCS is to test technologies on a larger scale in demonstration projects. The IEA and the Carbon Sequestration Leadership Forum recommended building 20 large-scale demonstration projects for CCS. Full-scale demonstration projects (often 300 MW and 2 Mt/a of CO_2 are mentioned) are critical for learning, but involve unusually high costs and risks, making it necessary for the government to still play a role, by taking away (financial) risks.[77]

Some demonstration projects are already in operation and several other projects have been planned, in the Netherlands as well as worldwide. The goal of these demonstration projects is to allow learning in a way that makes large-scale CCS commercially viable for all new fossil fuel power plants by 2020; in the case of the Netherlands between 2015 and 2020.[78]

The European Commission decided to set up the EU Flagship Programme, under which 10 to 12 large-scale integrated demonstration projects must be developed and become operational by 2015. The demo's should be developed with different capture technologies and fuels, be tested in a variety of geographical and geological settings Europe-wide. The expected costs for these 10 to 12

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[74] Tom Wigley in EurActiv.com 7 April 2008. *UN climate panel making 'dangerous assumptions' say scientists;* Pielke, R., Wigley, T. and Green, C. Dangerous assumptions. *Nature.* Vol. 452. Nature Publishing Group. 3 April 2008.
[75] In general, especially radical changes – which may still be needed for CCS to become commercially viable– may require a large degree of diversity, because then the probability of realizing major innovative combinations is high (Olson and Frey, 2002).
[76] Zero Emission Fossil Fuel Power Plants (ZEP). *The EU Flagship Porgramme for CO_2 capture and storage (CCS). ZEP Recommendations: Implementation and Funding.* February 2008.
[77] World Resources Institute. *Capturing King Coal. Deploying Carbon Capture and Storage Systems in the U.S. at Scale.* Washington D.C. June 2008.
[78] Ministry of Environment. Press release 3 April 2008. *Cramer: 'Nederland koploper ontwikkeling CO2 afvang en opslag';* European Commission. *Energy for a Changing World.* COM (2007) 1, Final. Brussels. 2007.

demonstration projects are €6 – 10 billion euros, according to estimates of the European Technology Platform.[79] Other sources point at cost levels in the range of €10 – 16 billion.[80]

The European Commission seems to have little room in its 2008 – 2013 budget to co-finance the CCS projects together with the industry. Member-States are therefore expected to grant subsidies to companies that are willing to operate such demonstration projects. To facilitate this, the Commission already proposed a softening of the rules for state-aid in relation to CCS. A financing option that could be available before 2013, but politically very challenging, is using the surplus of agriculture funds for CCS. Another way could be to use (a part of) the revenues from the auctioning of CO_2 allowances that is planned for EU ETS 2, for the support of low carbon energy, including CCS. The Dutch government strives for the development of four demonstration projects for the capturing of CO_2 and two storage demonstration projects. It tries to persuade companies to start such projects by tendering investment subsidies.[81]

Some remarks on the demonstration projects

Currently, a number of CCS projects are running. The existing projects are often built for other reasons than the development of CCS as a mitigation technology. The projects were often developed because the amount of CO_2 in natural gas was too high, at certain sites, to be sold directly to the market. Therefore, the CO_2 had to be removed to be able to reap the economic benefits of gas production. In such a project, removing CO_2 has a positive value (i.e. revenues from gas sales) and refers to completely different economics than a CCS project that is developed with the aim of reducing CO_2 emissions.

Many new projects have been proposed or planned and are awaiting final approval to start construction. This final approval will depend on the different elements discussed earlier in this report (CO_2 price, incentives and other uncertainties related to long-term storage). As long as no clarity is provided about these areas, it is unlikely that the hoped "*hausse*" of demonstration projects will occur.

Finally, it should be noted that the number of integrated projects that cover the full chain of capturing CO_2, transporting it and storing it underground is limited, thus far. Until now, most projects cover only one separate segment of the CCS value chain, capturing or storing. Several plans for larger integrated projects have already been announced, Europe-wide, and also in the Netherlands. RWE, for example, announced that it will build a 35MW test plant in north Netherlands (for further information on the initiatives in north Netherlands see Annex II).

5.2. Timing of carbon capture and storage: a crucial factor

It has been argued more often than not that action is needed now to ensure that CCS can be developed as a commercial technology.[82] With respect to taking this action, it should be remembered that CCS consists of a chain of technologies whose timing and learning are interlinked. To make large-scale CCS happen within the desired timeframe, timing at each of the different steps should fit together. This means that storage reservoirs, transport lines and point sources with viable capture technology should be available simultaneously, and so should the required economic and regulatory conditions (including public acceptance).

The timing of the availability of storage reservoirs in the Netherlands has two sides. On the one hand, it depends on the remaining time of gas production. Rising gas prices can mean that fields will remain in production longer than would have otherwise been the case, making them available later for CO_2

[79] Zero Emission Fossil Fuel Power Plants (ZEP). *The EU Flagship Programme. The key to making CO_2 Capture and Storage (CCS) commercially viable by 2020.* October 2007.
[80] Mabey, N. Taming King Coal – The EU's energy policy. *Carbon capture journal.* Issue 3. May - June 2008.
[81] Ministry of Environment. *Kabinetsbrede aanpak duurzame ontwikkeling.* 6 May 2008. DGM/BREM2008050615.
[82] Zero Emission Fossil Fuel Power Plants (ZEP). *The EU Flagship Programme for CO_2 capture and storage (CCS). ZEP Recommendations: Implementation and Funding.* February 2008; Guardian, June 2008. *The Carbon Question. Carbon capture and storage's role in preventing global disaster.* Societyguardian.co.uk.

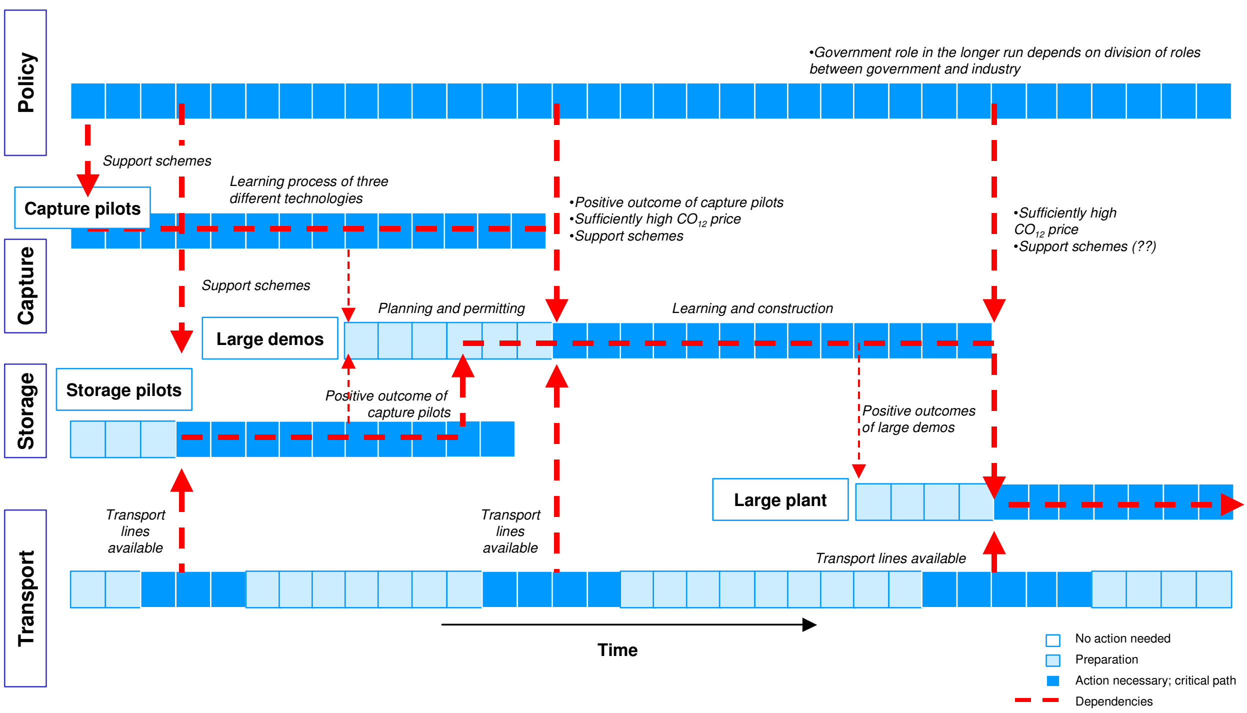
storage. On the other hand, it depends on the moment that production in a field ends and it gets abandoned. Ideally, this moment matches the start of CO_2 storage because it would enable optimal use of the existing infrastructure, and the condition of the reservoir would be well known. Since many of the fields that could be used for CCS are still in production, coordination of the activities at the reservoirs is desirable.

For transport, timing depends on the time it takes to build a new pipeline, typically 3-4 years, and on the possibility of re-using existing pipelines. A pipeline that is still in use for gas transport cannot be used for other purposes, not even when capacity usage is very low. Availability of existing pipelines is, therefore, likely to coincide with the availability of clusters of storage fields and could be a proper match. However, it should be carefully checked to determine whether a gas pipeline that was constructed for 30 years of transport could last another period for CO_2 transport.

Zooming in on the timing of the demonstration plants and the capture technology, it should be noted that the preparation phase of design, permitting, planning, tendering procedures and construction will require several years. Similarly, learning about and testing operational pilot and demonstration projects will take time. ZEP calculates that a minimum learning period of 4 years is needed; other private parties state that they need less time (1.5 – 2 years) for learning.[83] Obviously, learning in one project or phase of the technology development cycle can go in tandem with the design and preparation of the following phase and, as such, shorten the learning process. There are various other ways that can shorten the learning period, like retrofitting existing plants instead of building completely new plants, or testing different technologies on the same demo installation. Moreover, starting with the "easy" (pure) CO_2 sources involves less learning than starting with a coal-fired power station where capturing still needs to be tested more thoroughly.

In Figure 12 the timing and dependencies of the CCS learning process are illustrated. The picture shows different action lines that need to take place sequentially to bring CCS forward and, as such, draws the "critical path" towards full-scale implementation.

Figure 12: Timing and dependencies of the CCS learning process



[83] Zero Emission Fossil Fuel Power Plants (ZEP). *The EU Flagship Programme. The key to making CO_2 Capture and Storage (CCS) commercially viable by 2020.* October 2007.

The purely illustrative figure above aims to show the dependencies that exist between the different CCS related ‘action lines’: policy, capture, storage and transport. The red dotted arrows show that some actions can only start after other actions have been finished. In addition, the text next to the arrows shows the conditions that need to be in place to go to the other action line.

The government will have to kick-start the development by creating the right regulatory and economic conditions. The government will have to begin with some simultaneous actions: ensuring clear permitting procedures, providing clarity on the liability for long-term storage, providing incentives for private action with support schemes and, if needed, coordinating storage locations. These are preconditions for the start of pilot- and smaller-scale demonstration projects. Less urgently, policy makers should set up a clear regulatory framework and a predictable and strict climate policy that results in CO_2 prices high enough to enable CCS. Larger-scale projects will not appear if these latter conditions are not put in place.

Once industry has gained enough experience with the pilot projects, the preparation for large-scale demonstration projects, and after that large-scale power plants, can start. The (expected) value of CO_2 credits and possible additional government incentives will become even more important at this stage, since the economic risks are increasing as well. Ensuring the required transport infrastructure will become more complex as more point sources and storage locations will need to be used.

The process towards large-scale CCS is obviously related to risks and uncertainties. Investors could, for example, need more time to gain experience with storage and to find out about the underground behaviour of CO_2; monitoring and verification will take at least three years.[84] Lack of public acceptance could also delay/cancel CO_2 storage projects and cause a delay in the development of CCS in the Netherlands, especially onshore.

5.3. Different models for a large-scale operational system

There is little documentation around the considerations and implications of a fully operational CCS system. So far there is no shared vision regarding the business model, organisation or roll-out of a commercial application. Such vision should come from the government and, indeed, this has been recognised in the recently published *Energierapport* from the Dutch Ministry of Economic Affairs.[85]

Ideas around the roles and responsibilities vary significantly:

- *Full public utility-type business:* responsible for collecting and storing CO_2 from emitting sites
- *Complete reliance on private initiatives:* private parties bid to collect and store CO_2 within a framework of rules, and coordination set by the government.
- *Public/private partnerships:* somewhere in between the two, where the state can participate in storage projects.

Such a public utility-type of CO_2 transport and storage company could either be the ultimate model or just serve to kick-start CCS and take away part of the risks only for the initial phase. The benefit of this model is that it takes away a number of uncertainties that can be difficult for the industry to control, like legal matters relating to networks, storage and public acceptance of storage.

The following will elaborate on some questions to consider about rolling out a commercial CCS system. Some of these are dependent on a certain vision for a model; others seem to impose an inevitable conclusion.

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[84] International Risk Governance Council. *Regulation of Carbon Capture and Storage.* Policy Brief. IRGC, Geneva, 2008.
[85] Ministry of Economic Affairs. *Energierapport 2008.* (www.ez.nl). June 2008.

Storage

- There seems little disagreement that the custodianship of CO_2 fields after injection should be in public hands. This is one of the elements on the critical path, as not even the first pilot project will have been conducted while this matter remains unresolved. However, arrangements must also be in place to ensure that the custodial party is involved and satisfied with the processes of storage.
- The government must grant licenses for CO_2 storage. Should this be done on a reactive basis, with the government responding only to parties applying for such licences, or more proactively, with the government making an inventory of potential reservoirs and "earmarking" suitable fields? The latter could avoid having a core field in a storage cluster hampering CO_2 storage.
- If there is a limited amount of potentially suitable reservoirs for CO_2 storage, who should maintain these fields in a condition that would allow storage in due course, with efficient use of existing facilities? There will probably be a cost associated with the preservation of depleted fields. So, who should carry these costs? How soon will these measures be needed before potentially valuable storage is abandoned?
- What capability will be required for future operators of CO_2 storage? Are these capabilities different compared to what is required from current producers of gas fields?
- The clustering of fields may be a necessary condition for continuous, large-scale storage: is it best to rely on private industries to develop such clusters? The offshore natural gas evacuation systems such as NOGAT, NGT, WGT are examples of private industries' success in developing clusters. Or, does it require a coordinating approach by government to identify fields as belonging to a CCS cluster and allocate priorities?
- What will be the (commercial) terms under which the field owners/operators will be prepared and/or allowed to store CO_2?

The first three points need early resolution. They lie on the critical path for the development of a full CCS system. Resolution on the other points could take a bit more time; these do not seem to be critical at this point in time, but need to be resolved before preparations for a large-scale system need to start.

Transportation

Contrary to gas distribution, there seems to be little need for interconnection between pipelines, so the notion of different entities collecting CO_2 on a stand-alone basis seems feasible. However, the Netherlands is too "full" to allow for competing pipelines. Some measure of coordination will be required. The process of creating a pipeline infrastructure is, by most parties' estimation, going to take 3 – 4 years from licensing to laying the hardware. It, therefore, does not seem to lie on the critical path today.

Capturing: one customer at a time?

If the choice to store or emit CO_2 is with the emitting party (i.e. there will be no obligation on any party to store CO_2), their choice will have an impact on the layout of the system. Consequently, each emitting party may come to the decision to store CO_2 in its own time, and depending on its own economic evaluations. Even today, these may be very different for different parties, and their decision to seek storage could be made at very different times. This could have a profound effect on timing, sizing, economies, risk distribution, and, hence, on the cost of developing the infrastructure for collecting CO_2.

Is there a time constraint?

Apart from the minimum requirements on custodianship and licensing, there seems to be time to develop the master plan without incurring delays in the targets set by government.[86] If true, this leaves the question of whether a vision/organisation could affect the competitiveness of new power plants and the selection of locations? If the government choice would be for the private market model,

[86] Breunese, J.N. *The Netherlands: a case of optimisation of recovery and opportunities for re-use of natural gas assets.* 23rd World Gas Conference, Amsterdam 2006.

removal of CO_2 becomes a matter of economics and, for some industries, this could be more costly than for others, depending on location. Whether this could make so much difference that it would affect the choice of sites for new investments remains to be seen.

Key messages

- In a learning process, government involvement is vital to get the ball rolling. For CCS, the first steps should include providing clarity around permitting, making clear arrangements for long-term liabilities and providing incentives for CCS, among others, through funding of demonstration projects.
- Action is needed now because learning and the coordination of activities will require some time as well.
- Accelerating the learning process will be needed to get the technology in place within the desired timeframe. It should be carefully monitored so that no immature and more expensive technology gets locked in.
- CCS consists of a chain of technologies that all have to work as an integrated process. This process needs to be tested in integrated demonstration projects, before large-scale CCS will be deployed.
- There are several dependencies between the different activities. Storage reservoirs, transport pipelines and capture from point sources should be available simultaneously with the required economic and regulatory conditions in place. To make it work in time, the various timelines should fit together, which will require some sort of coordination.
- There is no shared vision of the business model, organisation or roll-out of a future (commercial) CCS system in the Netherlands.
- A decision on the definition of the role of government and that of private industry could have a major impact on the allocation of risks, costs and on the timing of the preparations for a large-scale CCS system.
- However, with the exception of a few elementary aspects (e.g., custodianship, licensing), a decision by the government on the *structure* does not seem to lie on a critical path. Nor does the absence of such a decision appear to impact the timing and/or decision to invest in new emitting plants or the current work on pilots and demo's.
- Hence, there is still time for further analysis and consideration, but not a lot. It would be wasteful, for example, if depleted gas fields were abandoned while they may still have a possible role for CO_2 storage.

6

6. Concluding remarks

This carbon capture and storage reality check for the Netherlands has been conducted to understand the role that CCS could play in the Netherlands and to find out what still needs to be done to move towards a large-scale CCS system by 2020. This analysis covered the entire CCS value chain and focussed on the required conditions to get CCS in place on time. As a conclusion, the four core questions will be addressed.

1. Do the physical sources and storage capacity underpin the storage of significant amounts (≥ 20Mt/year) of CO_2 in the Dutch underground, by when and for how long?

Storage capacity will become available over the coming two decades. The pace at which this happens will depend on the gas price because a high gas price makes it attractive to continue gas production. With the total storage capacity available in the Netherlands, it will be possible to store 35 – 40 Mt/a over a period of 40 years.

2. Are the required economic conditions and enough incentives for the industry in place to get CCS off the ground, and what additional measures could be taken?

The economic conditions thus far do not yet make large-scale CCS very attractive. A number of topics that need to be addressed are: a firm climate agreement with a cap and trade system, where CCS is allowed as a mitigation option; a decrease in the costs of CCS through learning; and, incentives to overcome the large price risk that is related to the CO_2 price. Especially during the demonstration phase, additional government incentives to remove uncertainties and lower first-mover costs will be needed. Since the CO_2 price is not yet high and stable enough to finance these investments, a lack of these incentives will slow down the development of CCS. An incentive that lowers the CO_2 price uncertainty, like a CO_2 price-dependent subsidy with a certain cap, might be very attractive.

3. What are the main barriers/risks that potentially block the accelerated development of CCS?

Uncertainty over liability for long-term CO_2 storage, the lack of a clear framework in which activities can take place (including permitting), and possible issues related to public acceptance of CO_2 storage are the main non-technical or economical issues related to the further development of CCS. If these issues are not resolved in the near-term future, it will delay the further uptake of CCS, since companies will not be willing to invest under such conditions.

4. Is there a realistic path to get from a few pilots to an accessible and operational system for large-scale CCS and what timelines relate to this? Is there a need to set up a full-scale centralised system for large-scale CCS or should single initiatives be supported?

Due to the different uncertainties involved in the learning process and in relation to the economic and regulatory conditions, it is hard to set timelines for a large-scale system to be operational. The path towards a large-scale system will have to consist of a process of trial and error with several demonstration projects being conducted. Coordination will be vital in a number of areas: the match between the end of gas production and the start of CO_2 storage (especially for offshore storage), and the setting up of a transport infrastructure that is linked to different “CCS earmarked” storage locations. Such infrastructure can either be stand-alone or a more centralised system, depending on the vision and division of roles between public and private parties. There are still a couple of years left to assess what model best suits the purpose of large-scale CCS to be available by 2020; however, it's not much time.

Key messages

- Realistically, the Netherlands has an estimated storage capacity of 35-40 per year Mt of CO_2 for a period of 40 years, using onshore and offshore reservoirs.
- CCS can contribute to 20 - 25% of emission reduction targets for a period of 40 years. After that period, CO_2 flows should be exported to storage locations abroad or CCS should be replaced by alternative reduction options.
- Expected CCS costs vary substantially, between €30 and €120. CO_2 price forecasts vary between €20 and €70. It is therefore difficult to predict when commercial viability of CCS will be a reality. However, still subject to uncertainty, there are prospects that somewhere between 2015 and 2025 CCS can become commercially attractive.
- Responsibility for long-term liability needs to become clear as soon as possible, next to agreed upon criteria that define safe storage.
- Active coordination is crucial for the timely availability of storage reservoirs, pipelines and large-scale CO_2 capture.
- Timing depends on many uncertainties and on the envisaged market model. It seems, therefore, unrealistic to set targets by certain dates.

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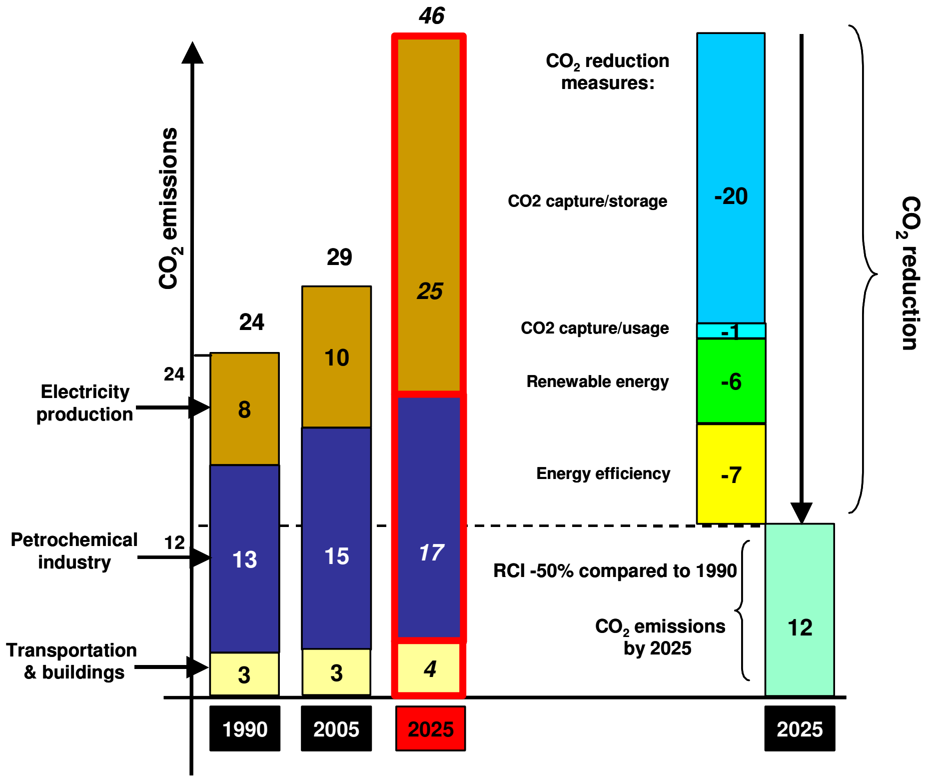
Annex I

Rotterdam Climate Initiative reduction targets



Annex II

In an attempt to foster employment and economic growth through the development of energy related activities, the Northern provinces have joined forces through an initiative called "Energy Valley". Included in this initiative is an agreement with the central government that aims to reduce greenhouse gas emissions by 4.5 Mt in 2011 and by 15 – 20 Mt in the years thereafter.[87] Two of the energy related activities are especially relevant for the development of CCS: the proposed power plants of RWE and Nuon. The nearby availability of empty gas fields offers an opportunity to lower carbon emissions using a large-scale carbon, capture and storage infrastructure.

RWE, Gasunie and a storage partner have announced the intention to realise a CCS demonstration project incorporating the post combustion capture technology. Once the pilot tests have been completed successfully, the large scale demonstration capture plant (0,2 Mt/a) is to be constructed in Eemshaven by 2015. When the demonstration project proves to be successful and CCS is commercially viable, this technology will be installed at the newly built hard-coal power plant. For RWE's power plant this could mean the phased construction of four capture-trains of 400 MW each to be built between 2017 and 2027. Nuon is constructing a 1200 MW power plant in two steps. The first step is the construction of a gas fired power plant, which should be followed by the construction of a coal and biomass gasification plant as from 2013. The gasification plant will enable pre-combustion capturing of CO_2.

[87] http://www.minvrom.nl/Docs/milieu/200710_convenant_energieakkoord.pdf

The planned infrastructure will be initially over-sized to quickly accommodate transport and storage of CO_2 when CCS becomes commercially available. The infrastructure should be able to accommodate CO_2 stream of 10 Mt/a by 2020.

Annex III

	IGCC-CCS	PCC-CCS	Oxyfuel capture

Advantages/ Opportunities +	▪ Potentially highest net efficiency of capture techniques (ca. 40%)
	▪ Fuel flexibility might be achieved in future
	▪ Gasification process itself is proven technology
	▪ High purity of CO_2
		▪ End of the pipe technology
		  ▪ Plant can be run without capture
		  ▪ Retro-fitting options
		▪ R&D development likely to reduce efficiency penalty to levels of IGCC
		▪ No changes in proven and optimized combustion
			▪ Technology is at the very beginning offering improvement potential on almost every single aspect
			  ▪ Net efficiency
			  ▪ Retro-fitting (of gas plants)
			  ▪ Plant availability without capture

Disadvantages/ Threads −	▪ Hydrogen combustion still in pilot phase (2008)
	▪ No end of the pipe technology
	▪ Retrofitting limited to gas plants, if at all
	▪ Plant can only run inefficient without capture
	▪ Relatively high CAPEX
		▪ Available technology today reduces plant efficiency by ca. 12% points
		▪ Relatively high operational cost (e.g. solvent)
		▪ Due to large flue gas volume, large space requirements for CO_2 capture
			▪ Uncertainties/technical hurdles still need to be overcome
			  ▪ Boiler design (high temperatures and flexibility)
			  ▪ H_2O content in the captured CO_2
			▪ Uncertain investment cost

Clingendael International Energy Programme