Catching carbon to clear the skies

Experiences and highlights of the Dutch R&D programme on CCS

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Foreword

Energy policy is a high priority area for the government of the Netherlands. It is our ambition for 2020 to be one of the most sustainable and efficient energy economies of Europe. This will require an annual increase in efficiency of 2%, a share of 20% in renewable energy sources and 30% reduction in greenhouse gas emissions.

Carbon dioxide capture and storage (CCS) plays an important role in the reduction of emissions. That is the reason why I applaud the efforts of the CATO research programme in the period 2004-2008 to create the necessary CCS knowledge structure in the Netherlands. CATO has gradually developed into the national CCS programme, which is expressed well in the conclusions of the international CATO midterm review committee: *"CATO has developed into a successful research network in the Netherlands and has "de facto" become the Dutch national CCS programme. -- CATO has initiated numerous CCS projects in the Netherlands that are now highly relevant to the new national Dutch policy on climate change where CCS is recognised as an important element. CATO is therefore a 'gift to government' and has established a much needed basis of a national capability in CCS".*

From 2004 to 2008,the view of CCS among important stakeholders has changed from a scientifically interesting area towards a serious and concrete technology to help reduce our emissions, both in the power sector as well as in the industrial sector. This is strongly supported by the rapid European developments, where the European stakeholders have joined forces in the Technology Platform for Zero Emission Power plants (ETP-ZEP), and formulated the ambition to have at least 10-12 large CCS demonstration projects running by 2015. The Netherlands' government is keen for the European Commission to select two large Dutch demonstration projects, one in the Rotterdam area and one in North Netherlands. CATO has laid the foundations for these demonstration projects, and the successor programme. CATO-2, has been tailored to support these large demonstration projects with the necessary additional research.

This CATO booklet describes the activities undertaken in the period 2004-2008, underlining the relevance of CCS for the Netherlands. The research accomplishments of the programme are described in a series of highlights, underlining the broad scope of the programme. I congratulate the CATO team with these accomplishments and wish the follow-up programme CATO-2 a similar success in supporting the demonstration and implementation of CCS in the Netherlands.

Maria J.A. van der Hoeven
Minister of Economic Affairs

1 – The origins of CATO

In 2000 a number of Dutch researchers, companies and environmental organisations decided to join forces. The result was a public-private partnership: the CATO research programme. Together, they pursued a single goal: to find out whether the promises of capture and storage of the greenhouse gas carbon dioxide will hold for the Netherlands.

CATO is the acronym for CO_2 Afvang, Transport en Opslag, which is Dutch for CO_2 capture, transport and storage. Capture and storage of the greenhouse gas carbon dioxide (CO_2) could free fossil-fuelled combustion installations from a major burden. Carbon dioxide Capture and Storage (CCS) technologies extract the CO_2 released during the combustion process, transport it and store it in a safe place to ensure that the CO_2 does not enter the atmosphere.

For many years CCS has held out this promise. By decarbonising fossil fuels such as coal and natural gas, they could become 'cleaner' in terms of climate change. Emissions of the main greenhouse gas CO_2 into the atmosphere could be largely reduced. But the technologies are still very young, particularly for application at large power stations. Since 2004, the CATO research programme has concentrated on bridging the gap between the potential and the reality.

About the CATO history

Dutch interest in carbon capture, transport and storage goes back many years. Already at the end of the eighties of the last century, policy makers and researchers were putting efforts into investigating CCS – be it somewhat academic at the time. This interest continued in a more practical way into the 21st century, for several reasons.

First, the status of greenhouse gas emissions and their effect on the world's climate are of great concern. From the CATO programme Plan: *"The evidence for the influence of these emissions on the global climate is becoming stronger and stronger. Most scientists agree that [..] the worldwide CO_2 emissions have to be reduced by more than 50%."*

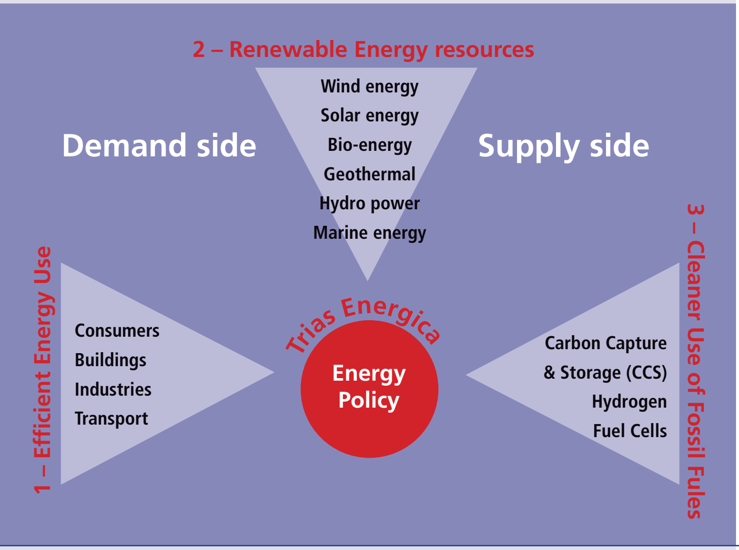
Dutch discussions about how to deal with these large reductions developed in their own particular way. As it became clear that, for a timely reduction of emissions, the combined effect of energy efficiency and renewables would not be sufficient, CCS was included in the so-called 'Trias Energetica' (see box on page 6).

Trias Energ(et)ica

CATO programme leader Erik Lysen coined the term 'Trias Energica' for the first time in a paper presented to the Eurosun conference in Freiburg in September 1996. The 'Trias' is an integrated package of three types of measures to reduce emissions:

1. Energy efficiency improvements (including efficient use of materials)
2. Use of renewable energy sources, which emit no (or little) CO_2
3. Cleaner use of fossil fuels, by capturing and storing CO_2 before it is released into the atmosphere.

Lysen borrowed the concept of 'Trias Politica' from Montesquieu. Montesquieu used his 'Trias' to separate legislative, judicial and executive powers. In energy strategies the 'Trias' integrates three elements: energy efficiency, renewables and cleaner use of fossil fuels. The term was quickly used by the agency NOVEM, for which Lysen worked at that time, but to make it easier to pronounce, the agency changed it into 'Trias Energetica'.



Again, from the project plan:
"It can be concluded that 'decarbonisation' of fossil fuels may also be required to reach the required stabilisation of the CO_2 concentration in the atmosphere, in bridging the gap to a fully renewable energy system."

The CATO consortium

Starting in 2004, the CATO programme was unique in terms of its volume of research and its broad, integrated scope. The research focused on system aspects, different capture techniques, storage in gas fields, enhanced coal-bed methane (ECBM), mineralisation, standardisation, safety and risk analysis, public perception, monitoring, the transition to a new energy infrastructure and test projects. Many stakeholders participated, from environmental organisations to universities, companies and research institutes.

Back in 2003 various actors in the Netherlands were working on different CCS topics. Joining these forces was a key component in the CATO objective:

" Building a strong knowledge network in the area of CO_2 capture, transport and storage, which in the period 2004-2008 will:

- *collect validated knowledge*
- *analyse the societal and industrial base*
- *generate the necessary technological expertise in order to be well-prepared for the possible transition to large-scale use of CCS options in the Netherlands energy economy."*

This combination of private and public participants was also a strong argument for the Dutch government to support the programme.

The Utrecht Centre for Energy research (UCE) became the natural coordinator, building on the CCS work of Prof. Wim Turkenburg and his team at Utrecht University.

Another important issue in CATO was its relationship to other international CCS activities. According to the mid-term review, which was carried out in August 2007 by the international Review Committee and chaired by the renowned CCS expert Dr. Kelly Thambimuthu, CATO has done this very well:

"CATO is well linked to CCS research activities internationally and especially in Europe. It is one of the few national European CCS programmes covering the entire CCS chain. The active participation of industry, research institutes universities and NGOs makes CATO a powerful consortium, which is similar in nature to the highly influential Zero Emission Power plant EU Technology Platform."

Participants to the CATO programme

Companies

- Shell (International Exploration and Production (SIEP) and Global Solutions)
- NAM (Nederlandse Aardolie Maatschappij)
- KEMA (through which the six Dutch electricity generating companies participated: Delta, Electrabel, E.ON, Essent, Nuon Power and Reliant)
- NV Nederlandse Gasunie
- Ecofys
- EBN (Energie Beheer Nederland)
- Geochem

Research institutions

- ECN (Energy research Centre of the Netherlands)
- TNO Science and Industry and TNO Built Environment and Geosciences

Universities

- Delft University of Technology (Faculty of Civil Engineering and Geosciences)
- Leiden University (Centre for Energy and Environmental Studies, Faculty of Social Sciences)
- University of Twente (Department of Chemical Technology)
- Utrecht University (Copernicus Institute; Faculty of Chemistry, Department of Earth Sciences and Department of Science, Technology and Society)
- UCE (Utrecht Centre for Energy Research)

Environmental organisations

- SNM (Netherlands Society for Nature and Environment)
- Greenpeace Netherlands
- WNF (World Wildlife Fund Netherlands)

A brief history of the birth of CATO

- **29 September 1999:** the Utrecht Centre of Energy research (UCE) held its first workshop on ‘Renewable energy versus clean fossil fuel with CO_2 storage?’ in the offices of the REMU Energy Company at the Atom Road in Utrecht.
- **September 2000:** UCE started preparing an ‘Expression of Interest’ for the ICES-KIS programme. This €800 million Dutch fund focused on building knowledge infrastructures.
- **July 2001:** on finding a name: Jip Lenstra of the Ministry of Environment mails UCE director Erik Lysen: “Dear Erik. How about CATO: CO_2 Afvang, Transport en Opslag? Jip”
- **6 July 2001:** the first CATO preparatory meeting for Expression of Interest
- **2002:** CATO entered the second ICES-KIS phase: writing a full project proposal. The crucial issue of 50% co-financing was solved by ECN and TNO.
- **15-16 February 2003:** high-pressure finalisation weekend of the proposal. Only a few days before, critical NGOs Greenpeace and Society for Nature and Environment agreed to participate.
- **November 2003:** CATO completed the first in a list of eight programmes in the group Sustainable System Innovations and was granted €12.7 million: 50% of the total funding of €25.4 million for the period 2004-2008.
- **7 April 2004:** kick-off meeting CATO, including the launch of the official logo.

cato

Reading guide

After five years of research, CATO has largely achieved its goal. Without providing all the definitive answers to the technological and economical questions about CCS, the research has provided much greater clarity on the perspectives for industrial applications. However, it will take many more answers and several more years before CCS can be demonstrated in large-scale installations.

This booklet will lead you through the main components and results of the CATO programme. It presents the main objectives and the highlights of the scientific research. Some research has moved out of the laboratory phase into practical pilot installations, and important aspects for society have been mapped. Interviews with third parties give an impression of how CATO is perceived in the world.

However, you will also learn that CCS developments do not stop here. Many questions still need to be answered. CATO-2 is now about to start. It will cover the research for the next steps towards implementing CCS in the Netherlands.

Kelly Thambimuthu

‘A good position in the world’

Dr. Kelly Thambimuthu is Chief Executive Officer of the Centre for Low Emission Technology (cLET) in Brisbane, Queensland (Australia). He is also chairman of the Greenhouse Gas R&D Programme of the International Energy Agency. In 2007 Dr. Thambimuthu chaired the mid-term CATO review committee.

“Once established, it became a well-coordinated research programme along the whole carbon capture and storage chain. It’s a real focal point for national activity, one of the few coordinated CCS programmes in the world.”

“The coordinated approach was very efficient. It also succeeded in bringing the results to the attention of the international CCS research community. Thanks to its high quality input, CATO has achieved a good position in the world. The Dutch participation in EU and global programmes was complimentary to the other international contributions and that made the CATO programme even more valuable.”

“The mid-term review noted that CATO was very effective in producing national-based skills and competences. The Dutch government should be very satisfied with such a programme, from which it can easily distil the key messages about carbon capture and storage. Not only regarding technologies but also concerning public outreach.”

“CATO has focused on research, which is a very good basis for the next ‘applied phase’. Piecing together the power block to the capture and storage technologies will be the next priority. The balance will shift towards the application of technologies, move up in scale and bring in more industry involvement. Some large Dutch industries have proved to be ready for that.”

“From an international perspective, the Netherlands is especially competitive in some CCS elements like storage in empty gas fields, pre-combustion capture of CO_2 at coal gasification plants and the use of solvents in post-combustion CO_2 capture at pulverised coal plants. When the EU decides to go ahead with ten to twelve demonstration projects, the Netherlands will have a head start in these fields.”

2 – Carbon dioxide capture and storage: the

broad picture

There is one overriding reason why carbon dioxide capture and storage should be used: to reduce the levels of greenhouse gas carbon dioxide (CO_2) in the atmosphere. Before going into the details of the research and the technology, let's first take a look at the potential role capturing and storing carbon dioxide could have in future energy supply.

In the last few years, the scientific community has almost unanimously accepted the evidence showing that human activities 'very likely' are the main cause of current climate change. The 2007 report of the Nobel Prize-winning Intergovernmental Panel on Climate Change (IPCC) states that anthropogenic global emissions have increased by 70% between 1970 and 2004. The report predicts that, if no action is taken, emissions will further increase by another 15 to 80% until 2030.

There is therefore an increasingly urgent need to reduce greenhouse gas emissions to levels that will limit the long-term rise in global temperature. If this increase can be limited to 2.0 to 2.4°C, it is expected that the worst impacts of climate change can be avoided. But to achieve this, most scientists agree that 50 to 80% cuts in global CO_2 emissions by 2050 will be needed, compared to 2000 levels.

There is no single 'technological fix'. The contribution of numerous technologies is required in all sectors. Increasing energy efficiency, switching to lower carbon fuels, using sources of renewable energy and nuclear energy can all help. Carbon dioxide capture and storage (CCS) technologies fit into this wider portfolio of technologies.

Capture potential

The CO_2 capture potential is substantial. On the short and the mid-term the best opportunities are available in industrial activities and power generation. In the longer run, CCS might also play a role in the transport sector and households, e.g. by increased use of electricity or hydrogen produced using CCS.

Worldwide, electricity generation is currently responsible for about 40% of the energy-related CO_2 emissions. Without additional policies, power demand will double or triple between now and 2050. Looking at these numbers, one thing is clear: the power sector needs to de-carbonise. CCS is expected to play a major role in this process over the next decades, buying time for renewables to be developed and deployed in a cost-efficient way.

In industry, CCS is one of the few options that are currently available to substantially reduce CO_2 emissions in sectors such as iron and steel, cement, ammonia and hydrogen production.

For the Netherlands, research conducted within CATO has assessed the potential of CO_2 capture over time and regions. Results show that about

60 million tonnes could be annually captured by 2050 (see Figure 2.1). The significant role played by the Rijnmond is due to the presence of coal based power plants that could be retrofitted with CO_2 capture units and the existence of so called early opportunities for CO_2 capture, i.e. industrial facilities where pure CO_2 flows are already being produced such as hydrogen and ethylene oxide production facilities. New large-scale power plants with CCS planned in Eemsmond and IJmond will also capture CO_2.

What is CCS?

Carbon capture and storage, also called CO_2 capture and storage (both abbreviated as CCS), is the generic term for a collection of processes with the aim to reduce the CO_2 content in the flue gases of power stations and industrial installations and store it safely to prevent it from entering the atmosphere.

These technologies start in the plant by capturing CO_2 or carbon. There are three main routes you can do this. The obvious one is remove the CO_2 from the flue gas before it is vented into the atmosphere. The CO_2 can be 'washed' out of the flue gas, for instance by using a solvent that absorbs CO_2. In a subsequent regeneration step, the solvent releases the CO_2, which is dried, compressed and made ready for transport and storage. This process is called '**post-combustion**' because the CO_2 is removed from the power generation or industrial process at the end of the pipe, after burning fuels.

An alternative is '**pre-combustion**' – removing the CO_2 or the carbon from the fuels before they are combusted. This process is often based on a gas shift, where the hydrocarbons in fossil fuels such as coal, natural gas and biomass are converted into a hydrogen-rich gas and CO_2 – which is removed for storage.

The third process is the '**oxyfuel**' method. By using oxygen instead of air, which only contains twenty percent of oxygen, the combustion of coal or natural gas produces much lower volumes of flue gases with higher concentrations of CO_2. After drying and compressing, the CO_2-rich flue gases can then be directly transported and stored. Depending on the case, removal of some impurities might be required.

CO_2 capture processes typically enable some 80-95% of the CO_2 produced to be captured.

CO_2 can be transported in different ways. Because of the large volumes involved, pipes are an obvious method. Shipping and trucks are alternatives.

The CO_2 can be stored underground in deep geological formations. Aquifers, i.e. geological layers containing saline water, (empty) oil and gas fields, as well as coal beds are all currently the subject of research. Also fixing CO_2 in rocks (mineralisation) and industrial applications for using CO_2 are being investigated.

Actual experience has been built up in storing CO_2 in oil fields. In order to recover oil more efficiently, the viscosity of the oil is reduced by pumping CO_2 into the field. There is also an equivalent to this 'Enhanced Oil Recovery' technique in gas production, both from gas fields and from coal beds.

Many of these technologies have been investigated within CATO. Chapter 3 presents several highlights of this research.

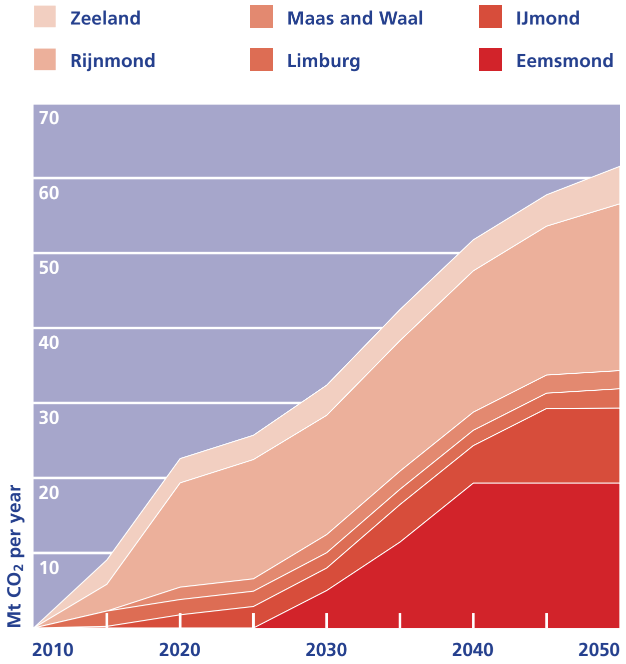


Figure 2.1 Projected amounts of CO_2 captured from power and industry by region in the Netherlands. Source: Van den Broek et al., 2008

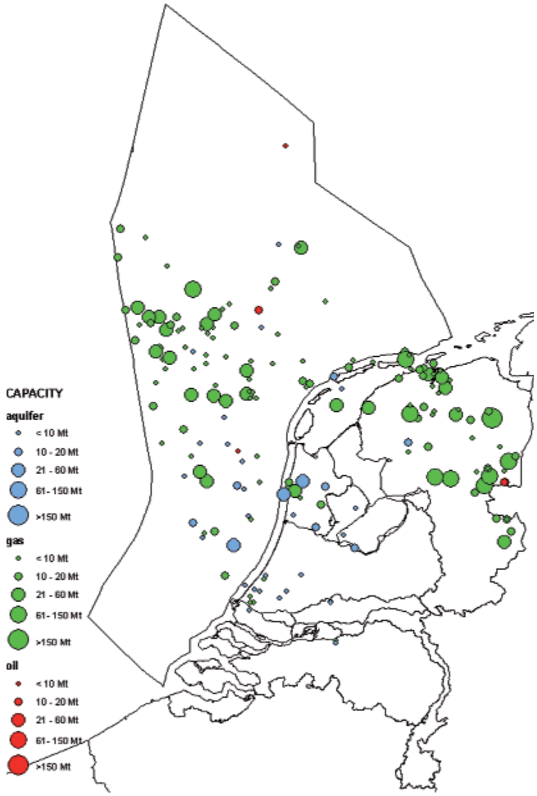


Figure 2.2 The locations and sizes of potential storage sites in the Netherlands.

Storage potential

The next question is of course: can these volumes be stored?

In 2005, the Intergovernmental Panel on Climate Change has estimated that the global CO_2 storage capacity is at least 2,000 billion tonnes of CO_2. If global CO_2 emissions would stay on the 2005 level, this would be enough to store eighty years of emissions from fossil fuel use. However, estimates of global and regional CO_2 storage capacities are subject to a great deal of uncertainty. A huge amount of R&D effort is currently going into calculating better values.

Due to resource constraints, CATO research only extensively considered geological storage in gas fields and coal seams. In scenario studies aquifers were also taken into account.

In the case of the Netherlands, many empty oil and gas fields are available and relatively close to the sources of CO_2. Figure 2.2 shows the location and size of the potential storage sites. Gas fields offer the potential to store about 10 billion tonnes of CO_2. Seventy five per cent of that capacity is situated in the Slochteren field in Groningen. However, field operators say this field would only be available for CO_2 storage after 2050. For that

reason, Slochteren is excluded from most inventories resulting in a Dutch potential storage capacity for the mid-term of about three billion tonnes of CO_2. About sixty percent of this capacity is located onshore.
The storage capacity of oil fields is rather limited with 54 million tonnes, while coal seams could store in the range of 40 to 600 million tonnes. Finally, the storage potential in saline aquifers is estimated to be 90 to 1100 million tonnes of CO_2. Research is planned to obtain more accurate figures.

The Dutch storage potential is certainly promising. Whether it can actually be used will depend on matching available capacity with requirements over time and the cost-effectiveness of storing CO_2 compared to other options. Both onshore and offshore locations are needed when implementing CCS on a large scale. An alternative storage location is the Utsira formation offshore of Norway. In that case, an offshore pipeline will need to be built by 2030. Gaining greater insight into such issues has been a central consideration within the CATO system analysis.

Transport and storage of CO_2

For large volumes of CO_2 pipelines or large ships will be the optimum means of transport. In the USA more than 3000 km of high-pressure pipelines currently transport CO_2 to enhance recovery from oil fields.

In the Netherlands an existing pipeline of 85 km is being used to transport CO_2 – at low pressure – from the Shell refinery in Pernis to greenhouses in the Westland area. However, large-scale CCS will require a new transportation infrastructure to link sources and sinks. In densely populated countries such as the Netherlands this can become a considerable challenge.

CATO research matched the availability of CO_2 flows and sinks over time and developed blueprints for the infrastructure network required in 2050. Figure 2.3 depicts the transport infrastructure in 2050, corresponding to the scenario outcomes shown in Figure 2.1.

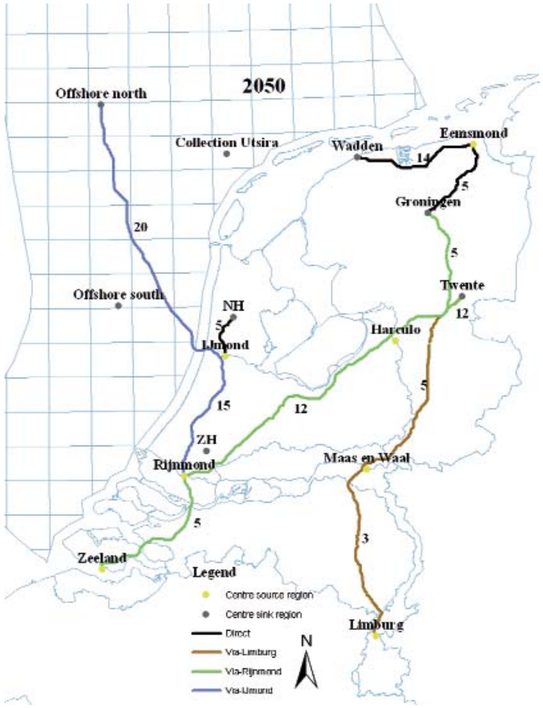


Figure 2.3 Blueprint for a pipeline infrastructure tranporting just over 60 million tonnes of CO_2 in 2050.

Costs

Costs are clearly crucial to the broad deployment of CCS. Within the full CCS chain from capture to storage, capture accounts for largest share of the costs. The capture costs are mainly determined by the additional fuel required and the investment and operational costs of additional equipment. These costs will vary according to the type of plant and fossil fuel prices.

For instance, investments costs for hard coal-based power plants with CO_2 capture in 2020 are estimated to be 30 to 130% higher than for power plants without CO_2 capture (in 2020). Figure 2.4 provides an indication by The European Technology Platform for Zero Emission Fossil Fuel Power Plants (ETP ZEP) of the increase of electricity costs. In 2008, a CCS cost study by McKinsey & Company estimated that for the reference case of new coal power installations, CO_2 capture costs could come down to around 30-45 € per tonne of CO_2 avoided in 2030. Early demonstration projects will be more costly (60-90 € per tonne of CO_2), due to their smaller scale, lower efficiency and fuel and equipment costs that were quite high at the time of the study. Technologies being developed as part of CATO have expected capture costs between 60 € per tonne of CO_2 (membrane case) and 74 € per tonne CO_2 for the SEWGS (see the highlights in Chapter 3).

The costs of CO_2 capture are expected to fall over time, either through gradual improvements in performance or as a result of breakthroughs in technologies. In the long term, economies of scale in plant construction and plant sizes are likely to reduce costs. Some experts expect cost reductions of up to twenty five percent by 2030 and fifty percent by 2050, when full-scale CCS is applied.

As a first indication, CATO calculated the need for 600 km of pipeline in 2020, requiring an investment of over €700 million. The total investment required between 2010 and 2050 is estimated to be about €1.4 billion, which translates into transport costs in the range of 1.4 to 3 € per tonne of CO_2. If only offshore locations are used, transport costs may be two to three times higher.

The costs of storage are mainly related to the location of the fields (onshore or offshore), their

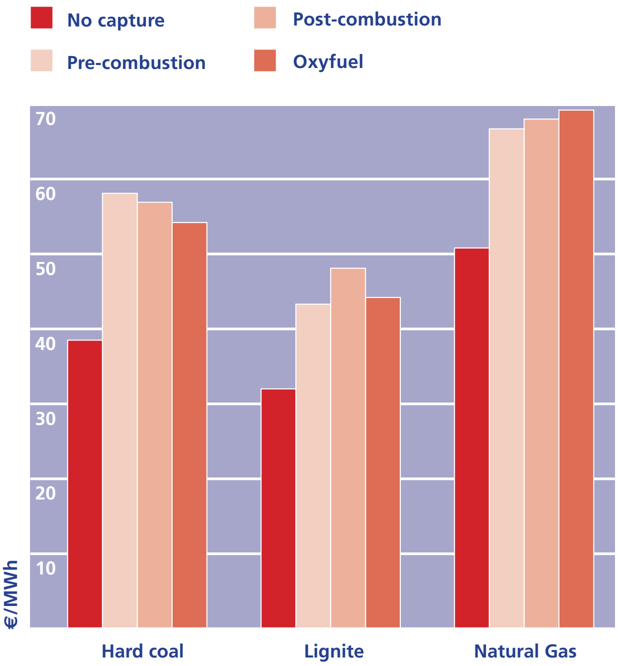


Figure 2.4 Expected power generation cost for large-scale power plants with capture in operation by 2020. Source: ETP-ZEP, 2006

depth, their size, the number of wells and platforms needed and the possibility of using existing infrastructure. Storage in deep saline formations is, initially, more expensive than existing oil and gas reservoirs, due to higher exploration and mapping costs. CATO calculated that investment costs for storage for the period 2010-2050 are likely to be approximately €2.2 billion. Over time, average storage costs are expected to increase from 1.4 € per tonne of CO_2 in 2015 to 3.3 € per tonne of CO_2 in 2050, mainly as a result of moving to offshore fields.

How much CCS can be applied?

Based on information on the separate CCS elements capture, transport and storage, the potential role of CCS has been evaluated in the broader context of other mitigation options. In a 2008 report the International Agency (IEA) concludes that by 2050, CCS could play a key role in two sectors: electricity generation and industry (see Figure 2.5).

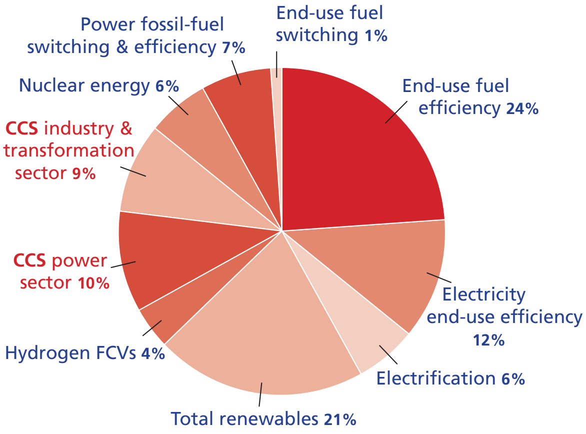


Figure 2.5 Projected reductions of global CO_2 emissions in 2050; total reduction: 48 billion tonnes of CO_2. Source: IEA, 2008

The CATO programme in the Netherlands has conducted several studies to gain a better understanding of the role of CCS in national mitigation portfolios. One of these indicates the potential of CCS in the power sector and industry in the Netherlands. If a 50% CO_2 emission reduction were to be achieved by 2050, 20% of the Dutch generation capacity is expected to consist of power plants equipped with carbon dioxide capture (Figure 2.6). This figure would rise to 40% if the target of 30% renewable energy sources by 2050 were not met.

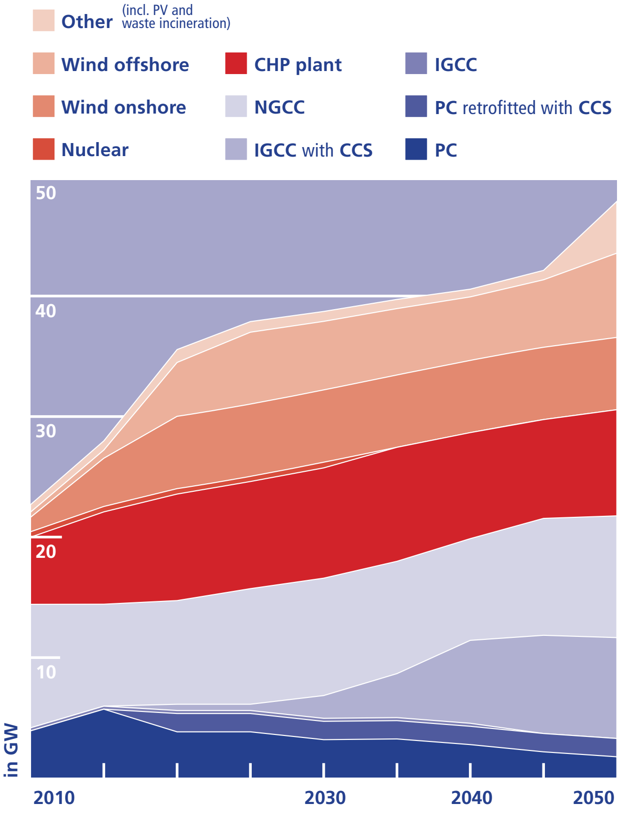


Figure 2.6 Projected developments in the Dutch electricity system. Source: Van den Broek et al., 2009

The challenges ahead

Whether CCS can really make a significant contribution globally and nationally will depend on a number of factors like costs, legal setting and public acceptance.

A major challenge is how to make CCS cost-competitive. Taking into account all the possible CCS standards and financial incentives, such as CO_2-price, subsidies and feed-in tariffs, CATO calculates that a combination of policies that serve both CCS and renewables will have the lowest cost per tonne of CO_2 avoided and achieve the largest emission reductions (Figure 2.7). Although further research is needed, one conclusion is already evident: a much better understanding of the long-term role of CCS in European and national climate policy is required. Another cornerstone for successful CCS deployment is legislation. A big step forward was the adoption of the Directive for geological storage of carbon dioxide by the European Parliament.

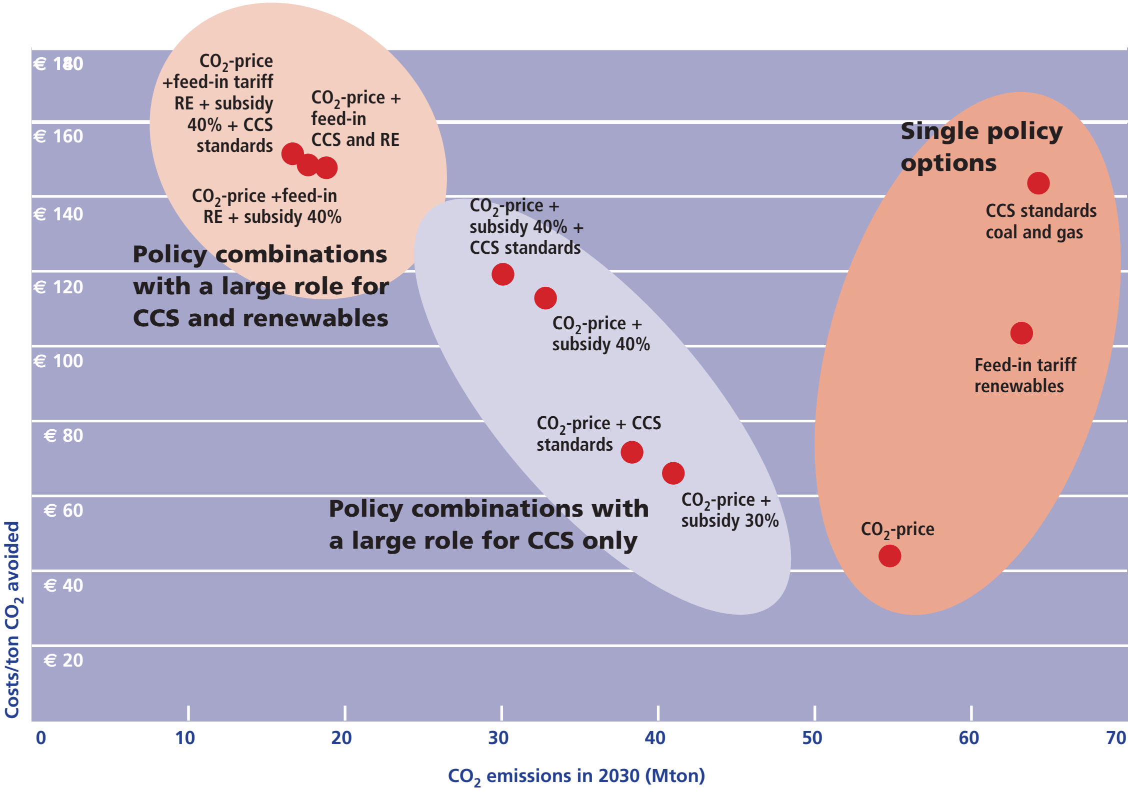


Figure 2.7 Example showing the effects of various policy scenarios for total CO_2 emissions in 2030 and the price of CO_2 avoided. Source: Vrijmoed et al., 2008

Fundamental to all regulatory regimes will be setting procedures and standards for selecting suitable storage sites. This will require evidence that CO_2 storage will be safe and secure over both the short and the long term.

Various international research programmes are now studying the safety of geological storage. Key issues include possible CO_2 migration pathways, the effects of the interaction between CO_2 and the reservoir, caprock and well bore. Risk assessment methodologies, reservoir computer-simulation techniques and monitoring techniques are being developed all over the world.

Last, but certainly not least, public awareness, opinion and support will be essential for CCS deployment. Most people seem to know little about global warming and even less about CCS technologies. A number of CATO studies have been conducted to assess current and future public opinions on CCS technology in the Netherlands. Most of the general Dutch public is currently not enthusiastic about CCS options, but does not reject large-scale implementation of these options either. Whether the public living nearby will accept a project will depend on aspects such as the perceived risks and trust in the information provided as well as in the messenger.

CATO has already answered many questions. Nevertheless, resolving the issues described above requires a lot more research.

Sible Schöne

‘NGOs should take their responsibility in CCS’

Sible Schöne currently heads the Klimaatbureau (Climate Office), which coordinates the national HIER campaign that was established to create greater awareness of climate change in the Netherlands. In the first two years of the CATO programme, Schöne participated in the programme on behalf of WWF Netherlands.

“As an environmental organisation WWF was interested in participating in the CATO programme for several reasons. In the first place, WWF – unlike several other environmental NGOs – regards carbon capture and storage as one possible element in a future integrated energy system. Instead of forcing a choice between wind energy and CCS – which would lead to an obvious answer from the NGOs – we should think in a broader framework.”

“For instance, we could consider gasification of coal – including carbon capture – as a source for hydrogen and chemical feedstock. Coal gasification could also pave the way towards biomass gasification. In my view, applying CCS is inevitable as an intermediate step in the transition towards a sustainable energy system, because it will be a hell of a job to increase the global share of renewable energy to 20 or 30% within the next two decades.”

“The CATO programme applied a systems approach. By participating in the programme, we made our contribution to choosing the technical questions that needed to be answered by CATO, for example, questions about the safety of CO_2 storage.”

“One other particularly interesting part of CATO was the research done by Leiden University on public acceptance, which is key for CCS. I wasn’t involved right up to the end of CATO, but this research has provided some very interesting insights. Although I don’t see these conclusions being acknowledged in the way the storage pilot projects are being launched in the Netherlands.”

“NGOs should take their responsibility in thinking about energy systems, safety and public support. But continued participation in the next CCS research programme will not be absolutely necessary. NGOs especially have to deal with the social and strategic problems concerning carbon capture. Questions like ‘Do we need to impose a CO_2 emission standard on fossil-fuelled power plants’ are of direct importance to CCS.”

3 – Highlights of CATO

3.1 – CATO CO_2 catcher puts laboratory results into practice

In April 2008 Minister Cramer officially opened the *CATO CO_2 Catcher* at the site of the E.ON coal power station in Rotterdam Rijnmond. The *Catcher* is a pilot plant designed for capturing CO_2 from the flue gases produced during electricity production. This is a fine example of capture technology reaching the pilot phase. The pilot has demonstrated the feasibility of a novel type of solvents for large-scale post-combustion capture. Commercial market introduction is expected between 2015 and 2020.

One of the main goals of the CATO programme is to develop new carbon capture and storage technologies. The *Catcher* uses a so-called *post-combustion* capture technology, which means that it captures the CO_2 from the flue gases, after combustion. The technology and the solvents, which were developed in the laboratories of TNO, are now in a pilot phase.

The technology is based on a scrubbing process, where the CO_2 gas is 'washed' out of the flue gases using special fluids. The Rotterdam pilot plant serves as a flexible research and demonstration tool (see Figure 3.1). The location, at the coal-fired power station of E.ON was chosen because of the opportunity to obtain flue gas derived from coal.

The pilot installation makes it possible to investigate the performance of CO_2 removal under real industrial conditions. The pilot plant tests novel gas scrubbing methods. The reliability of process models that have been developed by TNO using bench-scale test data can also be assessed.

Figure 3.1 CATO CO_2 Catcher at the coal-fired power station of E.ON.

The catcher will deliver essential information to E.ON, TNO and the other CATO partners on how to substantially improve the environmental and economic performance of existing and novel processes.

The principles

The construction of the pilot plant at the Rotterdam power plant has been a joint effort of TNO – as research partner - and E.ON Benelux – as industrial partner. The pilot plant is directly linked to the stack of the second unit of the power plant, which is situated behind the desulphurisation process, which removes the sulphur from the flue gases.

A small fraction of the flue gases are directed to the CO_2 capture pilot plant for carbon dioxide removal. A maximum of 250 kg CO_2 per hour can be removed from the stack. The installation in itself enables different CO_2 capture techniques to be evaluated, monitoring all process conditions such as temperature, pressure, flows and content of CO_2, SO_2 and soot. Other parameters (such as the stability of the solvents that are used) can be measured separately.

The pilot plant consists of a scrubber column (1) for removing extra SO_2, which might damage the solvents, a 20-metre-high CO_2 absorber column (2) and an 18-metre-high desorber column (3) as illustrated in Figure 3.2. In the first stage, the SO_2 is removed from the flue gas and the treated gas is transported to the absorber where the CO_2 is removed by absorption in a liquid. The purified flue gas is emitted to the stack of the power plant. The absorption liquid is regenerated in the desorber and is ready for use again in the absorber. For bringing gas and liquid into contact, in addition to packed columns, membrane contactors are also tested for both desulphurisation and CO_2 absorption. Membrane contactors are promising, because

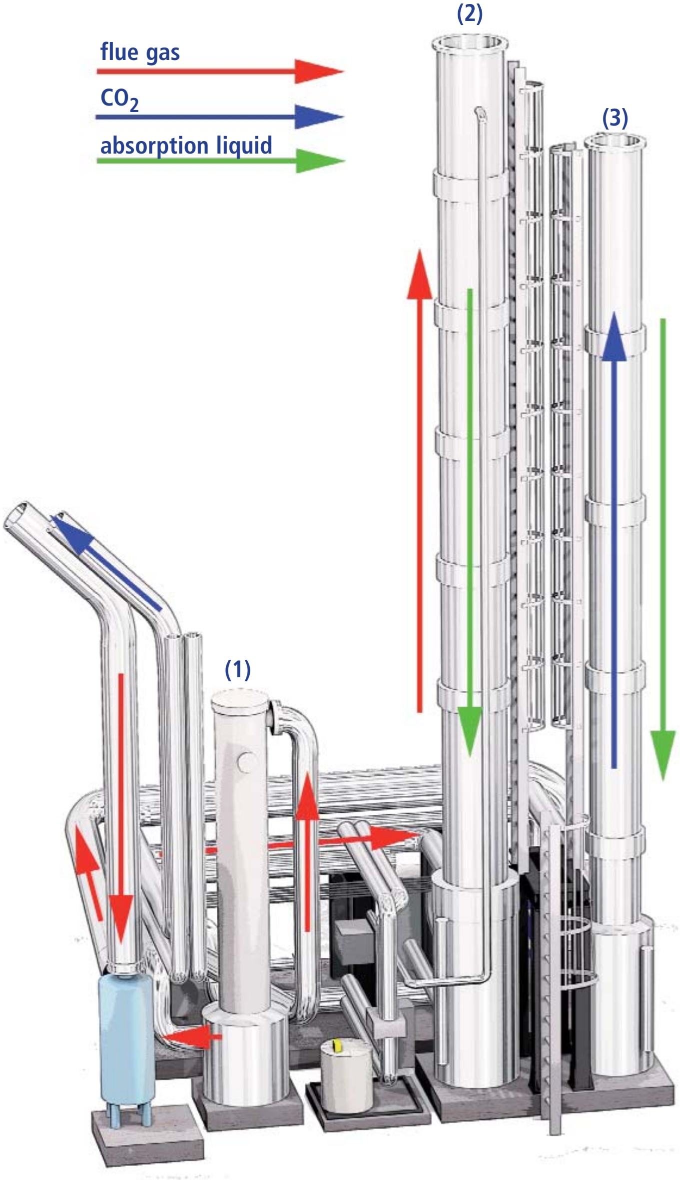


Figure 3.2 Schematic picture of the CATO CO_2 Catcher.

they are able to bring the flue gases in contact with the solvents in much less voluminous reactors. In further improvements to post-combustion capture, progress in developing low-energy (30 to 50% less), environmentally benign and economically efficient solvents is crucial. The development of new absorption liquids is based on thorough knowledge of the relevant organic, physical chemistry in combination with process engineering.

This has led to a methodology of finding and improving absorption liquids, based on statistical methods in combination with detailed analysis of the effects of different groups present in the absorption molecule on overall performance.

The main results

The pilot plant is a pivotal point in the scale-up of post-combustion capture. In itself, it is already quite an achievement to have created the opportunity to assess absorption liquids newly developed in the TNO laboratories under real conditions. With this pilot plant one major bottleneck in the implementation of post-combustion capture has been removed.

The main questions that still need to be answered involve further scaling up of the technology combined with improved economics. Although current typical capture in the pilot plant is approximately 250 kg of CO_2 per hour; conventional versions of this type of scrubbing process are already proven at a scale of 300 tonnes per day. In future this needs to be increased to around 700 tonnes of CO_2 per hour. The technological challenges associated with this kind of scaling up are significant. However, given extensive experience with this type of scrubbing process, scaling up to large commercial scale is expected to be feasible.

In the CATO programme a family of absorption liquids known as CORAL has been explored. The CORAL family is extremely interesting because they have greatly improved stability. Compared to the benchmark process with MEA, 90% less chemical consumption has been obtained. Using the CORAL type of solvents can also lead to a substantial improvement in energy efficiency. One particular example, CORAL XPT, has produced interesting practical results in pilot tests.

The CATO CO_2 Catcher is the first step towards commercial scale post-combustion technology. In preparing the next step, the focus of research will be on the specific knowledge needed to scale up towards a demonstration plant. This demonstration plant – the last step towards commercial scale – could be in operation by 2014-2015.

In the demonstration plant solvents and improved process concepts will be further tested. Within a few years the technology is expected to be ready for commercial application. This would be in time for building large-scale capture units that could be in operation by 2020.

3.2 – From research to pilot plant: sorption-enhanced water-gas-

Carbon can be extracted from the fossil-fuelled power production process in several ways: washing the CO_2 out of the flue gases, the oxyfuel method and extracting the carbon before combusting the fuels. The CATO programme has made a big step towards the implementation of pre-combustion CO_2 capture, bringing sorption-enhanced water-gas-shift (SEWGS) technology closer to the market.

At the start of the CATO programme in 2004 the SEWGS technology development was a small internal project at the Energy research Centre of the Netherlands (ECN). Experiments were carried out using milligrams of CO_2 sorbent. At the end of the CATO programme in 2008, the technology was being developed by two large consortia, in which ECN collaborates closely with industrial end-users and companies that will market the technology. For this purpose, ECN has built a large SEWGS pilot unit for continuous production of hydrogen and CO_2 consisting of six tubes, each six metres tall.

SEWGS: the solution to a problem

In pre-combustion CO_2 capture, the fuel (coal or natural gas) is first converted into a mixture of hydrogen and carbon monoxide (CO). If the fuel is coal, this gas has to be thoroughly cleaned before further use is possible. Such a CO_2 capture section has a *water-gas shift step*, in which the hydrogen/ CO mixture is converted to CO_2 and additional hydrogen by adding steam.

Subsequently, the CO_2 must be separated from the hydrogen. Various solvents have been used to achieve this separation on an industrial scale for decades. Pre-combustion CO_2 capture technology is ready to be implemented in power plants in the short to medium term. But it has some major drawbacks. The gas needs to be cooled down and heated up several times in the process, which reduces the efficiency of the power plant. Also the equipment, especially the heat exchangers, is expensive.

Figure 3.3 SEWGS six-column pilot unit.

For these reasons, research and development for second-generation capture technologies is focusing on reducing the efficiency penalty and the costs. Several membrane technologies that are designed to achieve hot separation of hydrogen and CO_2 look promising, but these are still in an early stage of development. SEWGS is much closer to the market. Modelling studies show lower efficiency penalties and costs for CO_2 capture than with solvent technologies.

The process

SEWGS, which can be applied in both natural gas and coal-fired power plants, is especially suitable for IGCC (Integrated coal Gasification Combined Cycle) power plants.

The SEWGS process combines the water-gas-shift step and the CO_2 separation step in a single process. It delivers a low-carbon hydrogen fuel at the required pressure and temperature for use in gas turbines. Moreover, all the materials and equipment are already being used in industry today – it is just the combination that is new.

One major benefit is that the hydrogen product can be used in future cars equipped with fuel cells, but also in industrial processes such as refineries and steel plants.

A concise overview of the SEWGS process

In SEWGS a gas mixture from a natural gas reformer or a coal gasifier is led into a reactor containing a catalyst for the water-gas shift and a solid CO_2 sorbent. The purpose of the catalyst is to convert CO and steam to CO_2 and hydrogen.

The secret of SEWGS is the CO_2 sorbent that is added to the catalyst. This immediately removes all of the CO_2 as it is being produced. So the reverse reaction cannot take place. Eventually all of the CO is converted into CO_2.

At some point the CO_2 sorbent will become saturated with CO_2 and needs to be regenerated. This is done by dropping the pressure and purging the sorbent with steam.

ECN and Utrecht University have put a lot of effort into developing a sorbent that would meet two conflicting demands. It must efficiently adsorb a lot of CO_2 during the water-gas shift reaction, while easily releasing the CO_2 again in the regeneration step, thus minimising the amount of steam required.

Because the process alternates between reaction and regeneration, more than one reactor is required to produce a continuous stream of hydrogen and CO_2. SEWGS is called a *pressure swing adsorption* (PSA) process. PSAs have been used in industry for decades, although usually at lower temperatures.

Progress made in CATO

In 2004, at the start of the CATO programme, ECN had already discovered that hydrotalcites met the CO_2 sorbent requirements. So subsequent research focused on combining the CO_2 sorbent with the water gas shift reaction at 400°C.

Meanwhile, the potentially low costs of using SEWGS for CO_2 capture started to draw international attention. Several industrial partners, such as Air Products joined the team. This American company, which initially developed the SEWGS concept, is also a candidate for marketing the SEWGS units. In addition to CATO funding, the EU CACHET project and the CO_2 Capture Project (including leading oil and gas companies from Europe and South & North America) provided funding.

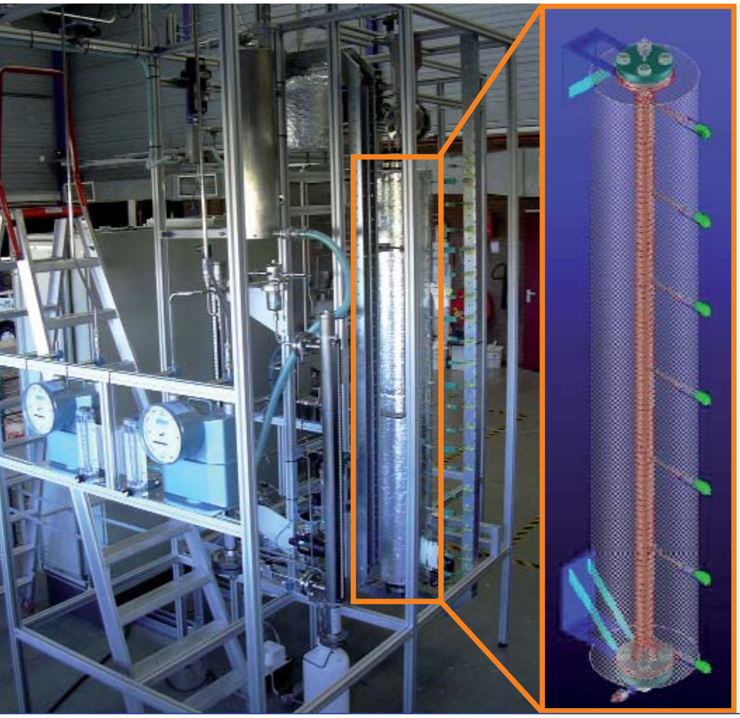


Figure 3.4 SEWGS single column test unit.

In 2006, the CACHET project facilitated the construction of a high-pressure single-column SEWGS test unit that could test a few kilogramms of sorbent and catalyst under realistic conditions. These tests provided new data on the hydrotalcite sorbent material that had not previously been tested under these conditions.

These results inspired new fundamental research to resolve the issue of the working mechanism of hydrotalcites and to improve the sorption/desorption characteristics. This work, together with CATO partner Utrecht University, delivered valuable answers and some improved sorbents.

It was shown that hydrotalcite could be loaded and unloaded with CO_2 for several thousands of cycles without losing capacity. This discovery provided the final stimulus for building a six-column demonstration plant and running SEWGS cycles in practice: an important step towards bringing this technology to the market (see Figure 3.3)

The next step is expected to be a Dutch pilot installation within the CATO-2 programme, with the participation of several industrial partners. Successful piloting will be the predecessor of a large-scale demonstration and finally a full-scale demonstration. In ten to fifteen years, SEWGS technology should be commercially available.

3.3 – Trapping CO_2 in solid rock

To minimise risks and maximise performance, it is important to understand the fate of CO_2 injected into empty gas reservoirs and to determine how effectively it will be trapped. Apart from CO_2 residing in the reservoir's pores, chemical binding can occur by 'mineralisation'. CATO investigated this process and came to some enlightening conclusions.

In the Dutch concept of capture and storage – and indeed in most CCS approaches worldwide – capture of CO_2 will be followed by injection into empty gas or oil fields, saline aquifers or possibly coal seams. Given the scale of natural gas production in the Netherlands, empty gas reservoirs offer by far the most promising and accessible opportunity in the short term.

Such reservoirs, which typically lie at a depth of 1-4 kilometres, consist of sandstone layers covered by impermeable 'caprocks' that have sealed in the natural gas for tens or even hundreds of millions of years. As many natural gas reservoirs around the world also contain CO_2 as an impurity, storage in reservoirs has in many ways already been proven by nature. For added certainty, however, the physical and chemical processes that control injection and trapping of CO_2 need to be understood at a fundamental level.

Subsurface mineralisation

When CO_2 is injected into an empty gas reservoir, it first fills the rock pore space that was previously occupied by natural gas. It also gradually dissolves in the saline pore water or 'formation fluid' that generally occupies the lower levels of the reservoir. A major part of the stored CO_2 will therefore reside in the reservoir's pore space and in the formation fluid.

However, some CO_2 will also react chemically with some of the minerals present in the reservoir rock, notably feldspars, clays and oxides that contain significant amounts of calcium, iron or magnesium. These reactions have the potential to fix CO_2 permanently in the subsurface as insoluble carbonates and clays. Injected CO_2 thus becomes converted into new minerals within the reservoir rock.

This process, known as subsurface mineralisation, is very attractive as it completely immobilises stored CO_2 in solid mineral form, reducing the risk of any long-term leakage. On the other hand, whether subsurface mineralisation will occur to a useful extent in a given reservoir, how long it takes, and whether it might have any disadvantageous side effects are all questions that need to be addressed in developing a geological storage strategy.

CATO aims and approach

CATO has investigated subsurface mineralisation in detail. The initial research focused on such key questions as:

- What is the mineralisation capacity of typical reservoir sandstones?
- What is the likely rate of CO_2 uptake by mineralisation?
- What are the effects of reaction on the migration of CO_2 in the subsurface?
- Are there any effects of reaction and other CO_2-water-rock interactions on the integrity of typical reservoirs and caprocks?

The approach adopted has been one of laboratory experiments on simulated sandstones performed in the High Pressure and Temperature Laboratory at Utrecht University (Figure 3.5). The lab experiments were complemented by numerical modelling experiments and trapping potential assessment work performed by Shell.

Figure 3.5 Instron set-up (left) and Tuttle bomb set-up (right).

Key findings

The data obtained in the CATO study of subsurface mineralisation have shown that CO_2 mineralisation reactions involving reservoir rock components such as feldspars, clays and oxides are too slow to be precisely quantified in lab experiments. However, their rates can be estimated with reasonable accuracy.

The results imply that mineralisation reactions will occur after CO_2 injection into typical reservoir sandstones, fixing a maximum of 5-15% of injected CO_2 in solid form over periods of some 30-3000 years, depending on the composition of the sandstone. This degree of mineralisation is limited to these low values by the low concentration of reactive minerals found in Dutch reservoir sandstones.

The conclusion is therefore that trapping CO_2 will take place mainly by storing it in the pore space of the reservoir and by CO_2 dissolution in the formation fluid, with migration being prevented by the original seals and local flow regime (hydrodynamic trapping). Mineralisation will occur, but only to a limited extent, and over such a long timescale that it can only be regarded as a bonus that is poorly predictable.

An advantage of the low mineralisation rates found in the CATO study is that reservoir injectivity and integrity will not deteriorate due to reactions in the injection phase. In addition vertical reservoir compaction and land subsidence potentially triggered by the chemical effects of CO_2 injection will be negligible. Instead, CO_2 injection will generally cause a reversal of the subsidence produced during earlier natural gas production.

A much more important effect than mineralisation during the injection phase was found to be that of salt precipitation from the formation fluid, due to desiccation (dehydration) caused by injected CO_2. Numerical modelling by Shell scientists has shown that salt precipitation close to the injection point can drastically impair injectivity into fluid saturated rock. However, further simulations have shown that this can be overcome by brief pre-flushing with fresh water.

Caprock behaviour

The finding that CO_2 mineralisation is slow and that most CO_2 will remain trapped in the reservoir pores and pore fluid (hydrodynamic trapping) rendered caprock integrity a key priority for research. Midway through CATO, experimental resources were accordingly diverted from work on mineralisation towards the crucial issue of the effects of mechanical damage and chemical reaction on caprock integrity.

The focus has shifted to one of the main caprock formations above key Dutch gas reservoirs – the anhydrite formation that forms the base of the so-called ‘Zechstein’ rock salt sequence. Research on this material at Utrecht University has shown that it is highly resistant to mechanical damage and little affected by chemical interaction with CO_2 and water, retaining its integrity under a wide range of in-situ conditions. On the other hand, pre-existing faults in the material seem to rapidly react with CO_2. The impact of this on sealing capacity is not yet clear.

Outlook

The CATO results on CO_2 mineralisation have drawn this issue to a clear conclusion. We know roughly how fast mineralisation will proceed and we also know that it offers only a minor contribution to CO_2 storage in empty gas reservoirs (or aquifers) of typical Dutch composition.
The potential for fixing CO_2 in solid form on a useful timescale and the risk of mineral reactions blocking the CO_2 injection process are negligible. Much more important is the finding that CO_2 injection tends to precipitate salts that hinder injection, but that this can be solved by pre-injection of fresh water.

Perhaps the most important point to come to the fore is that since subsurface mineralisation will be insignificant, system integrity must rely on caprock and fault sealing potential. This has been shown to be good for intact anhydrite caprock of the type topping many Dutch reservoirs. However, both generic and site-specific studies will still be needed in future to assess any risk of leaking posed by the combined effects of mechanical stresses and chemical reactions resulting from CO_2 injection. Of particular relevance here will be combined experimental and numerical modelling studies of caprock and fault behaviour, using numerical modelling to address system-scale evolution in the short and long term.

Green Olivine?

In theory, it is possible to remove CO_2 from the atmosphere by accelerating natural weathering of certain kinds of rock above ground, as an alternative to the more orthodox CCS methods. The most suitable rocks are those rich in olivine – a green, silicate mineral that can neutralise acids. Olivine-rich rock is not ubiquitous, but it is abundant in localised massifs scattered around the world, for instance in Norway, Greenland and Turkey.

Dutch Emeritus Prof. R.D. Schuiling has attracted considerable media attention with his proposal to accelerate olivine weathering as an alternative to conventional CCS. His idea is to spread crushed olivine rock along large stretches of the world's coastlines, where the turbulent surf of the sea would accelerate the uptake of atmospheric CO_2 through weathering of the sand-grade olivine. In this process, absorbed CO_2 ends up dissolved as bicarbonate in the oceans.

CATO evaluated this interesting 'green beaches' concept. Vast amounts of crushed olivines are needed. Offsetting 25% of the current worldwide CO_2 emissions of 28 billion tonnes a year requires annual deposition of about 10 billion tonnes of typical olivine-rich rock. Moreover, at seawater temperatures of 15 to 25°C, beach weathering of sand-grade olivine takes 700 to 2100 years to achieve a suitably steady CO_2 uptake. To obtain a faster CO_2 uptake rate sufficient to produce an impact in ten or twenty years, dust-grade olivine with particles smaller than 10 micrometer is required. Processing and transporting such quantities of dust represents a major economic, infrastructural and environmental challenge. Dust emissions to the environment in the Netherlands already pose recognized health risks and would be increased dramatically by beach spreading of olivine dust. This presents a particular problem, since olivine rock often contains asbestos materials.

The CATO study concluded that coastal spreading of olivine is not a feasible method of CO_2 sequestration. In Northern Europe, in particular, seawater temperatures only permit olivine reactions that are far too slow. Some contribution to global CO_2 sequestration may be feasible in niche situations, especially on land in the tropics where higher temperatures and acid soils would generate a much faster reaction. Provided rock processing costs can be kept low, olivine could be locally mined, crushed and spread in tropical countries. Given the uncertain long-term ecological and health effects, it seems prudent to present this option as niche solution and not as panacea.

3.4 – Storing CO_2 in coal seams: new and promising

Storage of CO_2 in underground coal seams is an interesting option, for two reasons. The so-called *enhanced coal bed methane* (ECBM) process stores CO_2 in the coal seam, which in turn pushes out the coal gas (methane) and thus increases primary methane production. CATO research into this young technology has shown that storage of CO_2 in coal layers is technically feasible.

Storing CO_2 in coal seams has considerable potential. For instance, there are vast amounts of underground coal in the Netherlands at depths of over 1000 metres. Although the coal can not be mined economically, the seams could contain considerable amounts of coal gas (methane, CH_4). This suggests the possibility of storing CO_2 in coal seams in the Netherlands, with the spin-off of methane extraction.

From a broader geological point of view, there are often coal deposits in regions which lack access to alternative CO_2 storage reservoirs. This is the case in countries such as the United States, Canada, Australia, China and South Africa. Moreover, heavy industry is often located in regions were there is coal. The combination of large sources of CO_2 and storage potential makes this an attractive option.

However, the technology is not yet mature. There has so far only been one large-scale pilot programme. From 1996 to 2000, Burlington Resources injected CO_2, successfully enhancing the production of Coal Bed Methane (CBM) in New Mexico and Colorado (USA). Following this pilot, a few small ECBM pilots have been conducted worldwide, such as the Recopol project in Poland.

Lab research

The basic ECBM process is straightforward. CO_2 is injected into and stored in a coal seam via adsorption, which binds the CO_2 to the coal. CO_2 injection enhances the production of methane in two ways. CO_2 speeds up the desorption of methane from the coal seam and the injected CO_2 pushes methane towards the producing well (the CO_2 ‘drive effect’). The extra methane production could pay for part of the storage costs.

The coal reservoir is very different from classical reservoirs (those in empty gas fields, which consist of inorganic, heterogeneous porous sandstones and carbonates). However, coal seams consist of a matrix of organic matter with a system of fractures. The so-called ‘Darcy flows’, describing the transport of gases and fluids through a porous medium, can only partly be applied to the fracture system of a reactive coal seam. Processes such as sorption and diffusion are also involved.

The objective of the CATO research was to determine the technical feasibility of ECBM. One of the key uncertainties here is the permeability of a coal seam, which can change due to swelling of the coal. Another important mechanism is the exchange of methane and CO_2 in the coal via diffusion. If diffusion is too slow, this may reduce the effectiveness of ECBM and the storage potential. New reservoir models needed to be developed to predict the injection and production behaviour of a coal field during its CO_2 injection life cycle. In addition, the parameters that define the interaction between coal types, water and gases also had to be defined.

Within CATO, in cooperation with Shell, TNO, Delft University of Technology and Utrecht University, both these aspects were covered. Moreover, CATO became part of an extensive ECBM knowledge network involving industrial partners, research institutes and universities, both nationally and internationally. With partners in the USA, Germany, Belgium, Australia, UK, China, Slovenia and France, CATO is recognised internationally for its combination of in-depth fundamental research with field-scale applications.

Understanding flows and processes

The main aim of TU Delft and Utrecht University's extensive laboratory programme was to answer three scientific questions:

1 How do gases flow through the fracture system during injection and production?
2 What is the process of gas uptake, replacement and extraction in the coal matrix (sorption and diffusion)?
3 How does the presence of water enhance or frustrate this process?

Crushed coal was used to study the ability of the coal matrix to charge and discharge under dry and wet conditions. The research resulted in diffusion rates, sorption capacities, capillary behaviour and dielectric conduct. It became clear that diffusion may take more than seven days. For a field experiment this means that the density of fracture systems in the coal seam is of great importance. Whole coal samples (volumes up to 1000 cc) were used to study

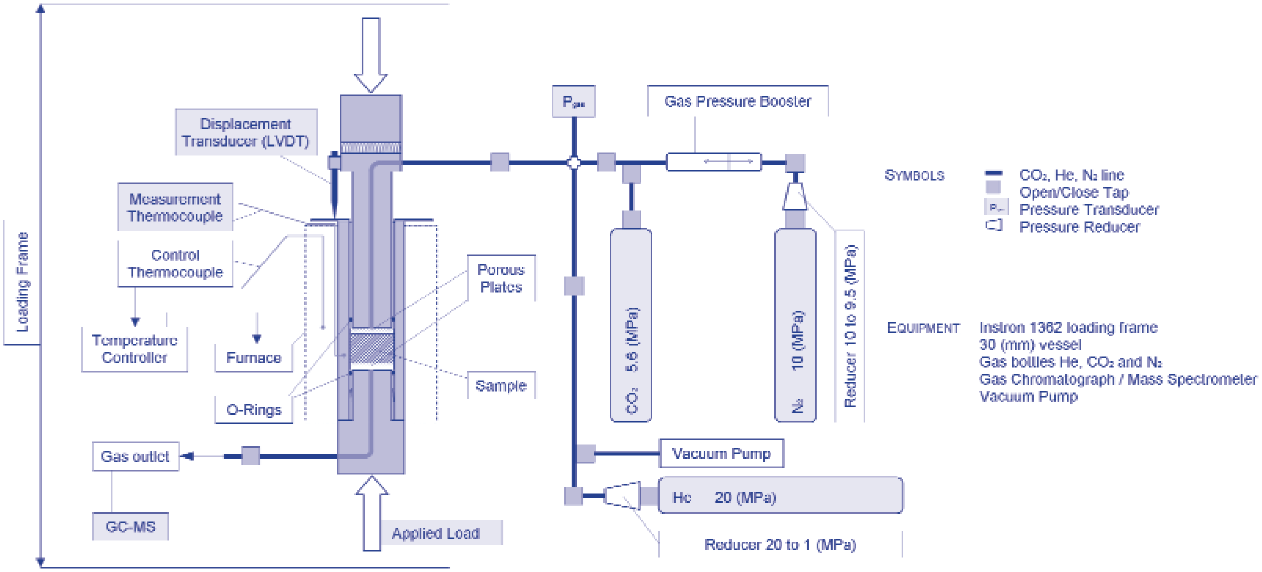


Figure 3.6 Set-up for measuring coal CO_2 sorption and associated swelling.

flow behaviour, volume changes, fracture characteristics and wettability. Partly newly developed equipment (Figure 3.6) helped determine the volumetric behaviour and the stresses that coal undergoes during swelling. Computed Tomography (CT) scans and image analysis provided 3-dimensional grid models that were used to determine the flow and the flow direction.

This CATO research has largely contributed to a better understanding of the behaviour of CO_2 in coal at lab scale. Adsorption has been shown to be linked to the mechanical stresses in the coal. The lab experiments provided vital parameters, such as the CO_2 adsorption capacity of various coals and the interaction between stress, strain and CO_2 adsorption. These parameters improved existing reservoir simulators and extended CATO models, such as a CO_2/water segregation model and a coal swelling model.

These results make it easier to predict the storage potential and the long-term fate of CO_2 in coal seams, which is of the utmost importance for field (pilot) projects. This knowledge has already been applied to field pilots in associated projects for the European Commission, such as a small-scale CO_2 injection experiment in a coal mine in Slovenia and the Recopol pilot in Poland. The combined field and laboratory results clearly indicate that the CO_2 is firmly locked in the coal seam, which is a positive result in light of the project goals.

Outlook in the Netherlands

Looking at CATO research as well as that taking place elsewhere in the world, the conclusion is that ECBM technology is almost ready for application. The concept is proven at pilot scale, but it has yet to be scaled up to large storage sites.

Given its potential and its complexity, ECBM could become of importance in parts of the world that have abundant unmineable coal and few alternative CO_2 storage options. In the Netherlands, applicability is limited to coal-rich areas such as Limburg. Two main factors may prevent large-scale application in the near future here. Firstly, many Dutch depleted gas reservoirs can be exploited more easily and secondly, there is no Coal Bed Methane (CBM) industry or infrastructure.

The economic bottleneck for large-scale exploitation is the drilling depth of over 1000 metres. It takes several years to develop CBM and ECBM projects: about five years to start up a large-scale CBM project and ECBM takes another five years. So, large-scale applications are unlikely in the Netherlands in the near future. However, smaller projects such as DSM's CO_2 storage project may be feasible. Elsewhere, for example, in Germany and Belgium, CBM and ECBM may be more attractive. These countries depend largely on natural gas supplies from abroad.

Before it becomes a mature technology worldwide, larger projects in mature CBM fields like the Burlington pilot or novel schemes such as a combination with aquifer storage (Zuid-Limburg) are required. Such projects could bridge the gap between the small research pilots that have taken place so far and larger projects, thus creating the potential for large-scale CO_2 storage in coal seams.

3.5 – Monitoring effective storage in a gas field

When investigating the CO_2 storage capacity in gas fields, characterisation and assessment are crucial to ensure safe and effective storage. For the K12-B gas field, located in the Dutch sector of the North Sea, a monitoring plan was developed and executed. This hands-on experience with the process, the results and the conclusions are of great importance for CCS deployment.

The K12-B gas field is located in the Dutch sector of the North Sea, some 150 km northwest of Amsterdam (Figure 3.7). The K12-B structure was discovered in 1982 and it has been producing from 1987 onwards. Currently it is operated by GDF Suez E&P Nederland B.V.

The gas field is part of the so-called 'Upper Slochteren Formation', which is sealed off by 'the Zechstein Group' (mainly rock salt, Figure 3.8). The reservoir lies at a depth of approximately 3800 metres below sea level, and the temperature is about 127°C. So far, K12-B has produced 12.6 billion cubic meters of gas, 88% of the initial gas in the field. The initial reservoir pressure of 400 bars has presently dropped to 40 bars.

The natural gas initially contained 13% of CO_2. Since the start of gas production, the CO_2 has been separated from the gas stream on-site. Since 2004 part of the separated CO_2 is re-injected into the gas field. The fact that the salt has trapped the natural gas with its 13% of CO_2 millions of years already provides proof of the field's natural gas storage capacity and sealing efficiency. However, for direct CO_2 re-injection it was necessary to

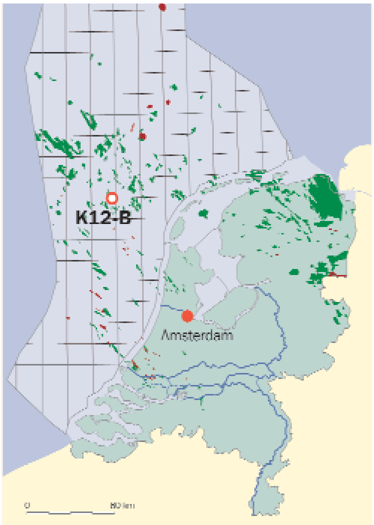


Figure 3.7 Location of K12-B.

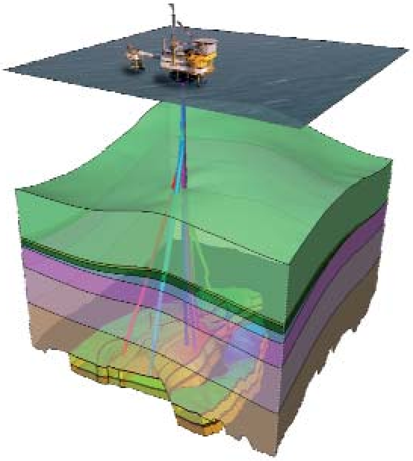


Figure 3.8 3-D impression of the K12-B platform and field (tertiary strata omitted).

characterise the reservoir and the cap rock and to develop a monitoring plan to ensure that the CO_2 remains stored. This makes K12-B a good example of CO_2 storage in a nearly depleted reservoir.

Injecting CO_2 into the K12-B field was necessary to test the feasibility of CO_2 storage in depleted and nearly depleted gas reservoirs. Two tests have been performed with the CO_2 separated from the produced natural gas. During the first test CO_2 was injected into a depleted compartment of the reservoir with only one well (K12-B8, see Figure 3.9). The objectives were to test the injection facility, to prove that injection is feasible and safe, to examine the behaviour of the CO_2 and the response of the reservoir. During the second test, which is still ongoing, CO_2 is injected into the nearly depleted compartment with several wells, from which natural gas is simultaneously being extracted (Figure 3.9).

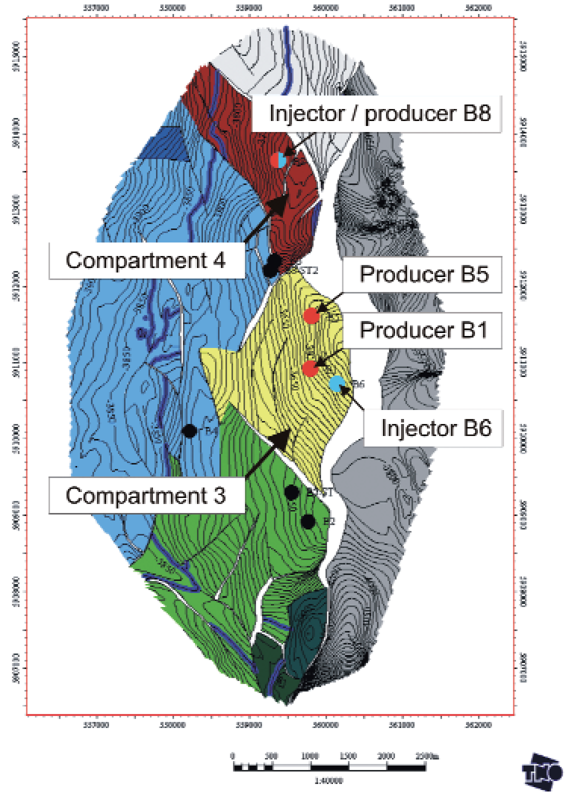


Figure 3.9 Schematic layout of the test locations.

The second offshore test facility is able to inject about 20,000 tonnes of CO_2 per year. Four important issues here are the potential for enhancing gas recovery by injecting CO_2, the degree of corrosion along the injection tubing, the behaviour of the CO_2 and the response of the reservoir.

Once the CO_2 has been injected, the monitoring process is key to demonstrating that CO_2 remains contained in the intended storage sites. A wide range of monitoring tools are available, including '3D surface seismic', 'geophysical well logging', 'down-hole fluid chemistry', 'pressure-temperature monitoring', and subsurface and seabed imaging. The choice of the tools to be deployed depends on a number of site characteristics (location, depth, injection volume etc), the technical information (objectives) required from the monitoring programme and, of course, the costs.

Two goals

Regarding K12-B, the caprock has proven its sealing capacity for millions of years and the current quantities of injected CO_2 are as yet relatively small. Performance assessment has demonstrated that, if migration of CO_2 to shallower underground layers or even to the surface should ever occur, the most likely migration pathways are along the wellbores penetrating the reservoir. Therefore monitoring of the injection of CO_2 into K12-B mainly focuses on the issue of the integrity of the wells. This is done by means of a 'caliper'. This device provides information on the possible pit depths due to corrosion and on the metal loss in the tubing.

A second important goal of the monitoring programme is to gain a better understanding of the enhanced gas recovery (EGR) potential of CO_2 injection, which might be of economic interest. Maintaining pressure in the reservoir through CO_2 injection can extend the lifetime of the producing field. However, early CO_2 breakthrough underground from depleted to almost depleted reservoir departments would make production uneconomical. This is why the flow and mixing of natural gas and CO_2 in the reservoir need to be studied.

Insight in the CO_2 migration within the reservoir could be obtained by sampling the production gas stream. Furthermore, two chemical gas tracers (Figure 3.10) were added to the CO_2 injection stream at the start of phase 2 of the CO_2 injection project. The tracers allow accurate assessment of the flow behaviour in the reservoir and the associated sweep efficiency of the injected CO_2. They make it possible to accurately determine the physical communication between the injecting and producing wells.

Weekly detection and analysis of tracers at the production wells (K12-B1 and B5) provide further insight into CO_2 breakthrough as well as the timing and shape of the breakthrough curve. Moreover, water samples were taken from the production wells. Comparison of these samples with the baseline (before CO_2 injection) determines possible geochemical effects in the reservoir due to an increase in CO_2.

Numerous pressure, temperature and flow measurements led to a better understanding of CO_2 injection in depleted gas fields. Pressure and temperature measurements provide deep insight into the phase behaviour of the CO_2 in the wellbore and in the reservoir. Also they provide information about gas-water contact and the movement of water. These monitoring results thus markedly improve the reservoir simulations.

Results

The most important results of the tests at K12-B have been that CO_2 injection has been proved feasible and that it can be conducted safely. The CO_2 injection did not have any negative effects regarding the gas production and infrastructure under the conditions of the K12-B field. The injection tubing integrity surveys showed pitting at certain depth intervals, but this might have been the case already before the start of CO_2 injection. The integrity of the injection tubing as well as the cement bond behind the casing requires additional measurements and investigation.

Reservoir and phase behaviour measurements were all within the ranges predicted in modelling work. Analyses of back-produced tracers made it possible to assess the flow behaviour in the reservoir. The quantities of CO_2 injected into K12-B, however, were too small to draw conclusions about whether EGR through CO_2 injection is viable under the conditions at K12-B.

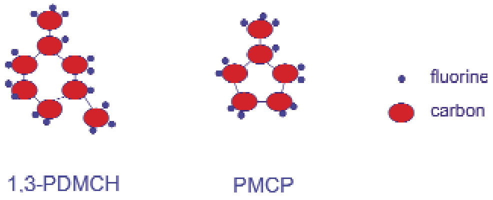


Figure 3.10 Molecular composition of the tracers injected in K12-B6.

3.6 – Exploring an empty gas field as a site for CO_2 storage

High-volume, safe, long-term storage of carbon dioxide is of course an essential part of any system for decarbonising fossil fuels. One obvious approach is to store it underground in empty gas reservoirs. The general principle is to replace the extracted gas with carbon dioxide. Within CATO, the Nederlandse Aardolie Maatschappij BV (NAM) considered the possibility of a demonstration project at the De Lier gas field.

When investigating underground CO_2 storage in gas fields, the basic technologies already exist. However, it is crucial to show stakeholders and the general public that CO_2 can be injected safely and effectively according to the regulations which are being developed for CCS. In particular it must be shown that a method for risk management of CO_2 storage works.

So this was the main objective of the De Lier case study: to assess the safe and effective containment of injected CO_2. With respect to safety, a great deal of attention was paid to the integrity of the seal, faults and the wells themselves, in order to make sure that injected CO_2 cannot escape. The compatibility of CO_2 with the reservoir, the ground movement and monitoring requirements were also investigated in practice.

De Lier

De Lier is a little town in the province of South Holland. One important asset of the gas field near this location is the proximity of a CO_2 transport network that supplies the greenhouses in the area with CO_2. The CO_2 originates from a hydrogen plant at the Shell refineries in the Botlek area, 15 km from the De Lier gas field. The availability of large CO_2

De Lier facts

- The gas field is one of the older NAM assets in the Rijswijk Concession, the production of which started in 1958 and ceased in 1992.
- The depleted De Lier gas reservoir, which is 45 m thick, belongs to the Holland Greensand Member with the top structure at a depth of 1350 m below the earth's surface (see Figure 4.11).
- The initial pressure in the Greensand reservoir was 150 Bar, the pressure at abandonment was 30 bar and the reservoir temperature is 58°C.
- A so-called 'reverse fault' bounds the southwest flank of the structure and a normal fault bounds the structure on the north-eastern side.
- The top seal of the Greensand reservoir consists of a 30 metre-thick Middle Holland Marl layer, which is overlain by a 70-100 metre-thick Upper Holland Marl layer.
- More than 50 wells were drilled, penetrating or transecting the De Lier gas reservoir.
- The storage capacity is about 8,000,000 tonnes of CO_2.

flows was one important reason why the De Lier field was an interesting candidate for investigation as to its suitability for storing CO_2.

Principles for storing CO_2

The production of natural gas from the porous reservoir has created the space for injecting CO_2. Gas extraction has reduced the pressure in the reservoir, which will increase when CO_2 is injected. As soon as the reservoir pressure approaches the initial pressure, injection will be stopped. Most of the CO_2 will then be structurally trapped in the reservoir that originally was filled with gas. Only a small amount is expected to dissolve in the ambient formation water or to mineralise.

Fault and seal integrity

One of the interesting findings of the De Lier experiment was that geochemical reactions of CO_2 with the minerals present in the seal are likely to improve the sealing properties in time. The reactions of the minerals with CO_2-loaded fluids can lead to a substantial mineral re-arrangement on the long term, if they are in contact with CO_2-loaded fluids. Overall, an increase in volume (thus a decrease in porosity) is more likely than a decrease in volume.

Also it was found that seal integrity is not an issue. Fractures initiated in the Holland Greensand may propagate upwards into the top seal (more than 100 metres layer of marl) but at most by 6 metres. Applying the so-called Shale Gouge Ratio approach showed that the boundary faults of the De Lier field above the gas-water contact are completely sealed. The potential for re-activation of the faults adjoining the Holland Greensand reservoir in the De Lier field is low.

Well integrity

Most wells in the De Lier field are plugged with cement and abandoned according to Dutch Mining Law for corrosive fluids. Only five wells are abandoned and plugged according to older regulation for abandoning wells. A literature review showed that CO_2 corrosion rates based on diffusion processes are very low.

Figure 3.11 a Geological cross-section of the De Lier gas field

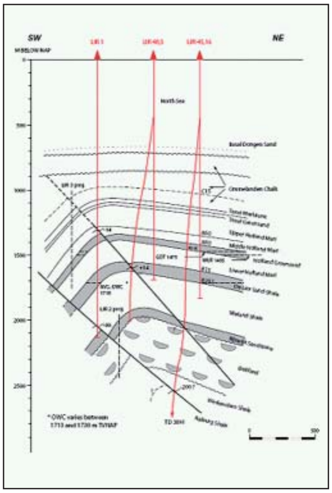


Figure 3.11 b The target reservoir for CO_2 injection is the Holland Greensand.

However, it cannot be assumed that gas wells which are abandoned according to Dutch Mining Law for non-corrosive natural gas are automatically sound for corrosive CO_2. Most of the wells penetrate the anticipated CO_2 injection zone and end in the deeper towards the lower oil reservoir. Since a cement plug at the level of reservoirs above the deeper target revervoir is not required according to the Dutch Mining Law, it is often not present. Besides well plugs, a primary cement sheath outside of the casing is often found in the wells. However, these sheaths are only a few centimetres thick and CO_2 loaded fluids could corrode away the few centimetres of primary cement sheath and casing of these wells within a timeframe in the order of decades. CO_2 can then leak quite far up into the well if the next cement plug is at a shallow level. Furthermore Dutch Mining Law does not explicitly prescribe the presence or absence of a primary cement sheath. This leaves room for possible leakage pathways between the casing and formation rock which could even bypass the seal. It appeared that these issues were observed for only a few wells at the De Lier gas field.

The degradation of cement will be considerably reduced because of the presence of immobile connate water instead of free water in most parts of the reservoir. Near the wells, the Portlandite mineral the cement will be transferred into the more stable calcite. Based on the literature, cement degradation is relatively slow. Chemical degradation of cement plugs by CO_2 loaded fluids is not an issue, unless fractures or other pathways through the cement are present. This transformation process will continue as long as CO_2 is transported by diffusion towards the well and as long as Portlandite is present. As such, the Portlandite is likely to act as a buffer to protect the steel casing from corrosion. However, the presence of Portlandite may be limited in the long term, considering the amount of CO_2 that is intended to be injected into the reservoir. There is also the risk of preferential pathways in the cement being present which lead the CO_2 in the formation water directly to the casing.

After an initial phase of relatively fast corrosion of the steel casing, the process will slow down due to a combination of factors. First, an iron carbonate ($FeCO_3$) cover is formed. Second, the removal of corrosion products through the water phase stagnates, while the increase in pH values over time (probably after a few months) is slow as a consequence of mineral reactions. Furthermore, there is a considerable reduction in the corrosion rate of cement and casing due to the presence of connate instead of free water in most parts of the reservoir.

The view from De Lier

After extensive investigations, some important conclusions can be drawn from the De Lier case. Geologically, the gas field performed well. No scenarios could be found where the CO_2 could leak through the seal and the faults.

On the other hand, the few wells that showed increased risk of CO_2 migration could not be remediated, because they were not accesible anymore. This was the main reason why the NAM looked for alternative storage sites near the Shell refinery. A promising site has been found at the Barendrecht gas field.

3.7 – The importance of public opinion

Public acceptance or rejection to Carbon Capture and Storage (CCS) may facilitate, slow down or even stop the implementation of CCS. It is therefore important to make accurate predictions of the public's support and to discover what would make communication about CCS with the public more successful. Studies within CATO, carried out by Leiden University, pursued both aims.

Uninformed opinions on CCS: useless

Current public opinions on carbon capture and storage options, assessed by traditional questionnaires, are mostly *pseudo-opinions*. Most lay people admit they have never heard of specific CCS options. Nevertheless, when asked, they provide their overall evaluations of these options instead of refraining from evaluation.

Most respondents admitted that they do not know anything about CCS in general or about the six specific CCS technologies. Only a minority stated not to know about global warming either. However, a knowledge test on these topics shows that the majority of the Dutch public neither understands how current energy use causes CO_2 emissions nor that CO_2 emissions contribute to global warming. They nevertheless provide opinions on these matters when asked.

These uninformed opinions are highly unstable. They are proven to change within twelve minutes and to be affected by insignificant, tiny amounts of information. Even the respondents' mood can influence their opinion. Clearly, polls based on traditional questionnaires don't have any value in predicting future public opinion on CCS options.

Based on these results, it is advisable:

- To distrust or better ignore results from conventional public opinion polls on CCS. These polls merely generate pseudo-opinions, without any indication of real public support or opposition.

- When experts attempt to communicate the concept of CCS to the public (for example via the media) they should spell out small steps in the causal chain (for example, "When electricity is produced in a coal-fired power plant, stack gases are emitted to the air. One of these stack gases is CO_2, a greenhouse gas. Much CO_2 in the air increases the greenhouse effect, which results in global warming. We can capture CO_2 from the stack gases of coal-fired power plants...", etc). Most of the Dutch public have no knowledge whatsoever of these links in the causal chain and an assertion like "CCS is one of the CO_2 mitigation options" is totally lost on most of the general public.

Informed opinions: neither enthusiastic nor opposed

As an alternative to the traditional questionnaires mentioned above, an Information-Choice Questionnaire (ICQ) provides respondents with information on the most relevant aspects and consequences before asking for their opinions. In addition, respondents are helped to process this information.

Of course, the information should be relevant, valid, balanced and comprehensible. So when preparing an ICQ on CCS options, this information was collected from experts with diverse backgrounds (for example, from universities, from non-governmental organisations such as Greenpeace and from companies such as Shell) who agreed on what is valid, relevant and balanced information about the consequences of CCS. This expert information was also made comprehensible for non-experts.

In the ICQ, respondents compared two CCS options to alternative methods for reducing CO_2 emissions (for example, nuclear energy, energy production with biomass, combinations of various energy efficiency measures and wind turbines at sea). A representative sample of the Dutch population (N=971) completed the ICQ in May 2007.

Once participants had read and evaluated the consequences of CCS, they were not enthusiastic about the CCS options: ‘Large coal and gas-fired power plants with CCS’ were given an average score of 5.3 on a scale of 1 to 10, ‘Conversion from natural gas to hydrogen with CCS’ scored an average of 5.9. However, a large majority were not seriously opposed to large-scale implementation of these CCS options (11% and 7% find these options ‘unacceptable’, respectively). Large-scale implementation of nuclear energy also scored 5.3 on average, but a much larger percentage perceived this option as unacceptable. The other alternatives (biomass, energy efficiency and wind energy) were evaluated significantly more positive.

A supplementary, experimental study showed that informed public opinions on CCS based on ICQ procedures are stable and unlikely to change as a result of (misleading media) information on catastrophic risks allegedly related to CCS (such as the Lake Nyos disaster).

Some readers might jump to the conclusion that there is public support for CCS (or at least no substantial public opposition), because a large majority of the Dutch public do not oppose large-scale implementation of CCS options. However, the ICQ results do not reflect *current* public support for CCS, but rather *potential, future* public support after people have been thoroughly informed about CCS. Another qualification is that the ICQ results reflect the opinions of the general public and not those of people living near onshore CCS activities.

Yet, the conclusion is justified that, after processing good quality information on pros and cons of CCS, the Dutch general public will probably agree to large-scale implementation of CCS, although reluctantly.

Effective communication is all about trust

Further research highlighted the importance of public trust in stakeholders in CCS communication. Public trust in CCS stakeholders can be thought of as people's willingness to rely on these organisations. It involves both their integrity and their competence. The reason that trust in stakeholders plays such an important role in opinion formation is that most people lack the knowledge or motivation to judge the merits of CCS by themselves.

The most important findings:

- People put more trust in environmental NGOs than in the industrial organisations that are involved, because they perceive NGOs to be more concerned with public interests than industrial organisations. However, both types of organisations are perceived to be equally competent with regard to CCS.
- 'Persuasive' communications that aim to promote CCS are likely to be counterproductive. It's better to provide balanced factual information about CCS that does not focus solely on the benefits of CCS.
- A lack of public trust in stakeholders negatively affects the way people process information. Both governmental and industrial organisations should be aware that their CCS communications are likely to be rejected by the public due to a lack of public trust, which may result in negative attitudes to CCS among the public.
- Communication strategies can activate or damage public trust in stakeholders. Industrial stakeholders do better if they confirm public expectations about their business motives (economic gain) in addition to public motives (concern about the environment). Providing only socially desirable information causes distrust rather than trust.
- Communication about CCS appears most successful when two stakeholders with different interests (for example, an oil company and an environmental NGO) provide information together. The reputation of the most trusted party (the environmental NGO) is not harmed by this collaboration.
- It is important for public acceptance of decisions about CCS to involve organisations with different interests in the decision-making process and to communicate to the public that this is indeed the case.

These effects regarding trust and communication, obtained under experimental conditions, are expected to be similar or larger in real life (for example when CCS stakeholders start informing local communities about actual CO_2 storage projects). But whether these effects indeed emerge at onshore demonstration sites should be confirmed by research on the spot.

Stan Dessens

‘An important role in society’

Stan Dessens is the chairman of the Dutch Taskforce CCS, a public-private partnership which was established in 2008 with the objective of accelerating the introduction of carbon capture, transport and storage. He also chairs the CATO steering Committee.

“The way in which all relevant parties have been involved from the start in the CATO programme is really impressive. I give all credit to the people who took the initiative for the programme. Back in 2003, the thoughts about climate policy in general and a CCS policy in particular were not yet fully developed. At the time when climate issues got full attention, the CATO train was already running.”

“Although CATO-2 has not yet been fully approved, the fact the government most likely will co-finance a follow-up programme may be the best proof of the success of CATO. The programme is well known and has broad support, from industry, scientists, public institutions and environmental NGOs.”

“I think CATO has provided some very useful building blocks for further development of CCS in the Netherlands. The technologies of capture, transport and storage are not that controversial, not even with the environmental NGOs. However, this doesn’t mean that there is broad public acceptance of CCS, especially at the local level.”

“I believe that politicians and public authorities have avoided public discussion for too long, especially about the storage component of CCS. Official green or white papers mention the necessity of CCS within climate policies, but too little effort has been invested in proving to the public that CCS is indispensable to climate change abatement.”

“In its social research, CATO concluded that confidence in the senders of a message matters even more than the content. The practical consequence of this conclusion is that we have to organise coalitions of groups that are trusted by the public and can thus help put carbon storage into practice.”

3.8 – Hints for policy makers: How to bring CCS to market

In most cases, sustainable innovations have a long way to go from basic research to commercialisation. This ‘valley of death’ is a graveyard of technologies, which cannot simply be bridged by putting extra money into research and development. Some clues for policy makers on how to accelerate the development of CCS technologies.

Sustainable innovations have to overcome many market and institutional barriers before they become mature. In the recent past, rapid diffusion of sustainable innovations mainly took place when environmental problems were considered to be extremely urgent. A good example is CFC-free cooling technology that was introduced to allow the hole in the ozone layer to recover, back in the 1980s and 1990s. But in many other cases – as with technologies that address climate change – market uptake has been slow.

The question as to how to accelerate the development of CCS is of great importance for policy makers all around the world. The Innovation Studies Group at Utrecht University adopted a multi-disciplinary research approach to tackling this topic within the CATO programme. After all, the innovation process is not only influenced by technological characteristics. The social-economic environment in which the technology is developed and diffused – the ‘technological innovation system’ – is also of great importance.

A well functioning innovation system would greatly support the market uptake of this technology. So identifying strengths and weaknesses in the present innovation system is of crucial importance to policy makers.

Seven keys

An innovation system can be analysed as consisting of seven key processes, which are known as ‘system functions’ (see list). These functions range from knowledge development and diffusion to its uptake by entrepreneurs. For a better understanding of these key processes, a comparison was made between the CCS innovation systems in the USA, Canada, Norway, Australia, the EU and the Netherlands. Such a comparison makes it possible to learn from each other’s experience with developing CCS.

Functions of Innovation Systems

1 Entrepreneurial Activity
2 Knowledge Development
3 Knowledge Diffusion
4 Guidance
5 Market Formation
6 Resource Mobilisation
7 Creation of Legitimacy

The data thus produced are the result of reviews of both scientific and 'grey' literature (newspaper articles, professional journals and policy documents), supported by more than 100 interviews with the main actors involved in the development of CCS in different countries. In addition, quantitative methods were developed in order to gain more (objective) insights into the way a particular function works.

One example of these quantitative methods is the use of social network analysis to show the growth in CCS networks (function 3: knowledge diffusion). Other examples are the media analysis used to assess the level of acceptance by the broader public (function 7: creation of legitimacy) and the project database, which contains over 500 CCS projects in North America and Europe, set up in order to gain insight into the volume and direction of technological activity (functions: 2. knowledge development, 1. entrepreneurial activities and 6. resource mobilisation).

One of the results (see figure 3.12a below) shows that investments in CCS in Europe (around €230 million in 2008) are significantly higher than those made by Canada and the United States together. These differences are mainly due to the large investments in CO_2 capture R&D and demonstration in Europe. Within Europe, investments in capture research and demonstration are evenly distributed among the three capture options. However, at the level of member states,

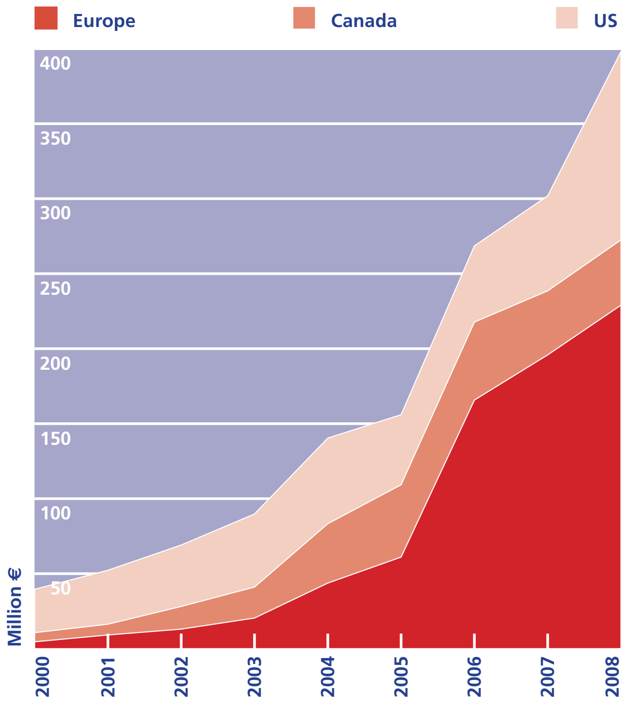


Figure 3.12 a CCS investments in Europe, Canada and US.

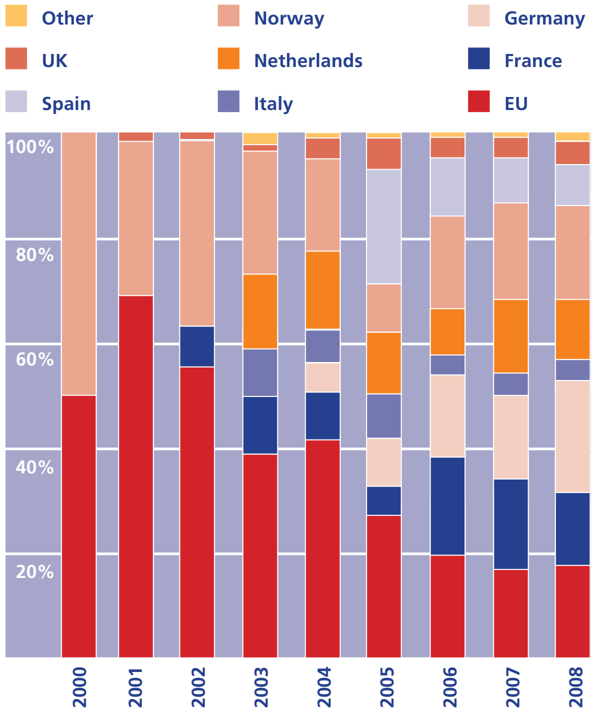


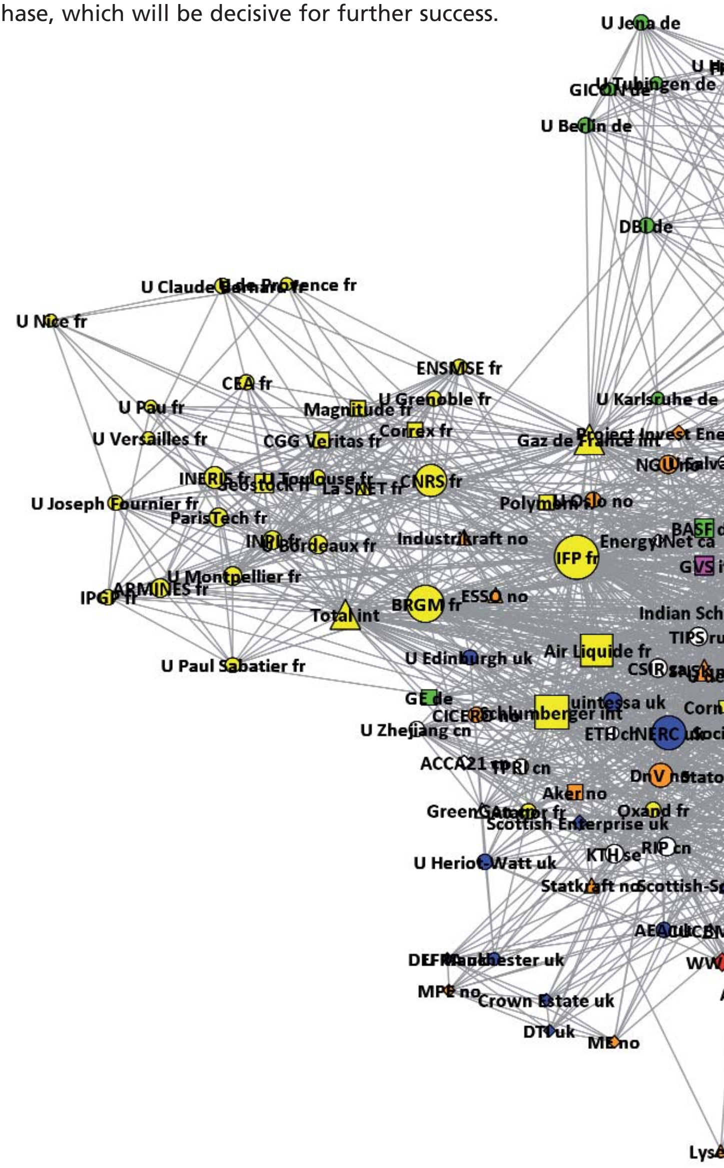
Figure 3.12 b Relative distribution of the research budget among countries.

some countries focus on particular capture technologies. Expenditures on CO_2 storage development are roughly the same in North America and Europe. The focus in these projects is mainly on CO_2 storage in both depleted and currently producing oil and gas reservoirs.

The relative distribution of the European budget for research among the different member states (see figure 3.12b) shows that the Netherlands is one of the top five countries investing in CCS in Europe. The importance of the Netherlands in the development of CCS is also illustrated by the central position of Dutch organisations such as TNO and ECN in the European CCS network (see figure 3.13). The European CCS network has grown rapidly in the last few years. Over 400 different actors are currently working together on the development of CCS, thus enhancing the creation and exchange of CCS knowledge in Europe.

The historical growth of the innovation system functions is interesting in itself. However, these insights don't directly reveal whether the performance of the system is optimal, or which functions need to be improved in order to enhance the growth of the system. For that purpose, CCS experts in five different countries were asked to score the fulfilment of each system function on a 5-point scale (5 = very good). Together with the quantitative results, these key stakeholders' assessments suggest how system functions should be further developed to achieve higher levels of performance.

The performance assessment led to the important conclusion that the various extensive knowledge bases and networks have not yet been valorised by entrepreneurs. This suggests that the construction of the innovation system has entered a critical phase, which will be decisive for further success.



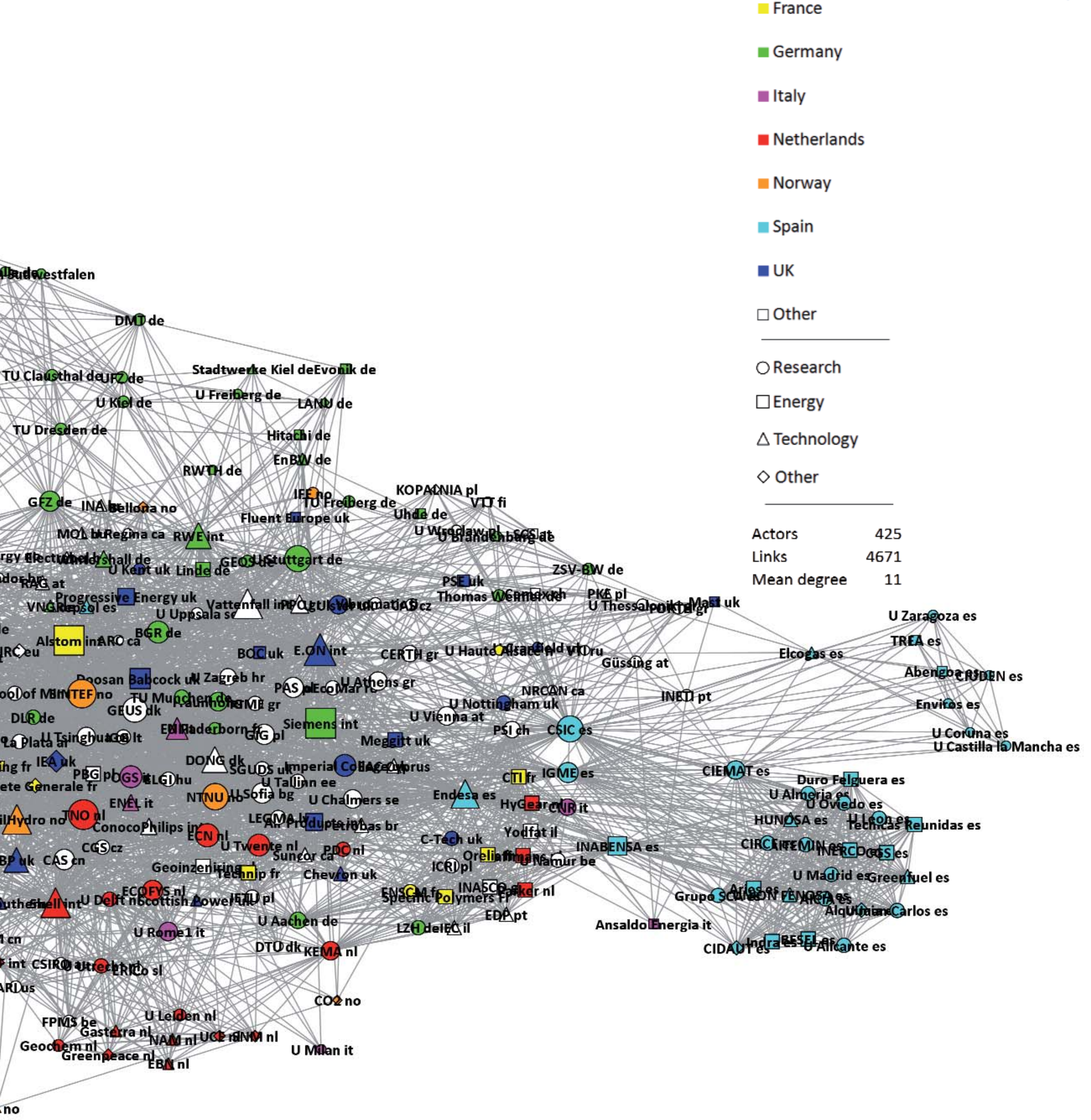


Figure 3.13 The European CCS network.

Some policy advice

Moving the CCS innovation system through this difficult phase requires direct policy initiatives to tackle the weakest system functions. In all countries, entrepreneurial activity, market formation and mobilisation of resources should improve. In some countries, governmental guidance and establishing legitimacy need extra attention as well.

Given these observations, governments should improve their guiding role. The research clearly indicates a few ways in which they could do this:

- By adding short-term CCS objectives to existing mid-term greenhouse gas emission reduction targets and long-term visions. These goals should be accompanied by a clear regulatory framework. This is important to stimulate the further involvement of private companies.
- By fostering market formation and entrepreneurial activity through financial support for demonstration projects in public/private partnerships. In this way the technology can advance, which is necessary to achieve the cost reductions and performance improvements needed for the technology to enter the market.
- By making sustainable changes in the institutional structure of the innovation system and creating a clear market for CCS. The industrial sectors that may be considering applying CCS in their daily operations cannot rely sufficiently on current temporary subsidies, taxes or cap-and-trade systems to justify their high investments. One option could be a guaranteed CO_2 price, while another would be introducing emission performance standards for power plants and industrial facilities.

These conclusions are the outcome of a thorough innovation systems analysis of CCS. The way in which the advice they contain will be followed is of course a matter for politicians.

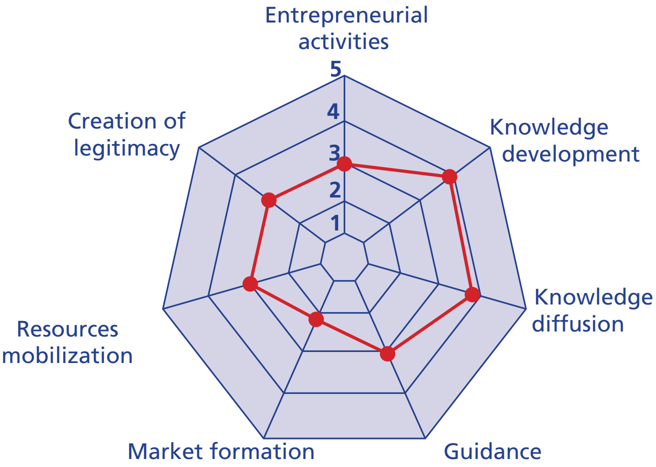


Figure 3.14 Overall score on the innovation system functions by 100 experts in Norway, Netherlands, United States, Canada and Australia.

3.9 – A sustainability framework for carbon capture and storage

Carbon capture and storage technologies are often the subject of debate, with many arguments being advanced, both for and against. Some oppose the technologies because they are considered to be unsafe and insufficient to achieve fast, substantial greenhouse gas reductions. Others argue that climate policies cannot do without CCS, at least in the short and medium term. Most of these arguments deal with the question: is CCS a sustainable energy solution?

To be able to answer this question, it is necessary to understand the concept of sustainability. In addition, we need to analyse whether CCS fits into this concept. In order to assess the key characteristics and the sustainability of CCS, the CATO programme developed a framework on the basis of two main elements:

- A clear understanding of the sustainability concept and a good overview on the current opinions about this concept;
- A set of adequate criteria to judge whether CCS can be seen as sustainable or contributes to a sustainable energy supply in the Netherlands.

Definitions

'Sustainability' and 'sustainable development' are not strictly defined concepts. In fact there are hundreds of definitions. The most common quote originates from the Brundtland Committee on Sustainable Development: "Development that meets the needs of the present without compromising the needs of future generations to meet their own needs" (Our Common Future, 1987). But then again, the definition of 'needs' is often discussed.

So what do these interpretations have in common? There seems to be consensus that sustainability contains not only ecological but also social and economic issues. Time and spatial dimensions are also relevant, including our obligation to future generations and to societies and regions elsewhere on the planet.

Applying these criteria to the energy system implies that energy supplies should not only be clean, but should also meet additional criteria such as safety, security and affordability.

A framework of criteria and concerns

An innovative aspect of the CATO study is that it acknowledges that a sustainability framework cannot be the result of scientific research by a single institution. Early involvement of stakeholders in this process is required, as the definition of sustainability has to be developed according to the context and the stakeholders' priorities and perceptions. In addition, as young technologies such as CCS often lack consistent information, involving different actors provides a better overview of the knowledge that is currently available.

In this project, actors were involved in several ways: via a so-called 'policy lab', a web-based survey and through interviews.

The **policy lab** put experts and stakeholders together in a room (see picture). A computer network and special software allowed them to comment on each another's ideas anonymously and simultaneously, while at the same time engaging in an open conversation. The policy lab addressed three main questions:

- Which criteria determine the sustainability of an energy system?
- Which concerns should be addressed if CCS is to be part of a sustainable energy system or of a transition towards a sustainable energy system?
- Which actors should undertake what kind of actions to overcome these concerns?

Together with an in-depth literature review, the policy lab produced a list of nine sustainability quality criteria (see Table 3.1).

During this process, 36 concerns related to the ability of CCS to fulfil these criteria were formulated. Each concern could prevent the sustainable implementation of CCS. Some examples are (with the associated criteria in brackets):

- Will pollutants other than CO_2 be sufficiently addressed (clean)?
- Will minor discharges of CO_2 not lead to significant emissions over time (clean)?
- In some parts of the world, coal mining is unsafe. Will the reliance of CCS in coal increase the number of mining accidents (safe)?
- Will a sustainable energy supply solution be imposed on future generations (just)?
- Will the current dependence on fossil fuels continue (flexible)?
- Could CCS investment lead to reduced investment in renewables and thus delay the transition towards a sustainable energy system (flexible)?
- Will large-scale CCS compete with decentralised supply systems (continuous)?
- Could CCS lead to 'storage company' monopolies and geo-political instabilities (continuous/ independent)?

- Are there any spin-offs for other sectors (affordable)?
- If CCS is not deployed internationally, could it adversely affect national economies (affordable)?

A subsequent **web-based survey** among 231 respondents who have worked in CCS and issues related to climate change produced a preliminary ranking of these concerns, together with data on preferences and views on the role of CCS in reducing CO_2 emissions.

Finally, the research included stakeholder interviews to assess the players and actions needed to deal with these concerns. In general, the government is seen as the most relevant

Table 3.1 Sustainability quality criteria.

Criteria of sustainability	Description
Clean	Placing a minimum burden on the environment in the widest sense; reducing emissions to the air, soil and water, including emissions that may contribute to the enhanced greenhouse effect and air pollution. In addition, this includes reducing transport of (dangerous) waste. There are both time and geographical dimensions, relating to future generations and to other countries.
Safe	Preventing catastrophic events and reducing negative health impacts for human beings. Special attention should be paid to risk exposure (the product of the probability and the impact of an event).
Just	This relates to both equity and manageability between regions and generations. The availability and accessibility of energy should be the same for all regions, as well as current and future generations. In addition, the potential risks and negative impacts of the energy system should also be the same. A balance is needed between benefits and burdens for all. The energy supply of the future should not lead to (increased) poverty.
Flexible	The energy system offers a variety of energy sources and carriers to reduce the dependence of regions on their own current and future energy supply. Choices made now should not cause any ‘lock-in’ for future technologies or institutional aspects.
Continuous	Energy sources are available for long periods. Sufficient time and insight are available to develop alternative sources.
Independent	An energy system is not over-dependent on sources in other regions for its energy supply.
Competitive or affordable	Energy technologies are affordable for consumers. A level playing field is guaranteed for industry and power companies.
Acceptable	The energy system should be acceptable to most people, should be transparent and should serve the common interest.
Reliable	The energy system should supply a near-continuous flow of energy. The complexity of the system should not reduce the constant supply of energy.

stakeholder in the Netherlands for the first phase of sustainable implementation of CCS. The authorities have a lot to do. First, they have to stimulate and finance research. Second, they need to improve health and safety standards in order to increase public acceptance. And third, they need to establish a policy structure for monitoring, ensuring safety standards and competitive implementation.

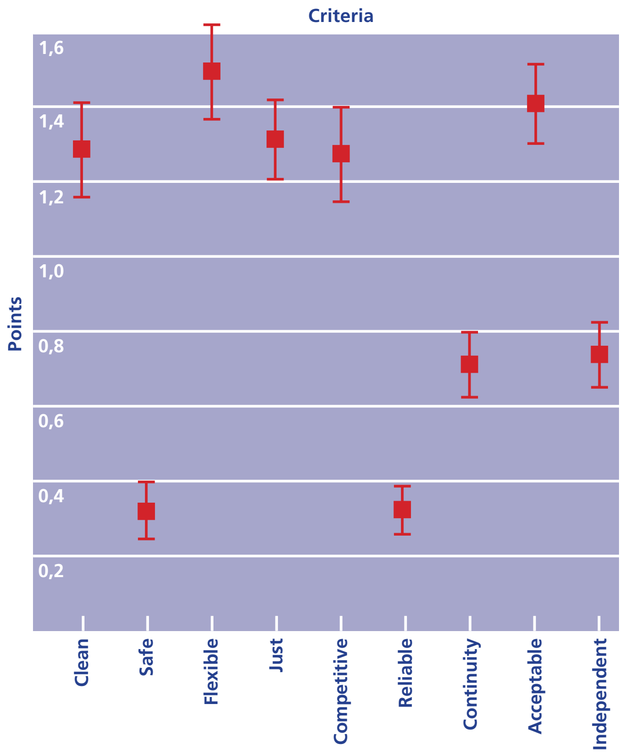


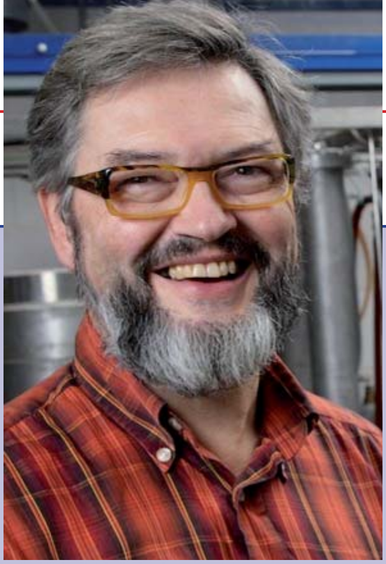
Figure 3.16 Appreciation ratings of the different sustainability criteria by 231 respondents who have worked in the field of CCS and climate change.

The ranking of concerns among 231 CCS professionals shows that they think safety and reliability are less relevant to ensuring that CCS makes a contribution to sustainability. (Figure 3.16) Concerns related to the criteria *clean, flexible, just, competitive and acceptable* were considered more important.

And furthermore…

The CATO programme has shown the viability of a concrete objective discussion about the role of CCS in a sustainable energy system. The framework of nine sustainability criteria is a good basis for describing aspects of CCS that should be addressed. This study identifies the main concerns, required actions and relevant stakeholders, which need to be known before large-scale CCS can contribute to a sustainable energy system.

Nevertheless, more work must be done on sustainability. The next step is to develop quantifiable indicators for all criteria, including the corresponding monitoring procedure. Developing these indicators is a considerable challenge. Only when these indicators have been fully identified, can objective sustainability limits be imposed on the application of CCS.



Michiel Groeneveld

'Eye-openers for industry'

At the start of CATO, Michiel Groeneveld was working at Shell. Since 1 January 2008 he's been a professor of Thermo-Chemical Conversion of Biomass at Twente University (NL), and he supervised two PhD students within CATO.

"CATO's main achievement was bringing together all voices about carbon capture and storage in one coordinated programme. For industry, this was the perfect opportunity to join a complete programme, without having to invest more money than it already did."

"Another major advantage was that industry, universities, research institutes and environmental NGOs were brought together to discuss CCS issues. Although positions could widely differ, the debate could be reduced to the content, e.g. real risks instead of just discussing *perceived* risks. Thanks to this transparency, policy makers were offered a more integrated view on CCS options."

"CATO combines knowledge about capture, storage and public acceptance. The last item particular was not regarded as a serious research issue for a long time. Looking back at CATO from my former Shell perspective, the social research was one of the eye-openers for the industry and technical research participants. Right now, I think social acceptance will be crucial to progress in carbon capture and storage."

"A second important lesson we learned is that carbon storage in coal seams is much more difficult than previously thought. Thirdly, the slow chemical reactions of stored CO_2 with rock provided the insight that at least in the long term, in hundreds or thousands of years, the stored CO_2 can be 100% securely stored if the reservoir is well selected."

"Carbon capture and storage is a societal problem, but also an opportunity for industry. In my view, in the Netherlands we will need carbon capture and storage on a large scale, around 100 million tons per year, as an intermediate technology to mitigate climate change. Taking no decision to do CCS and waiting for improved technologies is also a decision. CCS only has a limited window of opportunity. Building the infrastructure takes time. But in twenty years, CCS will get out of sight because of improving perspectives on other low-carbon technologies."

"In the next phase, the research will be focusing on practical results, engineering demonstration projects and a large CO_2 infrastructure in North-western Europe. Meanwhile, we should not forget to investigate new options. The conditions for CCS in the Netherlands are good, in terms of technological capabilities, the concentrated CO_2 sources and geological storage opportunities. If we cannot execute CCS here, we cannot do it anywhere."

4 – CCS in Dutch Energy Policy

The Netherlands' action plan for energy and climate is formulated in the *Clean and Efficient* programme. It calls for annual energy efficiency improvements of 2% by 2020, a 30% reduction in greenhouse gas emissions by 2020 (baseline: 1990) and 20% renewable energy in the energy mix by 2020. The Clean and Efficient policies are expected to reduce greenhouse gas emissions from 212 million tonnes in 2005 to 158 millon tonnes in 2020.

Given these objectives, CCS is seen as a third strategy in Dutch energy and climate policy, after energy efficiency and renewable energy. The Dutch government recognises CCS as a necessary intermediate step in the transition towards a sustainable energy system, since coal is expected to continue to be used in a significant proportion of the electricity production in the Netherlands.

The Dutch CCS Project

In 2008 the ministries of Public Housing, Spatial Planning and the Environment (VROM) and of Economic Affairs (EZ) initiated the Dutch 'CCS project'. This project, which represents a strategy for moving towards large-scale implementation of CCS, has four phases:

- Fundamental research
- Pilot projects
- Demonstration projects and
- Commercial projects.

The project is managed by the Netherlands interministerial Project Organisation CCS, which aims to create the prerequisites for large-scale CCS demonstration projects in the Rijnmond region and in the north of the Netherlands by 2015.

Moreover, the public-private Taskforce CCS was established in March 2008, in order to get Dutch industry closely involved. From 2020 onwards, CCS is expected to be commercially viable, without the need for government support.

The Dutch government has provided a budget for several research projects and pilots. In 2003, €12.7 million was made available for the CATO research programme.

In 2007 the government granted €30 million to three carbon capture projects. Two of these are currently underway, one was stopped because initial calculations indicated that the CO_2 avoidance costs would be too high. The CO_2 capture projects are financed by the 'Unique Opportunities Regulation' (Unieke Kansen Regeling, UKR). One project involves collaboration between Nuon Energy Sourcing and Delft University of Technology ('CO_2 Catch Up') and the other is a project run by SEQ entitled 'Zero Emission Power Plant' (ZEPP)'.

In November 2008, the government decided to allocate €60 million for two CO_2 storage demonstration projects. These projects are located in Barendrecht and Geleen. Both are now in the final stages of preparation (see later in this chapter).

In the next phase, two large-scale integrated demonstration projects are envisaged within the framework of the Clean and Efficient programme. These projects cover a range of technology options for capture, transport and storage. Potential locations for developing these projects are the north of the Netherlands and Rotterdam (as part of the so-called 'Rotterdam Climate Initiative').

Two quotes from the *Clean and Efficient* programme:

"New coal-fired power stations will be constructed in such a way that they will be able to capture CO_2 and store it underground in the future. Clean fossil fuels will thus be able to be used as a transitional technology on the way to renewable energy production. The government will make agreements with operators of new coal-fired power stations concerning reduced CO_2 emissions. From 2015 onwards large reductions will have to be achieved in power stations."

"The Netherlands is attempting to realise two large demonstrations on Carbon Capture and Storage (CCS). As soon as the technology for CCS has been sufficiently developed, this will need to be made mandatory on a European level for all new power stations."

Demonstrating capture

CO_2 Catch Up project

One of the capture projects that currently receives governmental support is the CO_2 Catch Up project, a joint initiative of Nuon Energy Sourcing and Delft University of Technology. This research and development project involves capturing CO_2 from the multi-fuel (coal and biomass) Willem Alexander Coal gasification plant in Buggenum. For Nuon, testing CO_2 capture technology is of particular interest with regard to the 1,200 megawatt multi-fuel Magnum gasification plant, which Nuon plans to build in the Eemshaven in the north of the Netherlands. In gasification plants, it's most advantageous to capture the CO_2 before conversion takes place, because this requires less space and gives less loss of energy conversion efficiency. If all goes well, full-scale CO_2 capture at the Nuon Magnum plant is feasible from 2013 onwards.

ZEPP

SEQ Nederland BV was launched to develop and market a Zero Emission Power Plant (ZEPP) concept. SEQ cooperates with Eneco Milieu b.v. and Delft University of Technology. Presently a site selection process is ongoing.

The SEQ ZEPP concept could capture around 250,000 tonnes of CO_2 annually, while the storage of the CO_2 in a natural gas field nearby would enhance the production of natural gas by 40 million m^3. This gas will be used in the ZEPP power plant, creating a climate-neutral closed cycle. The total project costs are estimated to be €60 million.

Demonstrating storage

Geleen project

At Chemelot, an industrial site in Geleen in the south of the Netherlands, three parties – the French/ Dutch company SUEZ/GTI, the Belgian company VITO and the Dutch company DSM – are collaborating on a demonstration CO_2 storage project using the space between and under coal seams.

The CO_2 to be injected and stored comes from an ammonia plant that currently produces 1 million tonnes of ammonia per year. For each tonne of ammonia produced around 1 tonne of pure CO_2 is also produced. Currently, 50% of the CO_2 (500 kilotonnes of CO_2) is used for other industrial purposes, such as the soft drinks industry and ureum production, the remaining CO_2 is vented to the atmosphere.

Part of the CO_2 that is currently vented to the atmosphere is planned to be stored underground.

Figure 4.1 Aerial view of the Geleen industrial site "Chemelot".

The CO_2 is injected at a depth of about 1800 metres into chalk sandstone layers that are situated under the coal layers, at a pressure of about 100 bar. Eventually all of the CO_2 that is injected will be chemically and physically bound to the chalk sandstone (as carbonates) and the coal, respectively.

The project is split into two phases. During the first phase a small amount of about 10 kilotonnes CO_2 will be injected into the storage reservoir. The main goal of this first phase is to learn more about injection technology. If the initial tests prove successful, the CO_2 storage project will be scaled up to store 2 million tonnes of CO_2 over a period of 10 years.

If proven, the technology may have considerable spin-off within the Netherlands and also for the rest of the world. Coal layers with sandstone are available in many places around the world. Often large industries that produce CO_2 are close to these locations.

Barendrecht

Early in 2006 Shell started preparations for a capture and storage demonstration project in the southwest of the Netherlands. The Shell Pernis refinery near Rotterdam produces 1 million tonnes of almost pure CO_2 annually. Some of this is used as an industrial feedstock (e.g. for carbonated beverages) and in greenhouses to stimulate the growth of vegetables. Mainly because of the lower demand in the winter, around 400,000 tonnes per year is still available for storage.

The first storage option that was studied in CATO by NAM in collaboration with TNO was the already abandoned De Lier gas field. Extensive feasibility studies indicated that although the field was in principle suitable and safe for CO_2 storage, some of the wells were no longer accessible for monitoring or remediation. The De Lier field was therefore dropped as an option. However, some significant learnings could be directly applied to the Barendrecht fields, which were identified as the next candidates for storage.

Barendrecht lies some 17 kilometres from Pernis, which is bridged by an existing pipeline. Starting in 2011, two depleted gas fields will be used to receive the CO_2 for a period of around 25 years. The reservoir in both fields is sandstone, but from a different geological age. In both fields the caprock is a thick layer of claystone. The smaller of the two fields (Barendrecht), which is at a depth of some 1,700 metres, can store about 0.8 million tonnes. The larger (Barendrecht-Ziedewij) is at some 2,700 metres deep and can store about 9.5 million tonnes.

The CO_2 from hydrogen production is very pure and dry (>99%). The CO_2 will be compressed to a pressure of 40 bar before entering the pipeline. A second compressor at the injection location will gradually increase the pressure towards the end of the injection period. For extra security reasons, CO_2 injection will cease when the pressure in the reservoir is below that in the original reservoir. Each field will have one injection well. In Barendrecht one monitoring well is available and Barendrecht-Ziedewij has two potential monitoring wells. OCAP will be responsible for the transport and the compression and Shell CO_2 Storage BV will handle storage and monitoring.

In November 2008 the Dutch Ministry of Housing, Spatial Planning and Environment announced that the project will be eligible for a €30 million government grant. Recently the Environmental Impact Assessment (EIA) was accepted by the authorities and stakeholders had the opportunity to express their views about the EIA and the project. Depending on the outcome of this extensive permitting process, a final investment decision is expected later in 2009.

No major new technology is needed for this project. The main learning objectives are in the areas of public acceptance (Barendrecht is a densely populated area), legal procedures and regulations, monitoring and verification, and obtaining CO_2 credits in the EU Emission Trading Scheme. A major advantage of starting with a very small field is that learnings over the complete life cycle of a project will be available relatively fast.

CATO-2 will play an important role in optimising and reviewing the monitoring programme in the Barendrecht project.

Demonstrating the full CCS chain

The Rotterdam Climate Initiative

In the Rotterdam area the Port of Rotterdam, the municipality of Rotterdam, Deltalinqs (as a representative of the companies in the Rijnmond region), and DCMR Environmental Protection Agency Rijnmond have established the Rotterdam Climate Initiative (RCI). Collaborating with local government, environmental organisations, individual companies, academic institutions and citizens, the Initiative aims to achieve a 50% reduction in CO_2 emissions in the region by 2025, while boosting the Rotterdam economy and preparing for the consequences of climate change.

The RCI concludes that, despite maximum efforts to increase energy savings and the use of renewable energy, CCS will be necessary. Because of its strategic location between possible storage sites on the continental shelf and large emitters of CO_2 in the North-western Europe, the area of Rotterdam is a good location for implementing CCS. Within Rotterdam's industrial complex, sources of pure CO_2 with low capture costs are available and the existing CO_2 pipeline infrastructure could become a stepping stone for a larger CO_2 transport network.

In July 2008 RCI published a report entitled *CO_2 capture, transport and storage in Rotterdam* about the potential for CCS in the Rotterdam area. The main conclusion of this report is that Rotterdam can start capturing, transporting and storing 5 million tonnes of CO_2 underground by 2015. By 2025, it will be possible to capture and store 20 million tonnes of CO_2 annually. These goals will require considerable effort and decisiveness from regional and national government as well as the EU, both in terms of providing financial resources and in developing clear legal conditions.

A short overview of the requirements: Investments in **infrastructure** are needed. The availability of 2.9 million tonnes of pure CO_2 makes an early start possible, but in the future larger CO_2 volumes will need to be transported and stored. The Port Authority is taking the lead in establishing the transport and storage business case.
Demonstration projects are essential to achieving the targets. Together with five to seven companies, RCI is carrying out engineering and cost studies for pilot capture plants which will will provide the data needed from the emitter side.
Together, the emitter data and the transport and storage business case will paint a clear picture of the **organisational and financial requirements**. Since no decisions about the allocation of EU

FASE 1: 2007-2015: Basisscenario 2 Mt/jr:
uitbreiden bestaande CO_2 net OCAP, aansluiten 2 demolocaties CO_2 opslag; Maximum scenario 5 Mt/jr: modificatie OCAP net en aansluiten cluster II W'hall, aansluiten E-pilots M'vlakte

FASE 2: 2015-2020: >20 Mt/jr:
nieuwe offshore leiding vanaf Maasvlakte; aansluiten Cluster III W'hall en andere NL velden; kolencentrales M'vlakte full scale; aansluiting industrie in Moerdijk en Antwerpen

FASE 3A: 2015-2025
uitbreiding naar het achterland, en transport CO_2 via R'dam naar Noordzee velden

FASE 3B: 2015-2025
transport CO_2 per zeeschip vanuit Rotterdam naar opslagvelden elders

Figure 4.2 Stepwise approach Business Case fundings have yet been taken, RCI has designed its plans to fit in with different investment schemes, in close cooperation with its industrial partners.

CCS in the Northern Netherlands

The Northern Netherlands also offers favourable possibilities for developing a national CO_2 cluster with international perpectives. The region has some large potential storage locations, while major power plants running on various types of fuels are planned, with the potential for large-scale capture of CO_2. Some industrial-scale CO_2 capture tests are already planned. Several initiatives in the region also include plans to re use CO_2. These activities match the objective of the Northern Netherlands to reduce 15 to 20 megatonnes of CO_2 annually from 2011 onwards.

In order to realise CCS in this region, a public-private partnership was formed: CCS Northern Netherlands. The partnership is formed by Gasunie, NAM, RWE, NUON, SEQ International, CO2ANN, AkzoNobel, NOM, the University of Groningen, Energy Valley Foundation and the provinces of Groningen, Drenthe and Friesland. In February 2009 the partnership published its Action Plan CCS Northern Netherlands.

One business case that covers all aspects of the CCS chain (capture, transport, reuse and storage) is central to this Action Plan. Furthermore, all CO_2 capture techniques have been allocated: pre-combustion (Nuon), post-combustion (RWE) and oxy-fuel combustion (SEQ International). Gasunie will be leading in facilitating the transport of CO_2, while NAM provides onshore gas fields for storing CO_2.

Starting with 2.6 million tonnes in the initial phase, the Action Plan anticipates that the CO_2 capture potential of the projects selected for the business case will be approximately 12.2 megatonnes per year.

Based on an indexed CO_2 price, the estimated average cost price will be between €40 and €60 per tonne of CO_2, including capture, onshore transport and storage costs.

Given the many facets involved, developing the CCS chain is complex, requiring the active involvement of many parties. Those involved in CCS Northern Netherlands intend to demonstrate that cooperation in an integrated approach can make large-scale CCS projects in the region work.

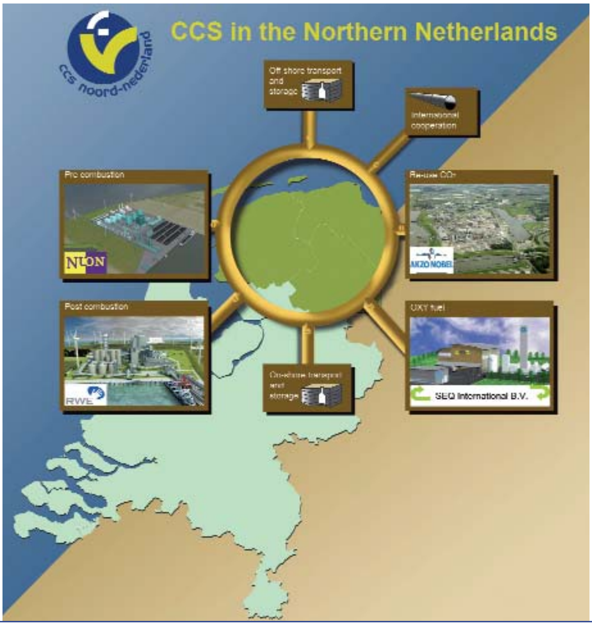


Figure 4.3 CCS Northern Netherlands

Kay Damen

‘Channeling knowledge to industry’

In March 2007 Dr. Kay Damen graduated from Utrecht University with his PhD thesis on CCS system analysis. After graduating, he continued his professional career at NUON. He is currently working on the technical development of the Magnum multi-fuel power plant and managing the R&D programme of the Buggenum CO_2 capture pilot plant.

“My PhD work was rather independent, although I regularly exchanged information with CATO participants. For instance, I provided the technical basis for the Leiden University research into public acceptance. I also received important data from TNO about Dutch sub-surface geology.”

“After my graduation, my ambition was to be involved with concrete aspects of CCS. NUON was preparing a CO_2 capture pilot plant at the Buggenum coal and biomass gasification plant. The Magnum multi-fuel gasification plant, planned in the North of the Netherlands, was also under development.”

“Magnum and the CO_2 capture pilot plant are rather autonomous industrial developments. But CATO has contributed a great deal to awareness about carbon capture in the Netherlands, bringing the academic work and knowledge from the 1990s and 1980s to another level. Thanks to CATO, knowledge about CCS has been channelled more effectively to industry.”

“Likewise, CATO-2 promises to answer questions that are of interest to all stakeholders. Fundamental research on novel capture technologies, public acceptance and licensing procedures will be central. Another important topic that requires further investigation is the set of specifications for CO_2 transport and storage.”

“At Buggenum, we have designed an R&D programme with partners such as the Delft University of Technology, ECN, TNO and KEMA. The R&D programme consists of both applied (measuring and modelling plant performance, corrosion and catalyst screening) and fundamental research (developing new solvents and detailed kinetic models of the catalyst).”

“We want to fit parts of this research into CATO-2. Doing this involves complex discussions on intellectual property rights and sharing information. But these issues have to a large extent been solved now.”

5 – Looking back and forward

CATO will continue to play a significant role in the development of carbon capture and storage. The research programme has generated knowledge, skills and answers to complicated questions. It has also resulted in an extensive national network with many international links. The follow-up programme CATO-2 will help move towards the demonstration phase.

Research networks

Looking back at more than five years of CATO, the Dutch research programme for CO_2 capture, transport and storage has delivered more than could have been hoped for. In meeting the main objective of the government subsidy programme (BSIK, formerly ICES/KIS), which provided 50% of the costs of CATO, the CCS research infrastructure has been expanded significantly.

One of the most tangible aspects of this network has been the graduation of twenty PhD students, with internationally appealing thesis topics. But there is more. Numerous articles and publications have been written and published in refereed scientific journals (see the References).

Many university faculty groups and research institutes have learned more about CCS. Partly due to their efforts within CATO, partners such as ECN, TNO and Delft University of Technology have gained an international reputation as experts in CCS-related issues. Meanwhile, thanks to their participation in the programme, organisations and companies can now define their CCS strategies more precisely. For instance, environmental organisations, as an interface with the public, had a direct interest in research carried out at Leiden University on public acceptance. From this research they can distil parameters that are of importance for informing and approaching the public.

As one of the few integrated national research programmes in the world, CATO also had considerable international impact. For instance, CATO was closely involved in European CCS projects such as Castor in Denmark and Recopol in Poland (see chapter 3, highlight 3.4). Within the seventh EU Framework Programme for research and development, CATO participants have taken the lead in two of the three major capture projects, Caesar and Cesar. One example of the status of CCS research in the Netherlands was the transfer of Paul Feron, the former carbon capture research leader at TNO to Australia. Feron currently leads the programme on post-combustion capture at CSIRO (the Commonwealth Scientific and Industrial Research Organisation).

Political issues

CATO also achieved another important objective, namely providing the answer to the main question: Is CCS a viable option for Dutch society? Roughly speaking, CATO research concluded: “Yes, it is the third option after energy efficiency and renewable energy. However, several conditions relating to technologies, safety, costs and legal aspects still need to be met.” Technologies that are ready to be applied in large demonstration projects have been assessed and the most applicable ones have been identified. So far no projects have been designed or approved, but CATO has laid the foundation for a well-considered choice.

One of these choices has already been made at a high political level. In 2008 Prime Minister Balkenende and several Dutch cabinet members publicly expressed the intention to build two large CCS demonstration plants in the Netherlands. Alongside developments coming from Brussels, the CATO programme has clearly helped to set the scene for this kind of development.

In this respect, the launch of the European Technology Platform for Zero Emission Plants (ETP-ZEP) late in 2005 was a major event. Quite rapidly, the ETP-ZEP managed to formulate a research agenda, in which the CATO programme fitted quite well. Meanwhile, the European Commission drafted a new CCS Directive, which was accepted late in 2008. As a result, the Dutch government is receiving support for CCS initiatives from two sides: on the one hand backed up by CATO studies and on the other by the drafts of new EU legislation.

Industrial perspectives

Although no companies in the Netherlands actually build large power plants or parts of these installations, CATO has created some interesting industrial perspectives for power companies in the Netherlands. Besides the availability of a number of Dutch-patented solvents and related technologies, they now have ready access to a solid CCS knowledge base. Large potential CCS users such as E.ON or RWE have already shown their interest in the next phase, in which the scale-up of technologies will be the main objective.

CATO has generated some direct spin-offs for Dutch industry. One interesting example is the application of post-combustion capture technologies – roughly the same as applied in the CATO CO_2 Catcher, (see Chapter 3, highlight 3.1) in greenhouses. Greenhouses often operate combined heat and power units, especially wintertime, to generate heat. By capturing the CO_2 from these units and storing it in large tanks, the CO_2 can be used during summer as a nutrient for the plants. The first commercial installation in this CCS niche market will be built and operated during 2009.

Towards large demonstration plants: CATO-2

Reviewing the results from CATO over the five years from 2004 to 2008, a next phase in carbon capture and storage research is clearly due. In 2007 the mid-term Review Committee of CATO concluded that the continuity of CATO will be particularly important for building a skills base for applying CCS in the Netherlands.

According to the Review Committee, CATO-2 should build on the current national knowledge platform and the Netherlands' leading position internationally, but it should also change the balance between basic R&D and applied research. *"To be able to support government policy, the follow-up of the CATO programme should be designed so that it can act in a flexible way towards addressing questions that arise in a changing policy environment."*

Both Europe and the Netherlands recognise CCS as a necessary measure to meet the CO_2 reduction goals. The European ZEP Flagship Program has proposed up to twelve large-scale demonstration plants, to be implemented throughout Europe over the next 10-15 years. Only recently, the European Commission explicitly mentioned the Netherlands as a possible target for EU financing of CCS demonstration plants. Continuation of CATO is considered to be essential to underpin Dutch demonstration projects.

Regions to explore

CATO-2 will initially focus on several regions: Rijnmond (near Rotterdam), the North of the Netherlands and the Dutch offshore region. Within each region there are a number of industry partners that intend to link large-scale research locations to pilot and small-scale demonstrations.

The ambition of the follow-up programme is to help support the realisation of large-scale projects in the Netherlands before 2015, which will demonstrate the complete integration of CO_2 capture, transport and storage. By achieving this objective, CATO-2 will put the Netherlands in a lead position internationally, both in terms of in knowledge and of technology.

The Outline of CATO-2

CATO-2 has proposed the following three main activities:

- Piloting various capture technologies and scaling them up to industrial scale, at acceptable cost and with acceptable environmental impacts
- Preparing the integration of capture, transport and storage within the regions
- Enhancing public awareness and perception of CCS.

At a more detailed level, the sub-programmes tackle the following issues:

- Capture (post-combustion, pre-combustion and oxyfuel-combustion)
- Techno-economic system analyses, including transport and infrastructure development
- Storage in the subsurface, monitoring and verification
- Regulation and safety
- Public perception
- Dissemination and international cooperation.

The partners that have applied to participate in CATO-2 are:

Corus, DAP, DCMR/RCI, Delft University of Technology, DSM-Agro, E.ON Benelux, EBN, ECN, Ecofys, GdF-Suez (Electrabel), Energy Valley, Essent, Gasunie, Grontmij, IF Technology, KEMA, NAM, NUON, PDC, Procede, Province Groningen, RWE, Saxion Hogescholen, Schlumberger, SEQ, Shell, Stichting de Noordzee, Stichting Natuur en Milieu, TAQA, TNO, Twence, Leiden University, University of Twente, Utrecht University (including UU Copernicus and UCE), University of Groningen – Energy Delta Research Centre, VU University Amsterdam, Wageningen Imares, Wintershall.

Compared to CATO, the follow-up R&D will be more demand-driven. Industry partners and government – the ‘problem owners’ – will set the research priorities for realisation at the sites. Industry partners will also coordinate the R&D that will be applied at their plants.

More than was the case with CATO, CATO-2 will explicitly develop and provide strategic information to support dedicated policy making and investment decisions. Issues such as techno-economic system analysis, CCS chain integration, transport and infrastructure, rules and regulation, communication and public perception will become more and more important. Meanwhile, fundamental research will focus on long-term technology development and innovation. Breakthroughs in technologies should be quickly integrated into the programme.

The hand over of knowledge from CATO to CATO-2, which informally took place during a reception on 13 January 2009 perfectly matches the phase shift in CCS that is taking place right now worldwide.

Figure 5.1 Hand over of knowledge from CATO to CATO-2

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Chapter 3 – Key publications CATO programme

Highlight 3.1 – CO_2 catcher puts laboratory results into practice

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Highlight 3.2 – From research to pilot plant: sorption enhanced water gas shift (SE-WGS)

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