Linking the Chain

Integrated CATO2 knowledge prepares for the next step in CO_2 Capture & Storage

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Colophon

Lead author

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Commissioned by the CATO2 Programme Office.

Contributing

- The R&D highlights in The Science of CATO2 have been written by researchers themselves (edited by Rolf de Vos).
- Coordinators of CATO2 sub-programmes had a decisive contribution in the respective chapters in the 'The Science of CATO2':
  - *Capture: reduce costs, improve and demonstrate performance*: Earl Goetheer (TNO), Erwin Giling (TNO), Gerard Stienstra (DNV-GL), Daan Jansen, Ruud van den Brink (ECN).
  - *Integrating the CCS chain*: Andrea Ramirez (UU), Chris Hendriks (Ecofys), Barend van Engelenburg (DCMR).
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Contributing to this book does not necessarily imply that visions, opinions (if any) and phrasing in the book are shared by all contributors. The lead author is responsible for the book contents.
A pdf of this book is available on www.co2-cato.org/LinkingTheChain. This site also provides access to further information on the CATO2 programme.

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Foreword

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Since the end of the 1990s, the Dutch government has identified carbon capture and storage, also known as CCS, as an important technological option for mitigating severe climate change. CCS is considered particularly necessary for reducing greenhouse gas emissions over the coming decades as it presents a cost-efficient bridge to a sustainable energy system built on efficient energy use from renewable sources.

The Netherlands, with its gas fields and infrastructure, energy intensive industry and extensive knowledge infrastructure, is a particularly good breeding ground for the further study of this opportunity. However, further research and development are needed before we can enter a mature market. Recently, in the national Dutch Energy Agreement it was agreed to develop a long-term strategy regarding the role of CCS.

This book is the account of a remarkable programme for research and development: CATO2. Almost five years of R&D into carbon capture and storage have provided some remarkable and useful results, in more than one way.

Firstly, as the successor to the CATO programme that ran from 2004 to 2008, CATO2 (2009-2014) has shown that carbon capture and storage has the potential to grow into a viable technology. Although many conditions still need to be met before this is economically feasible, CCS technologies have developed to a pre-commercial stage. CATO2 contributed significantly to cost reduction, technological development and understanding public perception, paving the way for the next phase.

Secondly, CATO2 has proven that cooperation between industry, science and other stakeholders can be very fruitful. More than ten companies from the energy sector as well as from energy intensive industries are involved. Currently, the Dutch innovation policy is based on such cooperation, established in the Top Consortia for Knowledge and Innovation (TKI). As a TKI 'avant-la-lettre', CATO2 has shown that the Dutch economy can benefit from such collaboration. In fact, CCS research and development continues within the framework of TKI Gas, even before the completion of CATO2 this year.

Thirdly, CATO2 has demonstrated a broad and effective combination of many scientific disciplines, such as combining economics with chemical research and geological research with public perception. This multidisciplinary approach has created a community that has been acknowledged as 'top notch' in global CCS research.

CATO2 has prepared CCS technologies for their next phase: a large-scale demonstration of a fully integrated project (capture, transport and storage). By bridging the gap from fundamental research to applied development, CATO2 has achieved its main mission. Also, by investigating important issues such as safety of CO_2 storage and

transport, emissions (e.g. nitrosamines) and public acceptance, CATO2 has placed CCS in a broader public context.

Partly thanks to CATO2, large-scale demonstration projects can now be implemented. However, demonstration projects not only depend on the status of innovation and technology, but also on many other socio-economic factors. An R&D programme may be the instrument to solve some of these issues, but a large-scale demonstration project is also a matter of economics, business development and politics.

When this book went to print, the final decision on the large-scale demonstration project ROAD was still pending. Both the Dutch government and the European Union strongly support this project. Together with the companies involved, we are looking for ways to realise the ROAD project and make it a success.

As this book shows, CATO2 provides the building blocks for a sound decision and knowledge base for the future of CCS in the Netherlands and the world, both in the short and in the longer term.

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INTRODUCTION

Dutch science and CCS

An introduction to the CATO2 research programme

In 2014, the research programme called CATO2 will come to an end. CATO is the acronym for 'CO_2 Afvang, Transport en Opslag', which is better known in English as CCS: Carbon dioxide Capture and Storage. These acronyms represent a number of technologies that collaborate to extract the greenhouse gas CO_2 from industrial processes and power generation and prevent their emission into the global atmosphere. The ending of CATO2 is the perfect occasion for looking back, for wrapping up the research and development executed within and outside the Dutch research programme. This book reflects on the achievements during ten years of consistent and coherent CCS research programmes in the Netherlands, with an emphasis on the last five years. Also, the book looks forward to the next steps.

What is CCS?

CCS (CO_2 capture and storage) is a term comprising a number of technologies that collaborate to extract the greenhouse gas CO_2 from industrial processes and power generation (capture) and isolate it permanently (storage) from the atmosphere.

CO_2 and climate change

Basically, CO_2 is the product of a chemical reaction between molecules of oxygen (O_2) and molecules of carbon (C). CO_2 originates from many processes. We produce it when we breathe. The man-made CO_2 we are discussing here is the CO_2 produced from burning hydrocarbons in fossil fuels (coal, natural gas, oil) and from manufacturing processes such as making steel or cement. We are discussing this man-made CO_2 because it is considered as the main contributor to (enhanced) climate change. Also, this concentrated production of CO_2 at power stations and industrial sites offer a relatively easy opportunity to capture large amounts of CO_2. CCS is one of the technologies (in addition to more efficient use of fossil fuels, energy saving devices and renewable energy) to reduce CO_2 emissions and mitigate climate change.

Basic CCS process

Explained in a few words, CCS captures CO_2 from power plants and factories, and stores it underground. Along this CCS chain, different technologies are applied, ranging from chemical processes that 'capture' CO_2 from industrial gases, via gas compression and long-distance pipelines to geophysical processes for injecting the CO_2 underground. This is an over-simplification, because many alternatives exist. CCS processes have one common denominator: preventing human-induced CO_2 from entering the atmosphere.

From lab to demonstration

This book largely answers the question: What did CATO2 achieve? While work is still in progress, answering this question is important for several reasons.

The answer matters with respect to the importance of CCS preventing severe climate change. Did CATO2 provide solutions? The subject of climate change is on the list of many politicians, policy makers and large parts of the public, despite many hesitations and delays in deciding about ambitious reductions of greenhouse gas emissions. There is a unanimous political agreement – although not yet operational in policies – not to allow a global average temperature increase above 2° C before the end of the century. This implies the necessity that emissions should be substantially reduced within several decades – at least in the high-consumption countries of the world. So it is relevant to assess the opportunities of CCS for drastic CO_2 emission reductions in our future economy. CCS is also regarded as a way to keep costs for climate change mitigation to a low level. Without applying CCS, costs for reaching climate change goals are expected to be higher.

A continuous, integrated private/public cooperation in an R&D programme reaching the milestone of almost ten years justifies an evaluation. In total, during more than ten years the Dutch public and private sectors have invested about € 90 million in CCS research and development. It is only right and fair to give account of those investments by showing the results to all relevant stakeholders: the government, business and, last but not least, the public.

The timing of such a broad assessment seems right. By 2015, global negotiations about climate change policies and measures are intended to result in an agreement between almost 200 countries, to be closed at the Climate Summit in Paris. An intermediate report on the status of

Four observations are important to put CCS in the right perspective. The book will extensively elaborate on these observations.

Climate change

The most important driver for CCS lies in mitigation of climate change by reducing (or rather: preventing) human-induced CO_2 emissions into the atmosphere. However, instead of putting it permanently underground, some CO_2 can also have useful purposes. Practical forms of utilisation are sometimes referred to by the slightly adapted term *CCUS*: CO_2 Capture, Utilisation and Storage. Utilisation is not identical to storage, but may be economically viable in niche markets and thereby provide a decisive kick-start for CCS capture technologies. In terms of amounts of CO_2, utilisation is only a couple of % of the total amount that should be stored permanently. These relative proportions are reflected in this book.

Link to a chain

Many parts of the CCS chain of technologies have existed for decades. Individual elements of capture, transport, utilisation and even storage of CO_2 have proved their viability in industrial applications. However, for the purpose of climate change mitigation, they need to link to each other and need to be optimised to the goal of reducing CO_2 emissions to the atmosphere. There are many ways to link this chain (see picture on page 13).

Socio-economic questions

CCS is not only a matter of matching technologies. CCS also has some socio-economic aspects that are quite essential for further development. Economics, organising the chains and establishing a legal framework are other subjects to be explored. And, finally, social effects and public acceptance are very important. If the public rejects CCS for any reason, CCS will have no future at all.

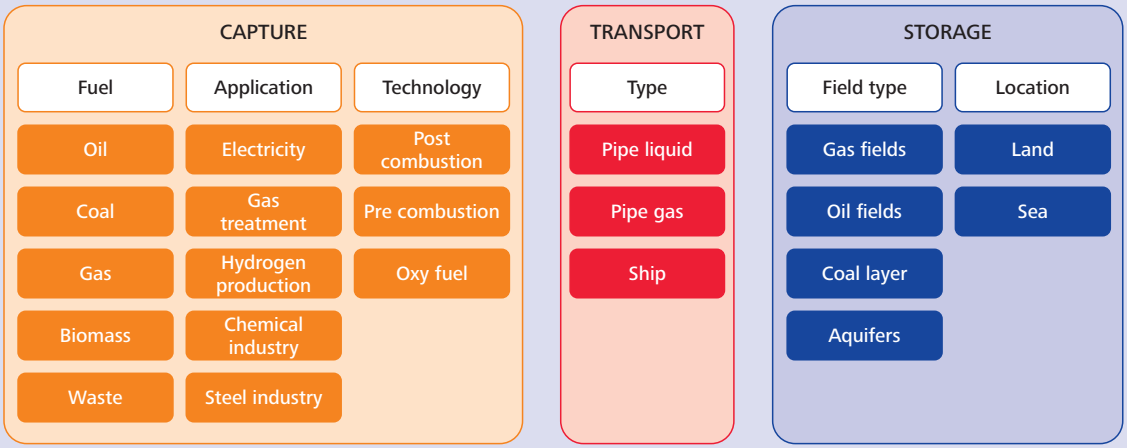
CCS in the Netherlands and abroad will help many to judge whether or not CCS can be a structural part of a future low-carbon society. Also with regard to the technological status of CCS, the world may be on the verge of a new era. Any innovation needs to be demonstrated to the world before entering the stage of commercial deployment. CCS technologies are no exception to that rule of thumb. Numerous practical results and scientific achievements from CATO and other efforts have paved the way for entering the phase of demonstrating the CCS chain on a pre-commercial scale.

The structure of the book

This book intends to present CATO2 achievements against the background of the global status of CCS. Much of its content will be science-based, always with links to business, economy and society. The book is not by any means intending to promote or defend CCS as a technology. For instance, safety and public perception issues are closely scrutinised, while the necessity of CCS is openly discussed.

The sections that describe the possible role of CCS in climate change mitigation breathe the notion that CCS may be an important part of the solution in the 21st century and even beyond. For several reasons, renewable or 'circular economy' technologies are preferred in a fully sustainable economy. But as they may not be ready yet to fight severe climate change, CCS turns up as a possible partial solution: intermediary in energy generation, for several decades, and eternally in energy intensive industries, where alternatives for low-carbon production are not available.

The first part of this book ('CATO2 in the context of global CCS') describes the position of CATO2 placed in an international perspective, the status of CCS in the Netherlands and in other parts of the world. It provides an



An overview of the possible CCS chains. The different chains can be composed by choosing one element from each column. Picture S. van Egmond and M.P. Hekkert (2012).

overview of the international and national context of CCS, the political status, the attitude of the public at large.

The executive summaries of the CATO2 programmes are the prelude of Part II of the book: 'The Science of CATO2'. This part consists of five sections, each representing the different scientific issues of CCS and – not coincidentally – also representing the five sub-programmes of the CATO2 research and development programme: Capture; Transport and Chain Integration; Storage and Monitoring; Regulation and Safety; and Public Perception.

Each of these sections provides an overview of CATO2 achievements on the topic. For further scientific exploration, each section also contains three highlights. Each highlight reviews a specific set of studies, selected for their remarkable results.

This book is written for a broad audience of policy makers, scientists, politicians, business developers, entrepreneurs, students, or anyone from the public with an interest in the topic. Anyone with some knowledge of innovation, technologies and climate change should be able to read this book. Also the imagination of readers with specific scientific interests will be triggered by its contents and the detailed outcomes of research.

The strategic importance

Applying CCS also implies answering the question: should we store CO_2 underground? This is an ethical question if you regard CO_2 as a waste gas, one would prefer not to produce CO_2 in the first place. In that case, building energy and industrial systems without using fossil fuels seems more logical than CCS. But it's also a strategic matter when considering the means for achieving global climate change goals (whenever they are defined). Catching CO_2 from fossil fuels before it can harm the climate may be necessary in the short and medium term, if the more fundamental solutions like non-carbon energy or saving energy are not sufficiently developed in time to meet these goals. These issues are quite extensively touched upon by the Argument Map (see page 52).

PART I
CATO2 in the context of global CCS

The necessity of capturing and storing CO_2

In the world, a general political consensus exists about limiting the consequences of climate change induced by human activities. Although a global agreement on climate change policies and measures is not established yet, most governments, companies and non-governmental organisations have set their targets to contribute to a general goal of not exceeding a 2°C increase in average global temperature. This chapter provides the background of CCS technologies and lists the arguments why CCS should have a role in limiting climate change damage. Hence, it also presents the rationale for the CATO R&D programme.

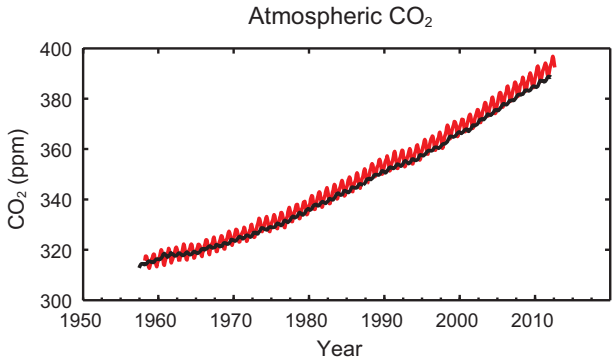
The foundation: the case of climate change

Climate change is the major trigger for applying CCS. Paying special attention to the climate can be regarded as a regular follow-up of the UN Framework Convention on Climate Change in Rio de Janeiro in 1992. There, countries unanimously agreed to consider what they could do to limit global temperature increases.

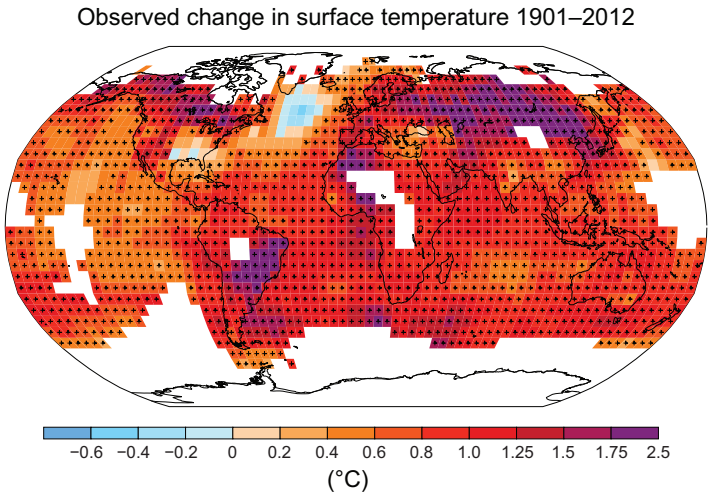
The term 'climate change' refers to the effect that greenhouse gases in the atmosphere change the climate. The basic mechanism is that greenhouse gases cause the global atmosphere to store heat, resulting in a balance at a higher global temperature than if greenhouse gases were missing. This mechanism is responsible for a liveable planet, because the greenhouse gas CO_2 has caused temperatures that allow higher forms of life. But the balance can be disturbed, changing the climate and enhancing climate change.

The mechanism of (enhanced) climate change has been subject to many scientific research programmes, resulting in an ever improving knowledge of climate change – and like in any part of science: raising new questions again. The main institution to rely on is the Intergovernmental Panel on Climate Change. Every five to seven years, this association of thousands of scientists from all over the world produces an Assessment Report, which has become the most important beacon for everyone (including policy makers) who wants to be informed about climate change, the link to human activities, the consequences and the ways for mitigation. During 2013 and 2014, the IPCC has published its Fifth Assessment Report. The IPCC assessment consists of three parts, plus an integrated publication called the Synthesis Report.

The first part, published in September 2013, assesses the physical climate science itself, evaluating climate change and linking this to natural causes and human-induced emissions. The report follows a logical order in the line of reasoning. First, it concludes from observations and analysis that warming of the climate system is unequivocal. Next, it concludes that the increase of the atmospheric concentration of CO_2 causes the global climate system to take up more (solar) energy. Models that indicate this are continuously improving, being confirmed or rejected by observations. And last but not least, the analysis of the



The development of CO_2 concentrations in the atmoshere at Manu Loa (red) and South Pole (black). Adaptation from the IPCC WG I AR5 Summary for Policymakers, Fig. SPM.4 (a).



The warming of the atmosphere, as presented by the authoritative Intergovernmental Panel on Climate Change in its latest Fifth Assessment report. Adaptation from the IPCC WG I AR5 Summary for Policymakers, Fig. SPM.1 (b).

models also leads to the conclusions that human influence on the climate system is clear, and that continued emissions of greenhouse gases will cause further climate change.

Looking at the future, the IPCC Assessment Report concludes that "limiting climate change will require substantial and sustained reductions of greenhouse gas emissions." This may seem a straightforward, evidence-based conclusion, but transposing this into a clear evidence-based set of policies and measures is quite complicated. Other issues than the physical evidence for climate change are at stake.

Adapt and mitigate

What are the consequences of the observation that human activities have an impact on the climate? The second and third parts of the IPCC Assessment Report go deeper into these issues.

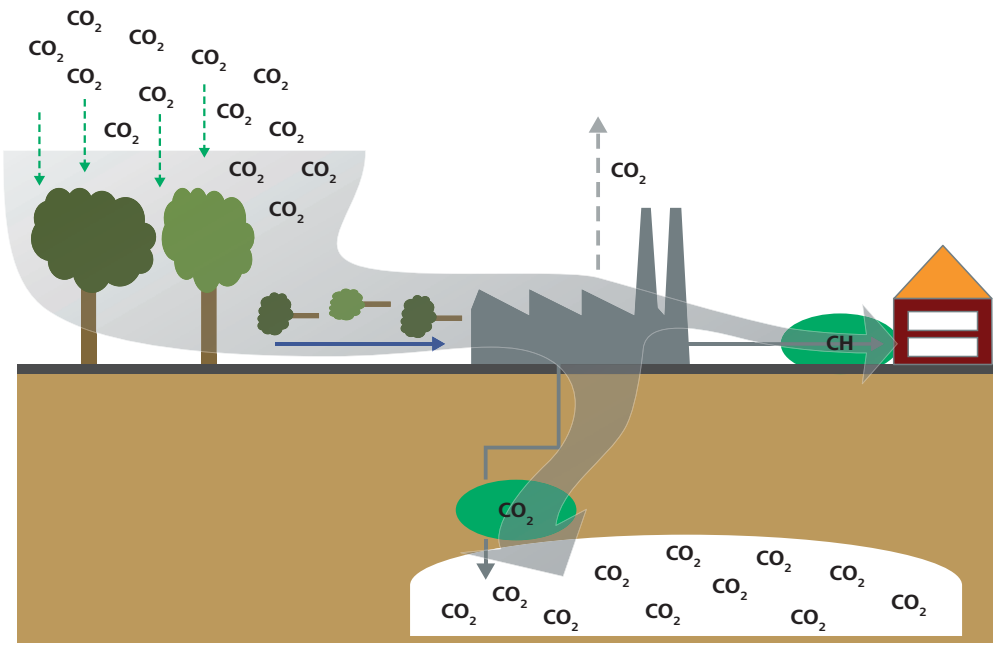
Building on the physical evidence of climate change, the IPCC Working Group II assessed the Impacts, Adaptation and Vulnerability. Their latest report, of which the summary was published in March 2014, updates the inventory of the consequences of climate change to economies and societies all over the world. Different societies show different vulnerabilities, ranging from the threat of flooding of

small islands in the Pacific Ocean to affecting biodiversity in different parts of the world or even improving harvests of certain crops in other parts of the globe. In logical coherence with this inventory of impacts and vulnerability, this report also lists the opportunities and costs of adaptation to climate change.

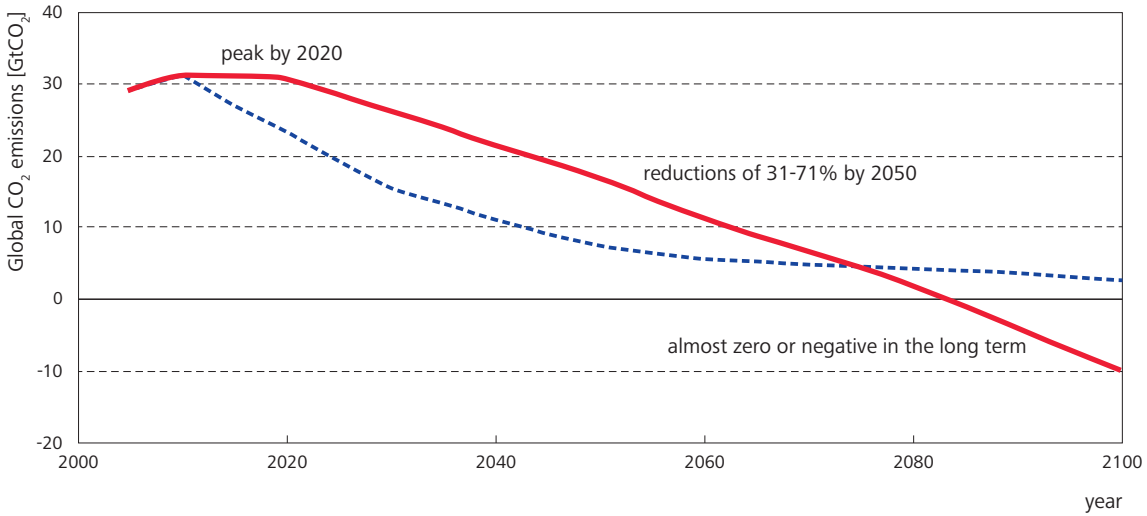
The third Working Group (summary published in April 2014) evaluated the possibilities to prevent severe climate change in the future. This is the publication where CCS appears as one of the measures to mitigate severe climate change. Along with other technologies like solar and wind energy, nuclear energy or energy savings, CCS is part of a large spectrum of technologies that can help bending the upward trends in CO_2 emissions downwards.

CCS can even do more than that. Since the fourth Assessment Report of 2007, seven years have been spent with practically no progress in reducing emissions of greenhouse gases. Hence, the urgency has increased for acting now and taking serious mitigation measures in order to prevent the world's average temperature from warming up by more than 2° C this century. This implies that CCS should already be considered and soon implemented as an emission reducing technology. Moreover, the longer the world waits to take action, the more CCS will be needed to compensate the additional emissions in this period combined with 'negative emissions' at a later stage.

These negative emissions can be understood through the concept of a 'carbon budget'. Not exceeding the threshold of 2°C allows humans to emit a certain amount of CO_2 and other greenhouse gases into the air during the 21st century. This is called the carbon budget. If emissions will not start to decrease soon, a large part of this budget will already be consumed in the next few years, leaving only a small part of the carbon budget for next generations. Negative emissions could effectively increase the carbon budget



Negative emissions explained in a picture: biomass growth captures CO_2 from the air; after combusting the biomass, CO_2 is captured from the flue gases and stored in the subsurface.



The way negative emissions could work. By compensating excess emissions in earlier years, combining biomass and CCS could still keep the carbon budget on a < 2°C track. Source: Global Energy Assessment, chapter 17, Figure 17.37.

by taking out CO_2 from the atmosphere. Or said in other words: emissions in excess of the carbon budget could be compensated later by negative emissions. For negative emissions, only a few future possibilities exist: changing land use in such a way that a net uptake of CO_2 is realised, applying CCS with bio-energy, which also results in net uptake of CO_2 (see also the figures on page 19 and 20) and directly capturing CO_2 from the air. The negative emissions will return later this chapter in the framework of scenarios.

CCS in the climate debate

Compared to alternatives for climate change mitigation, some main features put CCS in a special position. The main difference between CCS and other low-carbon options is that CCS does not yield any commercial products. Renewable energy technologies, nuclear energy and energy efficiency all require investments that can be earned back by the revenues of the saved or generated energy. CCS only 'saves' CO_2. This represents a commercial value too, but only in terms of climate change mitigation. That causes CCS to be solely dependent on the climate change issue, and how society values this issue. Or in economic terms: on the price of CO_2.

This needs further explanation, seen in the light of over two decades of climate change debates all over the globe. If the 1992 UN Framework Convention on Climate Change marks the starting point of this global debate – where some countries already showed further progress – the last two decades showed an ambivalent attitude of the world towards climate change. However modest in combating climate change, the Kyoto Protocol of 1997 was the biggest achievement in global climate change policies. Within the Kyoto Protocol, a large number of countries committed to some ambitions in reducing greenhouse gas emissions. But after achievement of the Kyoto goals in 2008-2012, no new global agreement was established.

There are several reasons for this lack of a global political agreement, such as the disagreement between rich and poor countries about who is responsible for climate change, and subsequently for the costs of adaptation and mitigation. This very complex matter is intrinsic to

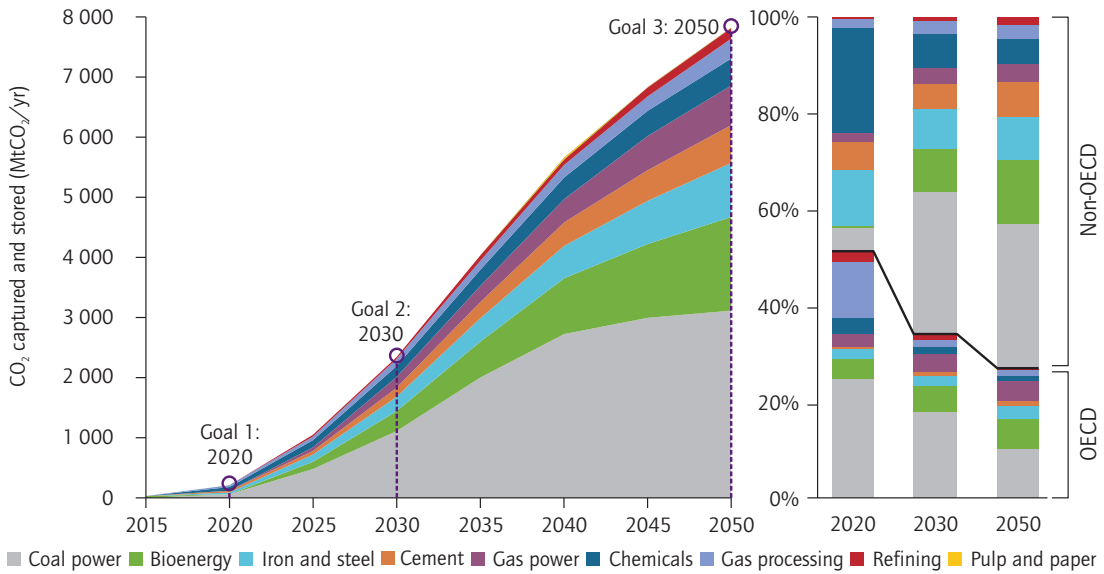
agreeing on the commitments and the mutual division of costs and investments. It gets even more complex because estimates about climate change consequences and damage are not very reliable yet. They are extrapolations from current knowledge or originating from models. In principle, cost/benefit assessments should paint a clear picture on the trade-offs between preventing greenhouse gas emissions and investments in low-carbon energy. But the inherent uncertainty in the estimates obscures this debate.

This obscurity also affects the position of CCS as a maturing low-carbon option, as the rather high investments miss out on the opportunity of earning substantial money from co-benefits (such as environmental benefits that go beyond climate change). This is one reason why exploring the utilisation of CO_2 is interesting. Utilisation helps to create a business case for capturing CO_2, providing more confidence in the technologies and in reducing costs, allowing the application of CCS on a larger scale.

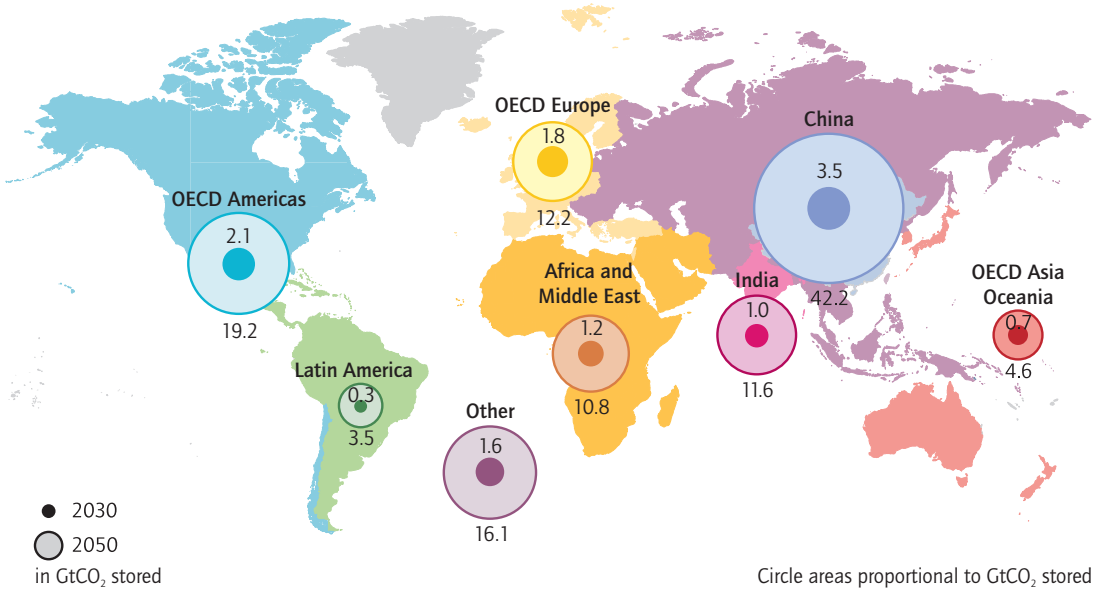
CCS as a cost-efficient option

Despite its lack of co-benefits, CCS proves to have a strong position in many scenarios as an alternative to other low-carbon options. In general, many scenarios estimate that CCS is needed to limit the costs of deep CO_2 emission cuts. Following the assessment reports of the international climate science community, global greenhouse gas emissions should be reduced by about 80% by 2050 in richer countries, in order not to exceed the internationally accepted threshold of 2°C temperature increase by 2100. Excluding CCS as an option will substantially increase the costs for appropriate emission reduction.

The most authoritative set of scenarios in the world is the World Energy Outlook of the International Energy



From the possible development of CCS in the 2°C scenario of the International Energy Agency (Technology Roadmap CCS 2013) it can be seen that towards 2050, non-OECD countries will develop the bigger part in CCS. Coal and gas power will be dominant, and industrial applications will increase. Picture Technology Roadmap: Carbon Capture and Storage, fig. 4, p. 22. © OECD/IEA 2013.



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

| **The IEA Technology Roadmap CCS shows that Asia has the largest potential for growth of CCS. Picture Technology Roadmap: Carbon Capture and Storage, fig. 5, p. 23. © OECD/IEA 2013.**

Agency. Annually the IEA, which consists of a large number of country members of the Organisation for Economic Cooperation and Development, publishes this Outlook, which looks at the global energy markets 20 years ahead, based on present insights. In the most recent World Energy Outlook, the IEA points out that a scenario achieving the <2°C goal would need that by 2035 two-third of all coal-fired power plants in the world will have to be fitted with CCS. If not, coal will have to be almost eradicated as a fuel, while an extraordinary burden will rest on other low-carbon technologies to deliver lower emissions. Delaying the introduction of CCS from 2020 to 2030 will increase the costs of a lower-than-2°C scenario by about $ 1 trillion in the years 2012-2035.

However, the same report is less optimistic about CCS in its New Policies scenario, which is considered to represent a realistic pathway to 2035. In this scenario only 1% of global fossil-fuelled power generation capacity (67 gigawatt, which is the equivalent of about 67 large power plants) is equipped with CCS by 2035. "Deployment support is lacking and the absence of a substantial price signal has so far impeded necessary technological development and more widespread uptake," according to the IEA.

In a publication concerning a 2050 technology roadmap for CCS, published in summer 2013, the IEA urges that the number of CCS projects should quickly increase in the next decades. The 2050 IEA scenario that projects an 80% chance of keeping global warming beneath an increase of 2°C in average global temperature requires a broad implementation of CCS. By 2050 CCS would cover 14% of all CO_2 emissions reduction that is required, compared to a business-as-usual scenario. The IEA thinks that the next seven years will be critical to the accelerated development of CCS. By 2020 at least 30 projects should demonstrate CO_2 capture.

The role of CCS in a carbon-constrained world

As said earlier, CCS has one predominant reason for its existence: saving the climate from severe changes. The logical consequence of large-scale implementation is that fossil fuels will remain as an important primary source of energy. The fact that CCS prolongs the lifetime of fossil fuels in the global energy systems is precisely the point in the strong opposition by some non-governmental environmental organisations. They rather want fossil fuels replaced by renewable energy sources.

Indeed, scenarios exist with very ambitious emission reduction goals of -80% or more compared to today, where CCS does not play any substantial role in a low-carbon global economy by 2050 and most of the fossil fuels are phased out. Perhaps such a low-carbon economy will be established this century. But even without CCS, there is no denying that fossil fuels will at least be a prominent primary energy source in the first decades on the pathway towards 2050.

Not the lack of resources, but the induced climate change is the biggest issue facing fossil fuels. CCS assists in sustaining a role for fossil fuels in developing a carbon-constrained world. How prominent this role will be, that will depend on costs, maturity of technologies, competition with other low-carbon options, vested interests and many other socio-economic factors. It will also depend on how the question is answered, whether we can afford further depletion of natural resources (facilitated by CCS), which may then not be available anymore for future generations.

Also from an industrial perspective, CCS has a role. Some energy-intensive activities, such as steel and cement production, hardly have any other technological means than CCS to deliver their equal part in ambitious CO_2 emission reductions of 50% or more. Their emissions are not the result of combusting fossil fuels, but of using the carbon from fossil fuels in their chemical processes. Carbon is an essential basic compound for manufacturing steel or cement; hence CO_2 is a process-inherent emission than cannot be circumvented without capturing and storing.

Finally, CCS is one of the rare technologies that will be able to extract CO_2 from the atmosphere and prevent severe climate change consequences (see also page 19). These 'negative emissions' might prove to be necessary if global emissions keep on increasing for too long.

Not many other technologies are able to do this at a relevant time-scale. On a time-scale of millions of years, nature succeeded in permanently storing carbon, which eventually resulted in the oil, natural gas and coal we now call 'fossil fuels'. CCS and bio-energy are actually a shortcut of this multi-million-years process. Other land-use processes also have the potential to do this. Growing crops with high carbon uptake which are then prevented from natural decay is another process that creates 'negative emissions'; air separation or geochemical storage (e.g. in olivine) are other alternatives that have been suggested.

How much, and where?

If deployed in the next decades, the technologies of CCS potentially represent a large business indeed. Referring to the International Energy Agency's more ambitious Two Degrees Scenario (2DS), some 2 billion tonnes of CO_2 ($GtCO_2$) a year have to be captured and stored by 2030, increasing to 7 $GtCO_2$ annually by 2050. To give an idea of the size of implementation: 7 $GtCO_2$ is the annual CO_2 production of about 1500 coal power plants of 1 gigawatt of capacity. Or compare this to the present overall global emissions that amount to about 35 billion tonnes ($GtCO_2$) a year.

This implies quite massive implementation, which has to be distributed over the entire globe and over all relevant sectors. The IEA 2DS scenario considers that by 2050 all new coal-fired power plants, half of all gas-fired power plants and one out of five power plants running on bio-energy are equipped with CCS, totalling just under a 1000

A very common sight on CO_2 utilisation: the bubbles in a drink. Picture ANP/Image Source.

gigawatts of power capacity. Also in industry, CCS capacity will be huge. Globally, about one third of all steel, cement and chemical factories are equipped with CCS. By then, CO_2 storage activities will have outpaced the natural gas and oil production industry of 2013.

Power generation and some specific industrial sectors such as hydrogen production, gas processing and bioenergy production will be the first sectors to host large-scale implementation of CCS. After 2030 further deployment in other industrial sectors will be added to these.

Deployment will also spread around the globe. In the first decades OECD countries will still be prominent, but in a scenario where CCS develops swiftly, non-OECD countries will become dominant soon after 2020, to cover over 70% of all CCS activities by 2050. This is in line with the assumption that the largest growth in industrial production will also occur in non-OECD countries. However, sector developments per region will differ.

Utilisation

In some cases, CO_2 is a feedstock for manufacturing and crop growth. Most famous examples of this application are the bubbles in drinks and beer and the use of CO_2 for growing crops in greenhouses. This application is an opportunity, because the value represented by CO_2 as a feedstock gas can improve the economics of capture. Also the lack of storage opportunities explains why utilisation is an upcoming topic.

Especially in the last couple of years, utilising CO_2 has become an interesting vehicle for increasing interests in CCS. Compared to the billions of tonnes of CO_2 that the global power generation and industry emit to the atmosphere, the 'storage' capacity of CO_2 utilisation is a tiny drop and can only be short term. At present, the amount of CO_2 that is commercially utilised is much smaller than the amounts of CO_2 that need to be stored for saving the climate from severe changes. The maximum global CO_2 utilisation market is estimated at only a few per cent of the yearly emission.

Moreover, utilising CO_2 does not automatically imply that CO_2 is permanently taken out of the atmosphere. CO_2 used in beer and soft drinks or in greenhouse horticultures will be emitted into the atmosphere with only a few months or years of delay. But in particular cases, utilisation of the captured CO_2 may be interesting. Selling CO_2 to these applications creates specific niche markets and thereby improves the business case for capturing CO_2. Selling this relatively small amount of CO_2 might smooth the commercial pathway to the next stage: large-scale capture and storage.

At present, by far the largest commercial use of carbon dioxide is Enhanced Oil Recovery (EOR). This application, regarded as the most matured technology for utilising CO_2, uses CO_2 injection for increasing the recovery factor

of oil from mature oil fields (and sometimes gas fields). In this case, some of the CO_2 is also permanently stored, especially when the CO_2 is recaptured and recycled.

Another well-known application is utilising CO_2 for enhancing crop growth, which is nothing more than lending a hand to nature. All crops need CO_2 and sunlight for their growth, so adding some CO_2 (and light) in principle increases the harvest. Greenhouse owners often apply this process themselves by diverting cleaned flue gases from gas-fired boilers into their greenhouse.

The principle of enhancing crop growth is also applied by the Dutch company OCAP that is transporting CO_2 from the Shell Pernis refinery to a greenhouse region at some 10-20 kilometres distance, already since 2005. Annually, a pipeline formerly used for oil transport brings 400 kilotonnes of CO_2 from Rotterdam to nearly 600 greenhouse companies. Obviously, this method does not prevent the CO_2 from entering the atmosphere. But if the crops that are grown would be energy crops, they may end up in biomass fuels, replacing fossil fuels, and thus reducing classic fossil fuel CO_2 emissions. And in addition, CO_2 from Shell Pernis replaces CO_2 produced from fossil-fueled boilers.

More utilisation options have been listed within CATO2, although not broadly investigated. Examples are 'Power to

Work on the CO_2 pipelines of OCAP in the Rotterdam area. Picture: Hans de Lijser.

gas' or 'Power to liquid', which use electricity to chemically bind CO_2 and water to hydrocarbons (methane or methanol). Furthermore, utilisation takes place when CO_2 is used as chemical feedstock. The carbon and sometimes also the oxygen within the carbon dioxide are used to build hydrocarbons that can be applied by the chemical industry to produce plastics. This kind of utilisation sequesters CO_2 in stable end products, but at the end of their lifetime the CO_2 will be emitted again. However, the CO_2 replaces refined fossil products (often oil) that are usually applied as chemical feedstock, so new CO_2 emissions are prevented.

In the Netherlands, several commercial activities in CO_2 utilisation have been established, for instance OCAP and biomass production. However, utilisation has not yet been a big strategic issue in bringing CCS to the next level and extending CCS to CCUS. That might change in the coming years. This preliminary research may be a prelude for further exploring interesting commercial opportunities in the near future. In policy strategies and in research and development, utilisation has been identified as a possible 'facilitator' for further development of CCS, or even as an integral part of future Dutch R&D programmes.

The history of CO_2 Capture & Storage in the Netherlands

Around 1988, when 'CO_2 capture and storage' was called 'Carbon Dioxide Removal', CCS started to attract Dutch attention. In those days climate change first became recognised as an issue. CCS research and discussions started in the slipstream. Since then, the Netherlands has played a significant role in CCS in the world. The pathway has passed many milestones, changes in sentiments and made actual progress. A large-scale demonstration is a next step.

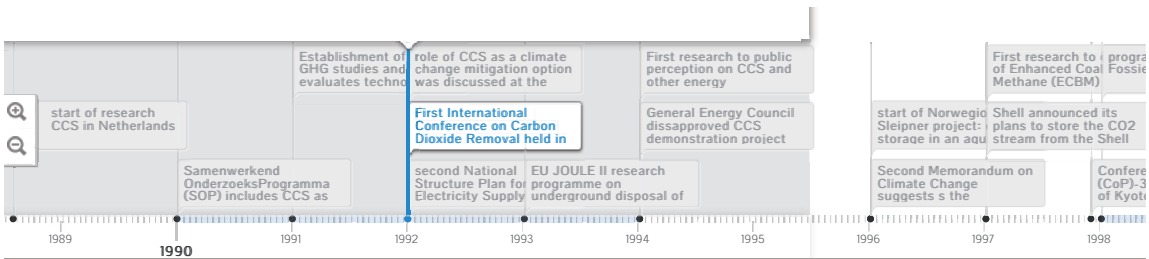
25 years of CCS developments

The last decade of CCS development in the Netherlands has shown steady progress, in R&D and projects, by academics and industries. This development has positioned the Netherlands at the forefront of global development, but some stagnation has occurred in the last three years.

In 1988 the Netherlands started to develop CCS activities, as one of the first countries in the world. The milestones in Dutch CCS development show the progress that up till now continued to be at the forefront. In 25 years, scientists, policy makers and companies have showed a large mutual interaction, stimulation and interest.

In 1992, the Dutch interest in CCS culminated in the First International Conference on Carbon Dioxide Removal in Amsterdam in 1992, which was the first of a series of global conferences that still survives. The Dutch ministry of Environment sponsored the conference.

In those first few years, CCS regularly gained importance along with the increasing interest in climate change. For instance, the Netherlands started participation in the IEA-GHG programme established in 1991. Also, Dutch researchers were involved in a CCS project in Canadian Alberta. In addition, national CCS projects were financed from clean coal research funds (funded by NWO and Novem), where CCS even became the main subject. And



Excerpt from the CCS Timeline, telling the history of CCS in the Netherlands. The timeline is an interactive tool on the website http://bit.ly/CCStimeline.

on a governmental level, climate change became an issue with CCS identified as one of the climate change mitigation options in R&D, scenarios and governmental papers. Also, Dutch researchers were involved in projects abroad such as Sleipner (see also page 41), laying a foundation for EU research in this field.

Meanwhile, in 1996 the Netherlands decided to spend a budget of 750 million guilders (around € 300 million) to increase climate change efforts. One possible project was a CO_2 storage project that actually was prepared, using CO_2 from Shell Pernis and storing it in a NAM gas field nearby. But before the project could start, the government cancelled the project again.

The CCS efforts reached real substance in the 1999 'Green Paper Climate Policy' (Uitvoeringsnota Klimaatbeleid), which proposed a new pilot project (following two earlier pilot proposals). Since 2004 this project, originally named CRUST (CO_2 Re-use through Underground Storage), has stored an annual 20,000 tonnes of CO_2, captured from the locally produced natural gas, into the gas field in sector K12-B in the North Sea.

2004 was also the year of the start-up of the CATO (the Dutch acronym for CO_2 Capture, Transport and Storage) R&D programme. The first five-year programme had a € 25 million budget, funded by government and industry. In 2006, also the EOS LT Captech R&D programme on cost reduction of capture started. Several tangible projects started or were prepared, demonstrating the progress in CCS. For instance, 2009 marked the start-up of the ROAD project by E.ON and GDF Suez (then called Electrabel, see also page 35). Moreover, R&D into CCS continued when CATO2 started in 2009. Meanwhile, tests with the new SEWGS capture process and the CO_2 Catch-up capture pilot plant in Buggenum continued the line of progress.

Two calls for tenders followed, for both capture and storage. However, in 2010 CCS in the Netherlands went through a serious hiccup. In that year, the preparation of a couple of storage projects, having reached different stages of development, was cancelled. The Barendrecht project was the project that drew the most attention. This project concerned storing CO_2 from the Shell refinery in Pernis in a 2 km deep gas field under Barendrecht. Also the Geleen project (storing CO_2 from ammonia production in a 1.8 km deep limestone layer below a coal layer) was being prepared. But the Dutch government decided to cancel the permitting procedure in Barendrecht and actually actually established a moratorium on on-shore CO_2 storage, which also affected new plans for storage in the North of the Netherlands. The government mainly justified this moratorium pointing at the large opposition of the public (see also highlight **The U-turn of Barendrecht** on page 29).

This shifted attention to offshore storage, and also to re-use of CO_2. The development of the ROAD project, using offshore storage opportunities, continued and even received funding commitments from the Dutch government and from the European Energy Programme for Recovery (EEPR). Another project, Green Hydrogen from Air Liquide, was nominated for the NER300 funding programme, but didn't make it through the first round. It was cancelled in 2013.

Developing CCS regulations

In parallel with the milestones above, the evolution of the Dutch legal framework was taking place.

Following some activities concerning CO_2 and storage in the underground within the framework of the Mining Law, a legal taskforce within the CRUST project (2004) represented the first serious effort to investigate the details of CCS regulations. In 2006, the Amesco project was established. This study on general environmental effects of CO_2 storage was an important milestone, because it offered a framework for future environmental impact assessment reports and procedures on specific onshore locations, supporting both authorities and project developers.

The U-turn in Barendrecht

The case of CO_2-storage in Barendrecht has been a major event in the development of CCS in the Netherlands. In 2007, Barendrecht represented the first onshore demonstration to be, providing proof that storage of CO_2 in depleted gas fields is viable. In 2010, the Dutch government decided to withdraw the project. Between these two events, many stories unfold. Although Barendrecht was not a CATO2 project, several research links developed along the way.

In December 2007, the Dutch Ministry of Housing, Spatial Planning and Environment (in Dutch: VROM) tendered for two projects, for € 30 million subsidy each, to demonstrate the feasibility of CO_2 transport and storage. One of the applicants was the Barendrecht project, initiated by Shell and NAM (the Dutch Natural Gas Company). This project was expected to store up to 10 million tonnes of CO_2 in two almost empty natural gas fields, both at 2 kilometres depth below the city of Barendrecht near Rotterdam.

Match

The amount of CO_2 is a by-product of hydrogen production at the Shell Pernis refinery in Rotterdam. At present, the major part of this rather pure CO_2 is vented into the air. A part is used by OCAP, a company that transports CO_2 to the greenhouse horticulture for improved growth of crops. The vented CO_2 was available for free at a transport distance of only 20 kilometres to the planned storage site. The storage plans also had a perfect match with the ambitions of the Rotterdam region to become a low-carbon industrial area.

Hence, in the 'Barendrecht project' the signs looked very positive to develop into a successful project. Early 2008, Shell and NAM started drafting an Environmental Impact Assessment, marking the start of a licensing procedure that normally takes approximately two years.

With a delay of almost a year, late 2008, the government took the decision in the tender process to award the Barendrecht project with € 30 million. However, events developed quite differently than had been foreseen at the start of the tender procedure. After just two years the Barendrecht project made a U-turn. In November 2010, the Dutch government decided to stop the licensing procedure and therefore cancel the project.

A short planning history

The storage project in Barendrecht intended to start with using a smaller gas field that was almost completely depleted (the pressure had decreased from the original 174 bar to 30 bar). After a few years, experiences with the storage cycle in the smaller field were expected to be the prelude for using the larger depleted gas field of Ziedewij, eventually reaching a stored amount of 10 million tonnes of CO_2 in 25 years. Originally, the CO_2 injection was foreseen to start by late 2009.

| Ministers Cramer (of Environment, right) and Van der Hoeven (of Economic Affairs, left) sitting in front of a full room with Barendrecht inhabitants, Picture Hollandse Hoogte.

Even though it was already clear that permitting procedures could not meet this deadline, the project team of Shell/NAM and the Dutch government did not expect further delay. All preparations continued. A public CCS website was launched in the beginning of 2009. And in the first half of 2009, the National Committee for Environmental Assessment judged that the Barendrecht Impact Assessment showed compliance with general safety standards. Late 2009, the national government decided that the project would start and would be carried out in two phases: first the small field will be filled and if that project is positively assessed the larger field will be filled.

A short history of opposition

In the meantime, local involvement increased. That became clear at some early public information meetings in Barendrecht that were linked to the licensing procedure. At the first meeting in February 2008 60 people were in the room, in April 180 and in February 2009 almost a thousand people attended (following a personal invitation). Signs of criticism increased along with the numbers.

The turbulence accumulated in a meeting in December 2009, where two Ministers (Cramer of Environment, Van der Hoeven of Economic Affairs, see the picture) explained their decision without being able to convince their audience. Opposition increased, and was also stirred up by a television documentary (Zembla) that made some critical remarks on the safety of CO_2 transport and storage. In the fall of 2010, the newly installed Dutch government decided to cancel the project. The formal ground for this decision was the local opposition in combination with a perceived decrease in necessity of the demonstration project due to the accumulated delay.

The local opposition triggered a debate on CO_2-storage in national politics. In the end, the Dutch government decided in February 2011 to adjourn all onshore CO_2 storage projects, including some newly developed plans in North-Netherlands. The focus has now shifted to the demonstration of *offshore* storage. Formally, the Dutch government will not lift the moratorium on onshore storage until offshore storage has proven to be insufficient for achieving Dutch climate and energy goals.

Barendrecht and CATO2

Although the Barendrecht project was not a specific CATO project, a considerable numbers of links existed. Along with some other research issues, CATO2 also organised specific activities regarding the issue of safety, like a workshop on risks. Also, abandoning the project (followed by cancelling onshore storage) had quite some influence on the course of CATO2 research. Not having any demonstration projects nearby prevented CATO2 researchers from testing laboratory or modelling results (economic, geographic, safety, etcetera) in real life situations. Also, because of the sudden changes in perspective in only a few years' time, the Barendrecht case became an interesting subject for research and analysis itself, especially concerning public acceptance and the interaction with policy making.

There are many elements that could explain the local opposition and the U-turn. In hindsight, preparations at national and industrial levels were deficient and communication was poor. Also the urgency for CCS was not broadly acknowledged, while the interactions (among politicians and policy makers, at national, regional and local level and with the diversity of target audiences) were underestimated. For instance, changing procedures had a broad impact in these interactions. Also, distrust of the project developer, lack of public engagement, the perceived local impact, a relatively unknown technology and the absence of benefits for the local population played a role. Finally, the time pressure had quite some effect on the ability to apprehend and to understand each other's interests and worries. Analysis revealed that not one aspect alone can explain the course of event. Only the whole set of (negative) elements in the planning process together can give that explanation.

The publication of the EU CCS Directive in 2009 guided further work on a Dutch legal framework for CCS. The Directive had to be transposed into national law by June 2011. The Dutch implementation of the CCS Directive into national law was finally completed in 2012. The most important changes concerned laws for spatial planning, mining and environmental acts and decrees. In addition, also the OSPAR 2007 decision (Convention for the Protection of the marine Environment of the North-East Atlantic) on CO_2 storage in geological formations under the seabed was included in Dutch mining laws.

Meanwhile, in 2010 the ROAD project published its 'starting note' for an environmental impact assessment procedure and its storage permit notification, marking the start of the permitting procedure, even before the EU law was transposed into Dutch laws.

Evolving CCS Policies

Initially, the Dutch government concentrated its CCS policies on laying the foundation with research and development. Later on, advancing interest in CCS started to focus on concrete implementation, as with subsidy for demonstration projects and some views on how CCS fits in future energy systems.

Looking back at 25 years of policies in the Netherlands, CCS perspectives have evolved continuously and gradually became more concrete. Although research was getting more momentum by (governmental) subsidies, in 1994 the General Energy Council advised against setting up a CCS demonstration. But large-scale demonstration is now seen as a key to further deployment.

In successive green and white policy papers on energy and climate, the government has ranked CCS higher and higher on the list of climate mitigation options. In 1996 CCS still only deserved 'stimulation'. In 1996 and 1997 the preparations of a demonstration project stranded, but by 1999 CCS was promoted to the status of a back-up option for meeting 2008-2012 Kyoto targets. The 2001 National Environmental Policy Plan even ranked CCS technologies (also called 'clean fossil') as the third option to reduce CO_2 emissions, next to energy conservation and renewable energy.

However, developments were modest and suffered from set-backs and changes of government. E.g. it took a few years before CCS earned itself a separate 'trajectory' within the 'Energy Transition', a government-led programme that was leading in energy innovation in the years 2002 up to around 2007. Meanwhile, the R&D programmes of CATO and CATO2 were seen as instrumental to sorting out one of the main challenges: reducing uncertainties regarding CCS. From 2009 on, an interdepartmental Project Organisation CCS was established to guide the further CCS developments. That was in a period where more and more policy focus was placed on pilots and demos. The fact that in 2009 and 2010, both the government and the market (EBN and Gasunie) presented documents with a longer view into future CCS industry developments proves that CCS was outgrowing its childhood and longing for further maturity.

A sound basis for further development was laid by the knowledge originating from research and development, along with increasing insight and ideas on policies and measures that further deploy CCS in the next decades. However, this was not enough to prevent the stalling of concrete development in the last three to four years. This delay is particularly due to the adjournment of larger demonstration projects and a lack of political will to proceed on the CCS track.

Despite this delay, CCS is still seen as a promising option. The present government, formed by liberals (VVD) and social-democrats (PvdA) that was installed in November 2012, made hardly any specific references to CCS yet. Upon completion of this book, no recent breakthroughs can be reported. But following the 2013 Energy Agreement (Energieakkoord) between all relevant stakeholders in the Netherlands, the Dutch government as co-signatory

confirmed the necessity of CCS and committed to formulating a long-term view on CCS. This largely confirms the official supportive position regarding CCS.

Pilots and demonstration projects

In addition to, and as a part of research and development, pilots and demonstrations represent an important stage in any technological development, just before commercial application. Many Dutch CCS demonstration plans were initiated, only a few survived. At present, only one (K12B) is running, whereas the ROAD demonstration project is pending, awaiting a final 'go' from the initiators, who, in turn, are negotiating with Dutch and EU authorities about covering financial risks.

Already a few years after the start of CCS research in the Netherlands, the idea for a demonstration project was raised. But it took quite some years before capture and storage was actually demonstrated at a medium size in the Netherlands.

Demonstration in pilots became part of the CRUST (CO_2 Reuse through Underground Storage) programme, dating back from 2004. The first CO_2 that was injected offshore into the Dutch subsurface was early 2005. The actual re-use of CO_2 evolved to be part of the OCAP (Organic Carbon dioxide for Assimilation of Plants) project that started with bringing 300 kilotonnes of CO_2 per year from the Shell Pernis refinery through an abandoned oil pipeline to greenhouses.

By 2006, already four CCS pilot projects were on the radar:

- SEQ: Zero Emission Power Plant with oxyfuel technology, combined with CO_2 storage (ca. 0.2 Mton/y) and Enhanced Gas Recovery;
- NUON: CO_2 capture pilot at the Buggenum power plant.
- Gaz de France (CRUST): prolongation and upscaling (from 20 kton to 0.4 Mton) of CO_2 storage project in the North Sea.
- NAM: storage of CO_2 (ca. 0.6 Mton/j) from a Shell refinery to the De Lier gas field.

In 2007, the Dutch ministry of Housing Spatial Planning and Environment (VROM) issued two tenders for co-funding CCS pilot projects: one for capture projects, one for storage projects. For the first tender two projects were selected. Shell and NAM were rewarded a subsidy of € 30 million for a project concerning maximally 10 Mt CO_2 captured from a refinery, transported by pipeline and stored in a depleted gas field in Barendrecht. Shell performed an environmental impact assessment and started licensing procedures in early 2008. But the Barendrecht project met significant public opposition and was cancelled at the end of 2010 (see also **The U-turn of Barendrecht** on page 29).

The other consortium that was awarded with € 30 million consisted of DSM Agro, GTI and VITO. This consortium planned to store CO_2 from ammonia production in Limburg in a 1.8 km deep limestone layer, under a coal layer. This project was put on hold in 2010.

The second tender (part of the larger innovation programme Unique Opportunity Arrangement or 'Unieke Kansen Regeling') was on 'innovative CO_2 capture'. Three projects were selected:

In the German volcanic Eifel area, CO2 bubbling from a natural well is a touristic attraction. A delegation of CATO2 researchers visited the well during an excursion. Picture Daniel Loeve.

- ZEPP: Zero Emission Power Plant by SEQ using oxyfuel combustion of natural gas.
- ENECOGEN using cryogenic capture of CO_2 at a natural gas power plant.
- CO_2 capture pilot from Integrated Gasification Combined Cycle (IGCC) power plant in Buggenum using pre-combustion capture.

Only the latter pilot plant, called CO_2 Catch-up, was realised and started CO_2 capture in early 2011. The power plant and the capture facility were closed in 2013.

Also innovative (but not funded within these tenders) was a pre-combustion capture pilot called SEWGS at the ECN facility in Petten. This project started in 2007 and was funded by the EU-Cachet programme, the Dutch CATO programme and the seven oil companies united in the Carbon Capture Project (CCP). This pre-combustion capture pilot has extensively been used in the CATO2 program and is still in operation.

In 2008, within the CATO programme a pilot capture plant CO_2 Catcher became operational, jointly funded by CATO, TNO and E.ON. This post-combustion facility at an existing coal fired power station in the harbour of Rotterdam captures 250 kg CO_2 per hour, i.e. a fraction of a full scale capture plant. The CATO CO_2 Catcher was one of the first pilot installations in Europe connected to a coal fired power plant. It has extensively been used for post-combustion capture research and is still in operation.

Started in 2011, Twence demonstrated an innovative technology for re-using carbon dioxide by capturing CO_2 from the flue gases of the Waste-To-Energy (WTE) plant and converting it to the usable sodium bicarbonate. The project captures 6 ktonnes on an annual basis up to 2015 and has a budget of approximately € 2 million funded within the EU Eco-Innovation programme and also by CATO2.

Large-scale CCS demonstration projects were foreseen for some large power plants. At the end of 2005 and early 2006, several permitting procedures started for coal-fired power plants to be built in Eemshaven and Rotterdam. Initially power producer Vattenfall/NUON planned to build the Magnum power plant as an Integrated Gasification Combined Cycle with CO_2 capture (pre-combustion), as a follow-up to developments in its IGCC plant in Buggenum. The company however decided in 2011 only to build the gas power plant part, and postpone the coal gasification/ CCS part.

In 2010 the Dutch government pre-selected a few sites in the Northern Netherlands to be investigated as candidates for onshore storage: Boerakker, Sebaldeburen and Eleveld. However, within the turmoil of public opposition around the Barendrecht case, parliamentary elections and the formation of a new government, in 2011 the government decided to put a moratorium on onshore storage. This decision was followed by power producer Essent/RWE that put the project development of a post-combustion capture demo at its coal-fired power plant on hold (see also view **Connecting to international R&D** on page 34).

As the moratorium did not affect offshore storage plans, another large project plan in the Rotterdam harbour proceeded. The ROAD project aims to capture CO_2 from a newly built coal-fired power plant in the Rotterdam area. The project by E.ON and GDF/Suez, for storage in the offshore reservoir of operator TAQA, received EU and national funding (total ~€ 330 million) and aimed to start with capturing and storing up to 1.1 Mt/yr in 2015. Decisions on this project are still pending.

Another CCS demonstration project dubbed 'Green Hydrogen' aimed to use the infrastructure for transporting and storage of the ROAD project. This project had been shortlisted (ranked nr 3) for the NER300 funding scheme, but eventually no CCS projects were awarded any funding under the first round of this funding scheme.

Connecting to international R&D

For ten years, the CCS activities of RWE (in the Netherlands also operating as Essent) in the Netherlands have been closely linked to the CATO programme. In many aspects, RWE contributed both in cash and in-kind to CATO, such as funding PhDs at Groningen University. In exchange, RWE had access to a knowledgeable network of science and industry.

The broad and multidisciplinary network was certainly a distinguishing part of CATO. But even more, the RWE plans of building a coal-fired power plant with the possibility for CCS in Eemshaven (in the North of the Netherlands), was an important driver for RWE to participate.

Eemshaven

In February 2011, RWE effectuated its plans with the Eemshaven power plant and submitted an application for a CCS demonstration project under the EU NER 300 subsidy programme. The application was submitted to the Dutch Ministry of Economic Affairs, following the request that any application for NER300 had to be supported by national governments, including co-funding. The Eemshaven demonstration project had been based on on-shore storage in depleted gas fields in the North of the Netherlands.

Only a few months after submitting the plans, however, the Dutch government decided that onshore CO_2 storage should not be permitted and therefore not be funded either. Given the new circumstances, RWE investigated several offshore alternatives for linking the Eemshaven power plant capture possibilities, such as partnerships with companies operating in or around the North Sea. In the end, the investments turned out to be economically unviable and therefore the adapted project did not run for the second NER300 round in April 2013.

Continued

However, this does not imply that RWE has turned its back on CCS activities! RWE continued its participation in CATO2, finalising running activities in 2014. Meanwhile, RWE also carries on its CCS R&D activities elsewhere in Europe. Right now, RWE is still working on all relevant topics of the CCS chain, such as the pilot-scale CO_2 separation plants in Aberthaw (UK) and Niederaußem (Germany) and the development of transport and storage opportunities.

RWE is convinced that in the long run CCS is an important option to meet the ambitious greenhouse gas mitigation targets as set for the European Union in the 2050 roadmap.

Roland Kok

RWE Generation Business Development Netherlands

Another demonstration project that was planned was the 'Pegasus project' by SEQ that revitalised its oxyfuel concept to be used at the TATA steel plant in IJmuiden. Also this project had a dead end.

Research programmes & conferences

R&D programmes have been the most robust and continuous element in CCS developments in the Netherlands. With the CATO and CATO2 programmes since 2004 as a backbone, some flanking programmes and EU R&D projects, Dutch knowledge on CCS has developed to a top position in the world (see also highlight **Review Committee rates CATO2 work as 'excellent'** on page 36). The combination of fundamental and applied research has always been a priority within all programmes.

At the start in 1988, CCS research may have been a bit fragmented and ad-hoc, but R&D efforts developed into a coherent and consistent programme that investigated the whole CCS chain. Some early predecessors, for instance SOP-CO_2 (The Integrated Research Programme on Carbon Dioxide Recovery and Storage), the Clean Coal programme, CRUST (CO_2 Re-use through Underground Storage) and 'Transition to sustainable use of fossil fuels' (NWO/SenterNovem) were the prelude to more integrated programmes such as CATO, Captech and CATO2.

The contents of these programmes also evolved: from elementary to integrative, covering the whole chain and integrating non-technical research, such as social science research and development of regulations. Also the participation of private companies and non-governmental organisations illustrate that CCS development is aligned with the economy and with society. Especially during the last five years, research in the Netherlands integrated pilot and demonstration projects, in order to combine learning-by-doing with learning-by-research. All this provides a top ranking of Dutch research, which was also rewarded in the EU R&D framework programme. In addition, Dutch researchers have been contracted all over the world, contributing to a further spreading of CCS knowledge.

Continuation of R&D of CCS is foreseen to be put under the umbrella of the Dutch Top Sector Structure, within the Top consortium for Knowledge and Innovation for gas (TKI-Gas, see also **Integrated Approach deserves follow-up** on page 38).

In 2010, Dutch CCS research people also played a major role in organising the Greenhouse Gas Technologies conference in Amsterdam. Back in 1989, this series of GHGT conferences started in Amsterdam, travelled around the globe and returned to Amsterdam to celebrate its tenth issue. Some 1500 people from all over the world attended.

The ROAD ahead

Pending a final investment decision, the ROAD project (Rotterdam Opslag en Afvang Demonstratieproject, or in English: Rotterdam storage and capture demo) is one of the few projects in the European Union that are still running for a large-scale demonstration of CCS. ROAD would become one of the first integrated CCS demo projects in power generation in the world (see also highlight **Creating the foundations for CCS deployment** on page 39).

The ROAD project is a joint venture of power producers E.ON Benelux and GDF Suez Energie Nederland (formerly Electrabel), that both run a power plant in the Rotterdam industrial area Maasvlakte. It aims to capture and store 1.1 million tonnes of CO_2 a year, for five years, in an offshore depleted gas field at a depth of 3.5 km, operated by TAQA. The P18A offshore platform that will be used for storage is at a distance of 26 km from the capture unit. The project is part of the E.ON coal fired power plant, where a capture unit will be installed equivalent to almost a quarter of the total capacity of 1070 Megawatt.

Outline of the CCS technologies

The capture technology that will be applied is of the post-combustion type (see page 68), also since pre-combustion and oxyfuel capture are not suitable for retrofitting. The

HIGHLIGHT

Review Committee rates CATO2 work as 'excellent'

At the time of publishing this book, the CATO2 programme reaches its finalisation and CCS R&D activities prepare to be accommodated within the Dutch Top Sector structure for innovation. This structure has been designed two years ago and targets at making innovation efforts work for the Dutch economy. On behalf of the Top Team Energy, a special committee reviewed the CATO and CATO2 programme. Main conclusion: CATO really has an added value for Dutch economy.

With the end of CATO2 in 2014 in mind, the CCS R&D community applied for a follow-up in the Dutch Top Sector Structure or a CATO3 programme at an early stage. After some debate, during 2013 this resulted in a preliminary decision of the Top Team Energy to include CCS R&D activities in TKI Gas (Top consortium for Knowledge and Innovation). No budgets or priorities were decided yet.

In summer 2013, The Top Team Energy assigned a Review Committee for assessing CATO and CATO2, in order to investigate this possible integration into the Dutch Top Sector Structure. The assignment was to prepare "a clear view of the results of CATO and CATO2, especially regarding the market potential of their portfolio" (Top Team chairman Michiel Boersma to CATO Programme Director Jan Brouwer, July 2013).

TOPSECTOR ENERGIE
Empowering the new economy

| **Logo of the Top Sector Energy, which will be the framework where future Dutch coordination of CCS R&D will be executed.**

The Top Team assigned four people to do the investigation: Kees de Groot (chair; former CEO Shell Netherlands), George Zon (formerly SEP and NUON), Leni van Rijn-Vellekoop (former Member of Dutch Parliament), Gerdi Breembroek (secretary; AgentschapNL). They interviewed seven prominent stakeholders in CCS and made use of CATO documents and open literature.

Within a short period, the committee drafted its conclusions. They concluded that the work in CATO and CATO2 was 'excellent'. Especially in CATO2 there was an effective co-operation between companies, knowledge institutions and universities, also internationally. Without the work carried out in CATO and CATO2, the proposition for the ROAD demonstration would not have been possible.

Accordingly, they concluded that "CCS matches the strengths of the Dutch economy and geographic location". Dutch organisations already profit from work in CATO. Therefore, continuation of some coherent CCS R&D programme is needed. If the demonstration project ROAD will be realised, the demo needs support in e.g. solving specific barriers in technology, monitoring, etcetera and for further developing next generation CCS at lower costs. If ROAD is not established, a follow-up of CATO is needed anyway for safeguarding Dutch stakes in developing next generation CCS and to preserve expertise. For in the view of the 2013 Dutch Energy Agreement between stakeholders, CCS is necessary in the long term anyway.

To the Review Committee's view, the predicate 'excellent' is supported unanimously. Some specific CATO achievements they mention:

- An effective cooperation between companies, universities and knowledge institutions, among different disciplines. This is a bottom line for every future Top Sector programme.

- CATO has become a focal point for international cooperation in CCS.
- CATO has made an important contribution to the ROAD project, e.g. with respect to reservoir characterisation, the storage permit and other permits, and with several technological solutions for possible problems.
- In general, CATO cleared many issues, like how to define communication strategies to the public and the media, how to reduce costs and energy use with capture, how to design transport infrastructure, how capture, transport and storage integrate into one CCS chain, and many others.
- Also the accessibility of the CATO work is considered 'very good', through the network and the website.

Importance of CATO for Dutch business

Besides drafting the reasons why CCS can become a large business and why CCS has not yet reached that stage, the Review Committee also assessed the value of CATO for Dutch business. One starting point was, that 20 companies in the Netherlands already signed a Letter of Intent (LOI) in support of a follow-up programme of CATO2, suggesting a joint (and conditional) business commitment of about € 4 million per year.

The Committee sees an opportunity for a prominent position worldwide for Dutch CCS business, in particular when ROAD will proceed. However, the CCS market is presently non-existent, especially because CO_2 prices are very low and sometimes zero. If the CCS market deploys in the near future, Dutch knowledge institutions, consultancy and also companies (energy generation, energy-intensive industry, oil and gas industry, transport) are in a good business position. However, scaling up from a successful laboratory scale process to demonstration requires a much larger deployment of people and resources.

Integrated approach deserves follow-up

Being a member of the CATO advisory board and leading the international IEA-GHG programme at the same time, I have been able to follow the R&D developments in CCS within CATO from a short distance. To a global background, the Dutch programme particularly distinguished itself by its integrated approach.

CATO's co-operative interactions between academia and industry have been a corner stone of its results. This remark also puts the Programme Office in the spotlight, because it is no mean feat to coordinate while bringing the multiple scientific research threads together on time and on budget.

Many results

From a technological viewpoint, many results have been achieved. I like to mention two examples at either end of the spectrum. The development of the SEWGS capture technology can be regarded as exemplary for CATO's technical results. As a very practical example, the programme's site characterisation work actually led to the first permit under the EU CCS Directive (for ROAD). The large amount of results is an outstanding apology for this book.

At the end of CATO2, the coordinated CCS R&D work in the Netherlands is now at crossroads. The approval of the Dutch Top Sector infrastructure for incorporating CCS as one of its programme lines is great news. However, that is not yet sufficient to build on the achievements. Obviously, the development of CCS is not yet done and needs more effort, and hence more funding. Technological results (like SEWGS) should not be shelved, but should move to a higher, (pre)commercial level. Continued coordination and a certain critical mass are required.

Bridging the gap

Moreover, a decreased attention for CCS R&D will also run the risk of key expertise drifting away from industry and academia. Any gap between the end of CATO2 and a full restart of a coordinated programme will require extensive recovering of this expertise. There is a high risk of CCS knowledge falling into the 'Valley of Death' – as we call the infamous barrier between R&D and commercial application.

CATO3, or any other quick follow-up for CATO2, should be the bridge, independent whether the ROAD demonstration project will be established or not. While formulating its long-term vision, the Dutch government should better not forget about preserving and continuing the CCS knowledge network of industry, academia and authorities.

John Gale

General manager IEA-GHG,

(International collaborative research programme established in 1991 as an Implementing Agreement under the International Energy Agency).

Creating the foundations for CCS deployment

As a major player in the European power market with an installed capacity of more than 37 GW in coal and gas power plants and more than 9 GW of renewables, E.ON is focused on reducing the environmental impact of its power generation business by researching and investing in renewable energies, energy efficiency and clean fossil energy.

As far back as 2005, the IPCC special report on carbon capture and storage identified CCS as a cost effective solution for the decarbonisation of power generation. However, at that time, it was not fully proven. The Dutch research program CATO has taken up the challenge to develop this important technology from laboratory to commercial deployment. Therefore E.ON was pleased to be an industrial partner in the CATO research program, supporting its development and working together with its researchers. We were also delighted to receive help in return from CATO in the development of the ROAD project (together with GDF Suez, see also: The ROAD ahead, page 35).

Wide range

The CATO programme triggered the development of a wide range of knowledge, skills and resources essential for the deployment for capture, transport, utilisation and storage of carbon dioxide in the Netherlands and abroad. Fortunately, the focus was not only on technology, but also included issues like public acceptance, energy system aspects and primary education. There has been a very fruitful and constructive cooperation between research and industry which created the conditions for the Netherlands to move from basic research through pilot testing to large-scale demonstration.

The CATO programme and the ROAD project created significant opportunities for cooperation, for example in the area of emissions reductions and improvements of capture facilities, including tests at the CATO pilot plant at Maasvlakte, as well as considerations for the optimal integration of a capture facility and the power plant. A substantial amount of work was undertaken by the CATO programme on reservoir suitability, storage potentials and environmental impact assessments. This valuable and necessary contribution resulted in the first CO_2 storage permit ever being granted in the EU under the framework of the EU CCS Directive. And not to forget the work on public acceptance which helped to better understand and address external stakeholder concerns and questions, helping to create broad societal support for the large-scale demonstration.

Essential

Without the successful work of the CATO program, it is doubtful that a project like ROAD could have advanced so far. The ROAD project has developed to be the most likely CCS project in Europe to be built. There is still hope that the success story of CCS written by CATO can be continued in the Netherlands. The recent IPCC WG III report Mitigation of Climate Change as well as the 2014 Technologies Perspectives report of the IEA highlighted again that the application of CCS for fossil fuels as well as for bioenergy is essential to achieve the 2°C climate change target. This has to include CCS for the energy intensive sectors of industry as well as power, making the development of the required CCS infrastructure essential for success.

Peter Radgen
Head of E.ON Innovation Center, Carbon Capture & Storage, E.ON Technologie & Innovation.

Fluor Econamine FG+ process won the tender competition for the capture process and is regarded as a matured capture technology, licensed in 28 industrial plants in different applications. The respective part of the flue gas from the power plant is cooled, cleaned and passed to the absorber vessel. An amine solvent will capture 90% of the CO_2, which is again removed from the solvent in the stripper vessel.

The clean CO_2 is then passed on to the compression system. Here, the CO_2 is cooled, dried and compressed, ready for transport. The multistage compressor delivers a CO_2 stream of more than 99.9% purity and less than 50 parts of water in every million parts of CO_2. Pressure can be as high as almost 130 bar.

The transport system is a 16 inch insulated pipeline, running for 5 km over land, and 20 km offshore. The pipeline has a capacity of at least 1.5 million tonnes of gaseous CO_2 per year.

The P18-4/A2 gas production well of TAQA will become the injection well. The storage capacity of the P18-4 reservoir is estimated at 8 million tonnes of CO_2, while the full capacity of the P18 block reservoirs is around 35 Mt.

Progress

The ROAD project has already been rewarded with substantial subsidies. In 2009, the European Commission selected the project for financing of € 180 million within its European Energy Programme for Recovery. In 2010, also the Dutch government confirmed its decision to grant € 150 million.

The ROAD project is now in an advanced status. Front-End Engineering Studies were already completed in 2010 for the capture plant and pipeline, while also the Environmental Impact Assessment has been executed. This led to the definitive and irrevocable permits for both capture and storage. However, the final investment decision has been postponed a few times and is still pending.

The main barrier here is the low price of CO_2 within the European Emissions Trading Scheme. The price of these EU emission allowances is crucial for the CCS business case, because unlike emitting the CO_2 through the chimney, storage will save the power station from the requirement to submit the equivalent of allowances. And here is a problem, because there is a huge price difference between initial calculations (assuming € 30 per tonne) and the present price of about € 5/t. this difference implies a deficit of more than € 100 million for the whole five-year-project.

ROAD and CATO

ROAD is not a part of CATO2, but the project has had many links to CATO2 research. Also for the future of CCS research in the Netherlands, ROAD is crucial, both in using and applying results and in raising new practical research questions.

In this book, many links have been identified between CATO2 and ROAD. CATO2 at least has been supportive to ROAD, such as in designing the processes, in permitting procedures and EIAs and in many other aspects. These links may be regarded as further proof of the integrative character of CATO2, connecting research to business.

The global progress in CCS projects

CCS activities have been occurring for tens of years now, concentrated in some regions all around the globe. On a commercial scale, CCS started some 35 years ago in North-America with the special application of Enhanced Oil Recovery (EOR). Especially in the last two decades, a critical mass in CCS research, development and (demonstration) projects for capture and geological storage also developed in Europe, Asia and Australia. At present, developments are mixed.

In the last decades, by far the largest volume of CO_2 in CCS activities related to EOR projects around the world. Climate change mitigation effects have been limited, because sometimes the CO_2 used originated from CO_2-rich gas fields, instead of from flue gas capture. The very idea to store CO_2 for the longer term for climate reasons deep underground was probably raised by several geo-scientists simultaneously, in the early 1980's.

Sleipner

It took quite some time before this idea was applied in practice on a large scale. The Sleipner project, offshore the Norwegian coast, is the world's first fully integrated industrial scale CCS for mitigation of climate change. Since 1996, this longest running non-EOR CCS project in the world injects about 1 million tonnes of CO_2 a year into a saltwater filled sandstone formation called 'Utsira', 1000 metres below the bottom of the North Sea. The CO_2 originates from the natural gas that is produced at Sleipner. This natural gas contains about 9% CO_2, which has to be reduced to 2.5% to be able to sell the gas. The CO_2 is captured in an amine-based separation process and injected into a 4 km long well, using a compressor. The project became viable since the Norwegian government introduced a CO_2 emissions tax in 1992.

In 2008, another Norwegian integrated industrial scale CCS project was established, called the Snohvit project. This project concerns injecting 0.75 Mt CO_2 per year. The first North American CCS project to avoid emitting fossil CO_2 of concern for the climate was the Weyburn-Middale project in Saskatchewan, Canada. Here, 2.5 Mt per year is injected.

The first climate-related project on the African continent was the In Salah project, which was also based on CO_2 removed from natural gas to meet sales quality. The first industrial scale storage project in Australia (the Gorgon project) has drilled its first wells, while the first project in Asia is yet to come. In Europe, North America and Australia a number of smaller pilot and research CO_2 injection projects exist, to prove concepts, to test monitoring techniques etcetera.

Projects in operation

The 'Global Status of CCS' (last update February 2014), the annual report by the Global CCS Institute, shows a somewhat mixed view on actual developments in CCS around the globe, and particularly on enhancing oil and

Sleipner, the world's first fully integrated industrial-scale CCS for mitigation of climate change. Statoil Annual Report 2007, Picture Harald Pettersen, Statoil ASA.

gas recovery projects. The overview identified 60 so-called 'large-scale integrated projects'. These are projects in different stages of realisation, from first identified opportunities to projects in actual operation. Overall, the total number of identified projects decreased compared to the 2012 overview, because 18 projects had been cancelled, scaled down or put on hold. However, some new projects were also identified, while the projects that are in operation increased from eight to twelve. Another nine are under construction, of which two are expected to come into operation during 2014. The twelve running projects annually store a total of some 26 million tonnes of CO_2.

Most of the projects in operation are dedicated to enhancing the recovery of oil and gas with CO_2 captured from natural gas processing, with a concentration of projects in the US. The geographical distribution of all 60 planned large-scale projects is more even around the world: US, Europe, China and some in Australia and the Middle East.

The coming years are expected to show a steady progress in construction and operation of large-scale CCS projects. A slight shift towards a somewhat larger share of non-EOR projects is likely to occur in future years, with some emphasis on dedicated geological storage in saline formations. In total, nine projects in the US, Canada, Saudi-Arabia (for an iron and steel factory) and Australia are planned to come online during 2014 and 2015. For the next years China – now ranking second to the US in the number of planned projects – is "well positioned to influence the future success of CCS". Outside China, the development of new projects into next stages has more or less stalled, particularly in Europe. The GCCSI also establishes that the steady growth of projects is far too slow to be of influence in combating climate change.

Europe: stalling ambitions

Zooming in on Europe, CCS progress in recent years has been very limited. Despite considerable policy initiatives, no new large-scale integrated CCS project (sized around 1 million tonnes of CO_2 a year) has entered operation since 2008. The EU is obviously struggling with CCS as a climate change mitigation issue.

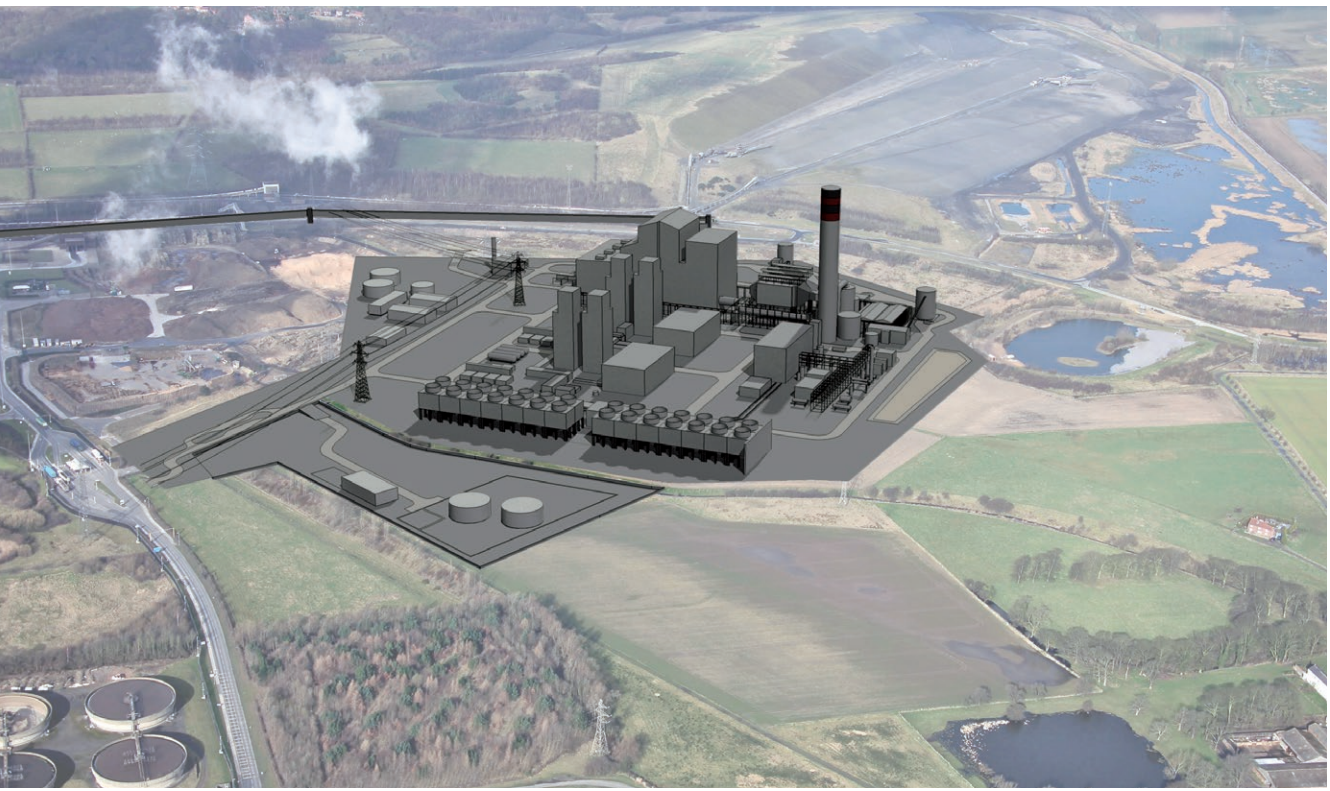
In formulating policies and strategies, both the EU and many of its member states have been clear: in general, CCS is regarded as a serious option to help achieving greenhouse gas emission reduction goals. This may be seen as a logical consequence of the ambitious climate change pledges that the EU formulated in its policies, such as the 20% emission reduction target by 2020 and – even more relevant for the case of CCS – the ambition to reach 80 to 95% emission reduction by 2050. The recent 2030 proposals from the European Commission (-40% by 2030) more or less confirm the position of the European Union as one of the most ambitious regions in the world regarding combating climate change.

Since 2007, a considerable number of green and white papers in the EU and its member states have been paying attention to a prominent position of CCS. Moreover, in

EU plans for the economic recovery after the 2008/2009 crisis, the EU reserved hundreds of millions for supporting CCS demonstration projects. A small number of demos have actually been shortlisted for allocation of these funds. The EU also reserved a budget within the subsidy programme called NER300. For climate change combating purposes, in 2010 the EU reserved the revenues of 300 million emission allowances units (from the New Entrants Reserve) within the EU emissions trading scheme (ETS) for support of demonstrations of CCS and innovative renewable energy options. At the moment of establishing the NER300 programme, the 300 million EUAs had a virtual value of over € 4 billion, but because the CO_2 prices dropped, the final budget was around € 1.5 billion. For this considerable amount of money two calls for tenders have been written out. But eventually, no CCS demo has been awarded any NER300 budget yet.

At the moment of finalising this book (1 June 2014), two projects are still on the list for receiving EU funding. If realised, the Dutch ROAD project will receive some € 180 million from the European Energy Programme for Recovery fund (see page 35), while the British White Rose project was recently nominated to receive € 300 million of EU funding. A final EU decision is expected around the publication date of this book in June 2014.

Except for the UK and the Netherlands, national initiatives in EU member states regarding demonstration of CCS are very modest. The Netherlands allocated € 150 million for



The UK White Rose Project in North Yorkshire is one of the few large-scale CCS demonstration projects that have been rewarded funding. © Capture Power Ltd.

the ROAD project, while the UK established a € 1.2 billion (£ 1 billion) fund for funding demonstration projects. In 2013, the UK CCS programme selected two demonstration proposals. The White Rose project in North Yorkshire and the Peterhead project in Aberdeenshire, Scotland have been awarded a contract for detailed engineering (FEED: Front End Engineering and Design). About nine other CCS demonstration plans in the EU (all shortlisted in the first round of NER300) have been cancelled during the last three years. In addition, also the Norwegian government cancelled an ambitious project in the Mongstad industrial area, stressing that it will look for another CCS demonstration opportunity within the country.

The key players

Around the globe – and also on a national scale in the Netherlands or any other country – we distinguish different kinds of stakeholders in CCS, each having its own role and interest in deploying future CCS business.

Key players are the energy companies and the energy intensive industry (steel, chemicals, refineries, etcetera). Because they are usually the large consumers of fossil fuels, they also produce a lot of greenhouse gas CO_2 when processing or combusting these carbon fuels. If they wish to continue using fossil fuels in a carbon-constrained world, CCS is an opportunity or even a prerequisite.

The oil and gas industry, including SMEs in this category, have an interest because they operate and maintain possible storage locations. The services include well drilling, monitoring, providing know-how, and many more.

Transporters (by pipe or by ship) will develop business in transporting CO_2 from sources to sinks. Dutch companies are particularly strong in both fields.

Manufacturers, chemical industry: multinationals already supply and develop capture solvents. In some cases, these multinationals are of Dutch origin or have Dutch offices.

Consultancy and engineering: the knowledge providers are involved in many stages of CCS, from R&D and design to operation and maintenance of installations.

Authorities and governments: authorities, from local to supra-national, play a crucial role in CCS development, both as policy makers and in stimulating (local) low-carbon and CCS business. For instance, the EU has laid the regulatory foundation for CO_2 storage, while also funding demonstration projects. In the Netherlands, the national government is an important stakeholder, and also harbour, provincial and even municipal authorities, for instance in Rotterdam, Groningen province and the North of the Netherlands (organised in Energy Valley).

NGOs (non-governmental environmental organisations) have always played a crucial and critical role in the debate on the necessity of CCS. Their positions differ. Some prioritise renewable energy and reject CCS as a mitigation option for climate change, while others see CCS as an indispensable technology in speeding up the transition to a low-carbon economy.

And last but not least: the scientists – which actually play the leading roles in this book – are the ones that have brought the CCS technology as well as the debate to the next level. They have contributed with knowledge, data and capacity that make any political or business decision more evidence-based than ever.

Barriers between policy and realisation

Many policy papers and other publications within the EU and abroad have deemed it necessary to establish large-scale demonstration of CCS as a next stage on the pathway to large-scale implementation. Up till now, 'large-scale' means storing more than 0.5 million tonnes of CO_2 a year; medium-sized testing (around 100,000 tonnes a year) is not expected to deliver pre-commercial insights. Such large-scale CCS implementation is quite expensive, and is now suffering from a serious delay, for several reasons.

First, it does not help that CO_2 prices around the world are quite low. While other CO_2 abatement measures may still benefit from other commercial drivers like saving energy and fuel costs, in CCS a low CO_2 price directly translates into lower income and lower commercial interests. This may also explain the lower political, corporate and public interest in multi-million investments in CCS. Such investments are essential for passing through the pre-commercial phase. For good reason, this phase in technology development is often referred to as the 'Valley of death'. Low CO_2 prices, subsidies and (still) relatively high CCS costs blur the commercial perspective that is obviously needed to mobilise the required funding.

On a global level, climate change ambitions have not increased, but rather diminished. The delay in finding a successor of the Kyoto Protocol in international climate change policy negotiations is not very supportive. Indeed, the world seemed to have agreed on not exceeding the 2° C temperature increase, but countries are still reluctant in translating the consequences of this into actual policies and technological measures. Or to put it another way: if the world would have agreed on a shared high ambition with regard to greenhouse gas emissions, a direct link between CO_2 emission reduction and implementing CCS would become more apparent.

Meanwhile, also on the level of public understanding and acceptance CCS has some problems to deal with. Political support and public funds cannot be justified without a fair public acceptance of CCS – which seems not to be there in some cases. In the Netherlands, local opposition against CO_2 storage demos has become apparent. Meanwhile, the essence of climate change is poorly understood by the public. Only a minor part of the public has a basic knowledge how CO_2 emissions from power or industrial production are linked to climate change. As climate change is by far the most important reason for CCS anyway, this might be crucial for CCS. (See also **Investigating the Rationale** on page 137)

The need for R&D

Meanwhile, R&D efforts all over the world are kept on a high level. Although no detailed global overview is available, CCS programmes seem to look after a continuous R&D effort around the globe. In some cases, this is expressed in multi-annual national programmes, sometimes in strengthening supra-national programmes that compensate for diminishing national R&D funds. Also, R&D is never completed, by definition.

For instance, on an EU level multi-million budgets are committed to CCS within the Horizon 2020 R&D programme, targeted at empowering the EU economy as a whole. The position of CCS in Horizon 2020 is explained as follows: "The assessments made in the context of the EU's Roadmap for the transition to a competitive low carbon economy in 2050 and the Energy Roadmap 2050 see CCS as an important technology contributing to decarbonisation scenarios in the EU, with 7% to 32% of all power generation using CCS by 2050. The application of CCS to industrial sectors other than power (e.g. steel, cement, lime, chemical industry, refining) is expected to deliver half of the global emissions reduction from CCS by 2050. For all applications, the demonstration of CO_2 storage is of major importance. Therefore, two key challenges in the short-term for driving CCS to deployment are geological storage and the application of CCS to industrial sectors other than power, including bio-CCS."

Within almost all R&D frameworks, cooperation between business and academia is especially rewarded.

A way forward

In its 2013 'Global Status' report, GCCSI concludes that "public policy for CCS has not succeeded in generating the necessary breadth and depth to the CCS demonstration effort necessary to allow it to play its full part in mitigating the predicted rise in global temperature. [..] An urgent policy response is required to ensure the successful global large – scale demonstration of CCS in the next five to 10 years."

It is not completely clear how such an urgent policy response would look nor what the following steps could look like, to prepare for a CCS future. Some components have been mentioned above: R&D, funding for demos, ambitious CO_2 targets resulting from the 2°C goal, informing the public about the reasons for CCS, and many more. This book will extensively go deeper into these issues, like the 'next steps' in a Dutch Roadmap (see page 94).

CATO2: The challenges

When CATO2 followed up on the CATO programme in 2009, many lessons had already been learned and remaining barriers on the pathway to implementation of CCS had become better visible. CATO2 started with formulating these barriers and focusing research questions on these barriers. The ultimate goals: linking the chain, improving the insight in economics, scaling up technology and reducing costs, and increasing the knowledge on public perception. Some other benefits in science and capacity building were also foreseen.

The start of CATO2

The CATO2 programme is the successor of the first national Programme on CO_2 Capture, Transport and Storage CATO, that was executed between 2004 and 2009. In CATO, 17 participating parties from industry, research institutes, universities and NGOs had established a knowledge platform, providing a leading position of the Dutch programme in the international community. CATO2 was expected to underpin Dutch participation in international research communities, such as the European Technology Platform for Zero Emission Power plants (ETP-ZEP). Moreover, CATO2 was expected to provide the basis for realising two large-scale CCS demonstrations in the Netherlands by 2015 – as was the goal formulated back in 2009.

In hindsight, the conditions for establishing the CATO2 programme were quite favourable. First, the preceding CATO programme already established a CCS network and developed some essential skills for further implementing of CCS in the Netherlands. Major industrial parties in the Netherlands were already engaged or were preparing to engage in pilots and in two integrated large-scale demonstration projects. This created a clear technology demand from industry. Furthermore, the intergovernmental project organisation on CCS, established in 2007, was highly supportive as a policy makers' counterpart of the scientific and business community.

Besides confirmation of the continued support from existing consortia members, CATO2 also gained support from new members, especially in the power sector (that was formerly represented by its common research institute KEMA, now DNV-GL) and in industry. Like in CATO, partners were allowed to participate with in-kind or cash contributions; both investments counted as eligible cost and were to be doubled by the government, to a maximum budget of € 61 million in total for the years up to 2014. This resulted in CATO2 participation by around 40 existing and new parties. These partners all signed a Letter of Interest, indicating their budgets. Initially partners even offered co-funding of up to approximately € 47 million, but that amount was reduced along the way to just above € 30 million. Basically, this broad support still exists at the end of CATO2, making the case for a continuation.

Drafting the programme

A conference in May 28th 2009 established the initial CATO-2 research agenda, as prepared by the Work Package leaders of the original CATO Program. One of the main messages was the desire by industry and government partners to organise the agenda around three regions Rijnmond, North Netherlands and IJmond (around the TATA/Corus steel factory) and their twelve candidate-locations for CCS, rather than around thematic lines. Regions and locations became leading in designing the programme and its governance structure (see also highlight **CATO2 governance: the best of both worlds** on page 49). Regional meetings were held to discuss the development of an integrated CCS research agenda for each region, in preparation of a regional blueprint for large-scale demonstrations. A programme matrix was designed on this basis.

The challenges per theme

The overall challenges of CATO2 were to get a better impression of the whole CCS chain and its economics and to further reduce costs.

For reaching the **demonstration phase**, upscaling of processes needed to be proven. Integration of different CCS elements had to be tested, as well as the performance of the whole system. Cost estimates needed to improve, regulation needed to be understood and tested.

Regarding **Capture (SP1)**, reduction of costs (both capital and operational) was the main challenge. One way to achieve this was further innovation or even creating a break-through in capture technologies, but cost reduction also possibly lies in upscaling and improving performance (also environmentally) of capture processes. In addition, environmental aspects such as emissions and safety were to be addressed.

Transport and chains analysis (SP2) especially needed to shed more light on the role of CCS in the energy and

economic systems, on integral costs and learning curves, on technical and economic aspects of transport systems and on macro-economic impacts. Typically, also long term perspectives and adjacent policies and measures had to be investigated.

Regarding **Storage (SP3)**, a better understanding of (underground) storage mechanisms and the linked safety issues were key. A lack of knowledge about site characterisation and about reliable storage capacity estimates was also identified as a barrier for larger scale implementation.

The **Regulation (SP4)** regarding CCS as a business activity was still quite unclear at the start of CATO2. Experience and data were missing, and best practices regarding e.g. permitting were needed to service any procedure design by authorities. Monitoring was also an important issue.

Public perception (SP5) and in particular public opposition have been identified as important possible barriers to the implementation of CCS. A better understanding of the mechanisms that determine the attitudes, perceptions and sometimes misconceptions of the public was key. Also trends in public knowledge and opinion, communication, and local decision-making had to be investigated.

Finally, CATO2 intended to **communicate (SP0)** about CCS in general and the CATO research results in particular. That was instrumental to establishing and strengthening the CATO2 network of participants and participating organisations, but also to informing the broader audiences (see also highlight **Two-way communication** on page 51).

CATO2 governance: the best of both worlds

Building on the accomplishments of CATO, the CATO2 programme was designed to further deliver on discovering, developing and deploying CCS technologies. One of the largest challenges was uniting the best of both worlds: fundamental science and applied technology. This challenge was met by the specific design of CATO2's governance structure.

The previous CATO programme 2004-2009 was divided into five sub-programmes (SPs), each lead by an SP coordinator: Capture; Transport and Chain Integration; Storage and Monitoring; Regulation and Safety; and Public Perception. This logical diversification of issues worked alright, but CATO2 – which received a larger budget – was expected to put a greater emphasis on pilots and demos.

This shift in focus met the demand of industries to deliver on CCS technology and get to the next phase, and also for further justification of their own investments into CCS research and development. So the SPs stayed, and the coherence of fundamental and applied science had to improve. Obviously the Programme Office and the Programme Director, in charge of daily CATO business, needed to account for this.

In addition, at the higher levels of governance, the shift was accounted for. Essentially this was done by installing the Programme Council as a governing body, judging all proposals for projects and programme changes on their content. The composition of the Programme Council – all SP and WP leaders, all coordinators of pilot and demo sites and regional coordinators – should safeguard this shifting focus.

The prominent place of this council within the governance structure assured that science and technological application became a joined effort. The Programme Council acts next to the General Assembly, the Advisory Board, the Programme Office and the Programme Director, with the Executive Board taking the final decisions (see figure).

Covering content and application

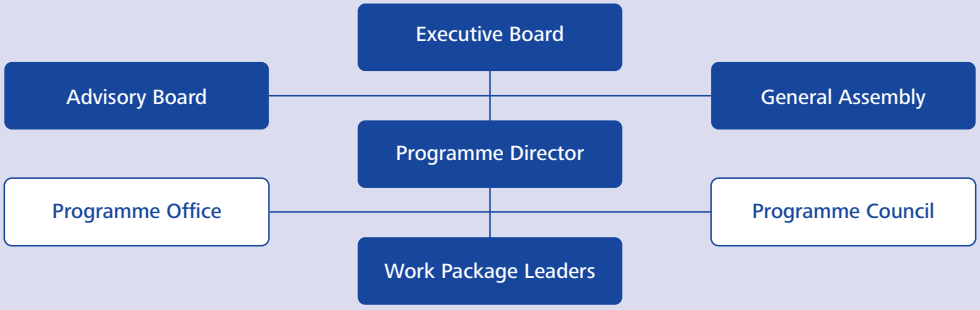
The programme's scope was defined at the start of CATO2 and built on CATO, which had already engaged industrial parties in the Netherlands. Like CATO, CATO2 focused on 'discovery, development and deployment', with a slight but essential shift towards the end of this technological chain.

At the start, specific new activities within this new scope were defined on the basis of earmarking of subjects by all relevant stakeholders. Only activities receiving sufficient support made it to the end list. This resulted in a Programme Matrix of Work Packages, defined within the five existing Sub-Programmes as mentioned above and covering the whole range of CCS knowledge (the X-axis of the Matrix). Meanwhile, the content of all these WPs together was to meet the actual demand from the pilot and demonstration sites and any regional preferences (the Y-axis).

Annual programme adjustments

Although this Matrix was defined for the entire duration of CATO2, the programme had to be flexible. A yearly revision allowed for adjustments according to newest insights and developments in CCS, for instance in establishing pilot and demonstration projects or in changing views from policy makers. The governance structure is also designed to annually assess any changes in activities against the background of fundamental science and technological application.

The top of the governance structure is the Executive Board, which is the highest authority and needs to sign off any final approval. However, any changes are proposed 'bottom-up'. Concerning updates of existing Work Packages, the WP leaders initiated them and discussed



| The way CATO2 has been governed.

them with the project stakeholders. The Programme Council gave advice on the scientific and technological consequences and advice on further improvement (if any). The Programme Office and the Programme Director provided their feedback on the practical implications like desired deliverables and budgets. Subsequently the updated proposals were sent to the General Assembly (in which representatives of all participating partners have a seat) and the Advisory Board for their advice, and brought to the Executive Board for final approval.

If completely new Work Packages were needed, this procedure worked a little bit differently. First the Executive Board decided what budget was available for a new proposal. Subsequently, all parties were allowed to submit their proposals. The Programme Council was again asked for advice and improvement, the Advisory Board was invited to rank the proposals and the Executive Board for a final decision based on this ranking.

Budget

Overall, CATO2 had a budget of € 61 million for the years 2009-2014. All CATO2 projects received a grant of 50% on all eligible costs, which in practice doubled in-kind and in-cash investments of all participants together. The CATO2 Programme Office received the grants and paid the respective partners on the basis of invoices accounting for their full efforts.

Three IP regimes

In an R&D programme where specific technologies are developed and prepared for a commercial phase, arranging the intellectual property is of high importance. As CATO2 is partly financed with public money, IPs are partly public and partly to the benefit of individual participants.

CATO2 recognises three IP regimes:

Public: information can be shared with parties in- and outside the consortium.

Restricted: information can be shared with partners within the consortium only.

Confidential: information may be shared with partners within the consortium to the level that allows all partners carrying out their part in the project. Parties will agree on a non-disclosure agreement (NDA).

The default status of CATO2 knowledge is restricted. This implies that publication of results outside the CATO2 community requires an explicit action, namely approval by consortium partners to change the status to Public. By default all Restricted documents become Public after 5 years. Information that has been classified Confidential cannot be shared between partners unless an NDA was signed. However, partners will have access to a public summary of that confidential information.

Two-way communication: linking CATO2 to the outside world

Additional to being an R&D programme, CATO2 has also been functioning as an information supplier, both internally for keeping the CATO research community up-to-date and externally for informing several broader audiences about CATO findings. The add-on sub-programme SP0 counted quite some successes in developing instruments and in balancing science outcomes with the broader public and political debate.

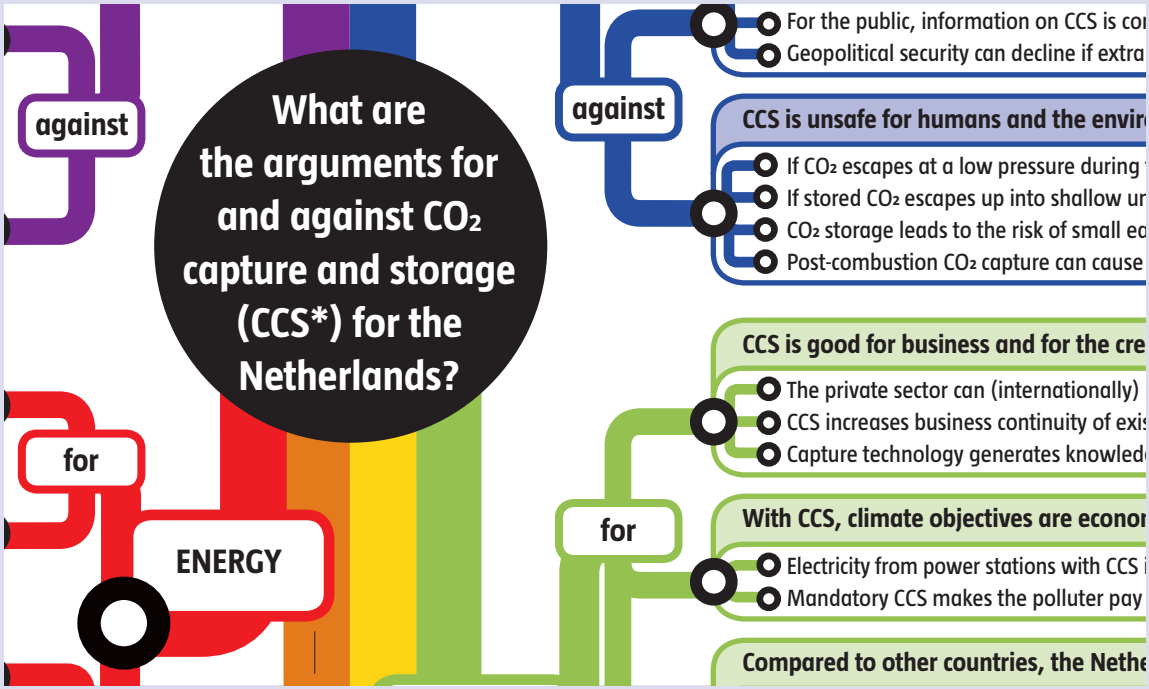
Internal communication is crucial for any business, and obviously fundamental for knowledge sharing in a broad R&D programme such as CATO2. SP0 has been crucial in 'lubricating' the CATO2 scientists into a well-running community and developed several instruments for that purpose. For instance, the (protected) CATO website has been a continuous source of information. Triggered by a daily news service (also by e-mail), all members of the CATO community have access to all completed reports, presentations and articles from their colleagues. With almost 40,000 page views in a year, the CATO2 website proves to be an important linkage between the CATO members.

In addition, CATO2 organised dozens of meetings, on different levels, in order to exchange sound scientific content while providing networking opportunities. Beside the regular meetings between coordinators at a programme governance level, other events were organised such as several meetings for the 40 PhD students within CATO2. These meetings served several purposes, like learning from each other, getting into contact with companies and social networking. Annually, some 100 people visited the CATO2 symposium in June each year and some 50 researchers attended the annual New Year's event.

Interface

The function of CATO2 as an interface between the outside world and CATO2 research was also considered important. Therefore, a lot of attention has been paid to two-way communication with different target audiences. Serving the CATO community, the focus was on getting information on the broader CCS developments in the world, such as in R&D, policy making and demonstration projects. For instance, the last four years have seen important changes in EU and national Member States policies regarding CCS and particularly demonstrations. Besides sketching the bigger picture, this information (a daily news service and a monthly review) also covered issues that were of specific interest to parts of the CATO2 programme.

CATO2 also organised events and workshops where specialists from industries, science and policy makers could meet and discuss CCS strategies and R&D results. In some ad-hoc cases, CATO2 also identified the need for deeper and balanced information within the public debate, especially during times where CCS made the newspaper headlines because of intended demonstration projects in Barendrecht, the Rotterdam harbour or North-Netherlands. By bringing scientists in contact with journalists, CATO2 managed to disclose a wealth of knowledge that was actually used in many newspapers articles and brought to the public. This was done both on an individual basis and in some events and CCS-related excursions attended by some representatives from the press. One example is the CATO2 excursion to the Eifel, where a lot of natural CO_2 occurs from volcanic activities. In 2011, this excursion resulted in several media articles that explained the relevance of CATO2 research. Another example is a workshop on the risks of nitrosamines emissions from capture plants (see also page 79). These



| Snapshot from The Argument Map (© Argumentenfabriek) for CCS, which pictures all relevant pros and cons of CCS. The full interactive Argument Map (in Dutch only) can be found on the CATO website: www.CO2-cato.nl; a pdf in English is available on the CATO2 website (bit.ly/ArgumentMapCCS).

emissions caused some public anxiety, which was countered and put into perspective by information exchange during this workshop.

Moreover, the public CATO2 website provides a lot of specialist CCS and CATO information translated into terms that the laymen public understands. Educational dossiers and Questions & Answers are a part of this public website.

Argument Map

Bringing more balance into the public and specialists debates on CCS was also the inspiration for several special communication projects within CATO. One bigger project concerns the 'Argument Map', which was drawn in a few brainstorm sessions by the CATO2 specialists guided by the Dutch Argument Factory ('Argumentenfabriek'). For the purpose of the public and political debate, the Argument Map (both in Dutch and English) lists all pros and cons of CCS and orders them in different categories such as 'Economy', 'Climate', 'Safety' and 'Ethics'. By deconstructing the arguments, the Map provides an insight in the backgrounds of CCS. In the online version members of the public can develop a clear view of their individual preferences, and thus weigh them against each other. This is exactly the opportunity that the websites of CATO2 provide to visitors: using the Argument Map in an interactive way. In addition, the Argument Map is available on paper and also got some attention from the daily press.

Other specific projects that combine CATO2 content with a strong communication component are the CCS Twister game (based on the classical Twister game) and the CarbonFuture simulation game, representing 'real life' issues in business strategies. This game takes into account

the impact of an emissions trading scheme and highlights the trade-offs for different players between profit and planet. Participants can win the game by becoming the energy or industry producer with either the lowest CO_2-emissions or the largest amount of money at the end. The game has been played at more than a dozen occasions, including at an international conference in Brazil.

International cooperation

Most of the research in CATO2 has been embedded in international cooperation, and in some specific cases CATO2 added some special elements to this 'working cooperation'. For instance, in 2010 CATO2 people and work played a major role in the Greenhouse Gas Technologies conference in Amsterdam. Back in 1989, this series of GHGT conferences started in Amsterdam, travelled around the globe and returned to Amsterdam to celebrate its tenth issue. Some 1500 people from all over the world attended. In 2013, at the occasion of the 11th GHGT in Kyoto, Japan, CATO2 filled a complete scientific journal with articles.

The CarbonFuture game – developed for communication purposes – simulates real life for a power plant or steel factory, against the background of emissions trading and changing rules. The participant with either the lowest CO_2-emissions or the largest amount of money at the end is the winner. Picture Floris Scheplitz.

The values of CATO2

Concluding CATO2 in 2014 does not only deliver on technological progress itself. Ten years of cooperation between science, business and authorities also had quite some value for all participants. Research by Utrecht University shows a coherent community around CATO2 that was able to increase CCS knowledge to the present pre-demonstration level. Observations about the scientific value are of large interest, also seen in the light of the Top Sector Structure that is presently being established focusing at making innovation work for the Dutch economy.

Valorisation of CATO-2 research

One important goal of a research programme like CATO2 is to create value for society, or in other words: valorisation of research results is of the essence. 'Value' can be new technology, new products or answers to important social issues. CATO2 has produced answers to important issues in companies and society, as can be read in the rest of the book. This knowledge was captured in papers, patents, reports and MSc and PhD theses. But in addition to and beyond physical products, value is also created in human and social capital.

Based on 32 interviews with 26 different parties, Utrecht University drew some general conclusions about the values of the CATO2 programme. This section is a summary of their views and opinions, which doesn't mean that there is no room for divergent opinions.

Public benefits

Until now, CATO2 delivered more than 700 papers, reports, articles, posters and presentations, which are in some cases available to the outside world. Apart from knowledge captured in reports and papers, the valorisation study recognises three different values:

Human capital (Experts): CATO2 produced experts in all relevant CCS fields. These experts don't necessarily stay in academia; they also support companies and governmental organisations.

Human capital (University teaching activities): CATO2 participants also contribute to teaching activities of universities through internships, connections with PhDs, lectures and workshops.

Social capital (Network): CATO2 created a network of people working on CCS, connecting the experts. The network facilitates finding information, discussing research topics and gathering data for research.

Benefits for consortium partners

In addition to the value to society, CATO2 offered specific benefits to the parties involved in the programme. Initially, reasons for participation were quite straightforward: looking for specific bits of knowledge tied to a practical project or willing to do research and offer this knowledge.

Additional benefits were sometimes recognised at the start, but became prevalent during the program, like:

Community: The programme has built a national CCS community. Researchers are connected to business, allowing easy contacting, gathering data and feedback. Also among PhDs and senior researchers a 'group sense' grew, reinforced by events such as the CATO days and symposia (see also highlight **PhD students: the backbone of CATO2** on page 58).

Overview of opportunities and barriers: The differentiated knowledge base provided all participants with an insight into CCS research and into opportunities and barriers for the implementation of CCS, on a wide range of topics. A major benefit was that the programme considers the entire CCS chain: not just technology, but also economics, legislation and public perception aspects.

Legitimacy: Participation in the programme by a great diversity of actors added to a more legitimate and credible image of CCS, at least as a field of research. This legitimacy was also important for the participating organisations.

Flexibility: The wide scope and length of the programme allowed for much flexibility in the selection and exploration of research topics.

Public engagement: CATO2 has taken a rather active role in the communication of research findings. Active participation of the research programme provided the general public with opportunities to engage with the subject.

Human resource pool: Access to the CATO2 network gave companies the opportunity to contact and even recruit people with a research background.

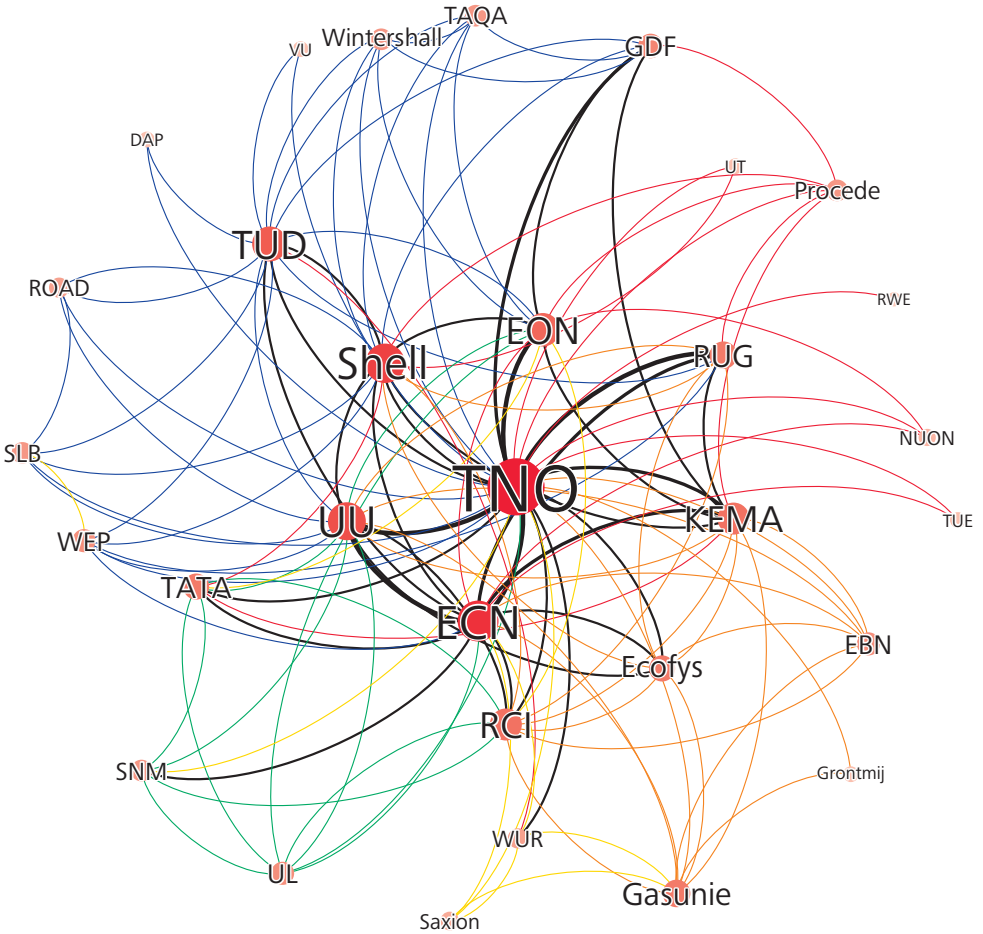
Shared facilities: In some cases partners used facilities from other partners, such as test laboratories and facilities.

The value of a network

One main achievement of CATO2 (following CATO) was the establishment of a Dutch CCS network (see the figure on the next page). A network analysis carried out by Utrecht University shows that connections between disciplines in the CATO2 programme cooperated on particular multi-disciplinary topics that resulted in deliverables, but they only rarely published scientific papers together. The research programme connected these separate groups by organising workshops and events (such as the CATO days) where different disciplines and organisations could share their knowledge.

The backbone of the network consisted of two types of people. *Coordinators* cooperated with many other participants within one topic, with a good overview of the content of the research (sub)programme. They were the person to go to if someone had a question about the topic. C*onnectors* worked on multi-disciplinary topics,

Some previous CATO publications for broader audiences.



| The network of organisations in CATO2. The lines represent contacts within Work Package teams, the colours the different subjects and the dots the CATO2 participants. Many contacts exist, focusing on about ten key players that are the 'spiders in the web'. Picture K.P.F. Broecks, Utrecht University.

transferred information between different disciplines and were able to come up with new and interesting ideas. Sometimes, connector and coordinator are one person.

The network played three major roles:

Coordinating research: A core group of organisations (mostly knowledge institutes and universities, some authorities and companies) were usually involved in multiple sub-programmes (SPs) and covered the coordinating tasks. They connected to a peripheral group with organisations that formed separate disciplinary groups with specific focus and often fewer interconnections.

Not all topics require the involvement of multiple disciplines. But in areas such as legislation or systems analysis this cooperation is vital. This requires connections between organisations that normally don't interact that much.

Translating research findings: The research programme played a role in translating research findings between disciplines and organisations. Different disciplines speak different languages, have different rules, routines and ideas. A translation is necessary to facilitate knowledge sharing, and this necessity particularly applies to translating the results to the bigger public. The research programme facilitated knowledge sharing by asking the participants to translate findings into common formats that a bigger audience can understand. C*onnectors* with a multi-disciplinary background were placed on key positions in the network.

Connecting individuals and organisations: Another important role of the network consisted of the professional interrelations between researchers, allowing any researcher to pin-point any other knowledgeable individual on a subject. This contact may be instrumental to answering specific questions, providing feedback or data gathering.

As the overlapping structure, the CATO2 research programme facilitated the development of a network and maintains connections. The programme thus played a major role in coordinating research topics, translating research findings and connecting individuals and organisations.

Lessons learned

Besides the achievements in terms of innovations, the UU study also reveals some lessons learned about possible bottlenecks for creating value. These lessons may be of value to future research programmes.

Multidisciplinary research: Effectively uniting different disciplines in multidisciplinary research requires mutual understanding and even a shared language. This takes a lot of time and effort. CATO2 was quite flexible in adjusting research along the way. Acknowledging all different views and reserving time for aligning interests in an early stage would speed up this process.

Knowledge dissemination: Evidently, participating organisations have a quick access to CATO2 knowledge. Concerning the outreach to public actors such as governments, environmental organisations and the public, some participants expressed that CATO2 could even improve its dissemination of knowledge.

Coordination of research topics & focus: The programme coordinated the research within its structure of working packages (WPs) and sub-programmes (SPs). Within CATO2, pilot and demonstration projects (in particular their location managers) were expected to improve the inter-WP cohesion, but most of these projects were delayed or cancelled. A challenge remains in finding an alternative coordinative structure.

Connecting different viewpoints: Depending on their background, partners obviously have different preferences for the length of research programmes, the focus on practical versus scientific issues, public engagement and its governance structure. Connecting these different viewpoints is challenging and will prevent dissatisfaction among partners.

External events: Changes in government policies, public opinion or energy prices affected CATO2. Changing commitments forced shifts in the focus of research, in which CATO2 proved to be very flexible. A clear roadmap for future development will account for uncertainties due to such social developments.

HIGHLIGHT

PhD students: the backbone of CATO2

In addition to the applied research issues, a considerable part of the CATO2 R&D programme concerns fundamental research, resulting in PhD theses at Dutch universities. By including some 40 PhD students in its community, CATO2 has generated a lot of knowledge. At the same time, by providing the opportunity for this PhD research, CATO2 lays a sound foundation for further CCS knowledge development with a new generation of scientists, working on CCS innovation in the Netherlands and abroad.

Being a part of a coherent, multidisciplinary R&D programme such as CATO2 seems to be a stimulus for PhD students in several ways. For instance, the rate of CATO PhD students that actually failed a thesis has been 0% up till now, which compares to the average failure rate of about 10% in the Netherlands. Also, experience with the preceding CATO programme has proved that many PhD graduates stay in the field of CCS for at least a couple of years. Obviously, CATO research is an incentive for further exploring career opportunities in CCS.

| Exchanging ideas and results was the central issue of several CATO2 meetings for PhD students in a year. Picture Floris Scheplitz.

PhD studies within CATO2 have been very much differentiated, with an even distribution among the different topics and sub-programmes, while also ranging from fundamental research to applied research, from very technical to socio-economic and social science. CATO2 put much emphasis on its multi-disciplinary character by organising several occasions a year where PhD students met, socialized and exchanged experiences and results of their research.

Moreover, almost every student has been linked with one or two CATO2 participants from industry. This resulted in a natural contact with industry, raising issues like: "What is the relevance of your R&D to the bigger picture of development, economy and industry?" Likewise, such contacts allowed the PhD student to use data from industry, which are often confidential and usually hard to get.

From a longer-term perspective, this generation of PhD students is also promising because it is the backbone of the future design, decision-making and implementation regarding CCS. The present PhD graduate who has a career in CCS could be the condensation nucleus of future commercial CCS activities, for instance in industry or as a policy maker. Anyhow, the coherent and integrated nature of the CATO2 programme has familiarised them with the interfaces between science, application, policies, public perception, government and industry.

PART II
The Science of CATO2

Summary for policy makers

In the second part of the book, you will find an extensive impression of the results and innovations that CATO2 research and development have achieved. CATO2 intended to prepare for large-scale demonstration of CCS. Despite the lack of such a demo at the moment of publication of this book, the overall conclusion is justified that CCS is ready for such large-scale demonstration. CATO2 reached up to the level of small-scale pilots; at present, demos are required to check the findings of research and development. Here are five years of CATO2 in summary.

Summary for policy makers

CATO2 covers all technological, economic and social issues that are relevant to CCS. For a well-coordinated and differentiated approach, CATO is divided in five sub-programmes, interlinked by the Programme Office:

- CO_2 Capture (SP1)
- CO_2 Transport and CCS chain integration (SP2)
- Subsurface storage of CO_2 and monitoring storage (SP3)
- Regulation and safety (SP4)
- Public perception (SP5)

This section will briefly introduce the main findings per sub-programme in short. The second part of the book will list these results much more extensively, while interested readers will be able to dive further into the science guided by the public literature listed in the section For further reading.

SP1: Capture: reduce costs, improve and demonstrate performance

Capturing CO_2 for the purpose of reducing greenhouse gas emissions at industry or power stations is still a young technology. As capture represents a large part of the costs in the whole CCS chain, cost reduction is the main challenge here. In this respect, CATO2 made considerable progress by improving existing processes and developing next generation technologies.

The main costs of CCS concern the so-called 'energy penalty': capturing CO_2 requires a lot of heat, which decreases the overall energy efficiency of a process. For instance, in a gas-fired power station the overall gross electrical efficiency, normally around 60%, decreases to less than 50% when applying e.g. chemical absorption. This implies higher power costs and lower capacity.

CATO2 research and development have reduced the costs of capture with a ballpark figure of around 20%. Several R&D activities have been instrumental to this, such as optimising the process by using better modelling. The existing modelling programmes used to lack the proper data, e.g. on chemical properties of the capture solvent

or on health and safety aspects. CATO2 lab and pilot experiments solved this issue for at least a large part. However, model results still need to be validated in long-term demonstration projects.

Basically, three types of capturing methods exist: preventing CO_2 emissions by taking out the carbon from the fuel before burning (pre-combustion); taking out the CO_2 from the flue gases after burning (post-combustion); or creating a CO_2-rich flue gas (ready for storage) by using pure oxygen for combustion of fuels (oxyfuel). In all three variants, CATO2 investigated and developed new processes and combinations of processes. Although it will take some time to bring these new technologies to the market, this research will eventually lead to a wider choice of opportunities for application in demonstration projects or commercial capture. In addition, CATO2 paid significant attention to health and safety aspects of capture processes.

SP2: Integrating the CCS chain

Most of the individual elements of CCS (capture, transport, storage) were already in an advanced stage of development, but CATO2 achieved much progress by linking these elements together and matching CCS chains with the energy system and in the economy. CCS is ready for further system optimisation and for strategies to pursue large-scale implementation.

Capturing, transporting and storing CO_2 may seem rather straightforward, but linking separate CCS elements (capture, transport, storage) to an effective and efficient chain is not trivial. Even at a small scale, applying CCS requires matching different worlds. For instance, building a CO_2 capture unit at a power plant means that chemical engineers enter the domain of electrical engineers.

The picture becomes even more complex in the case of large-scale CCS in industrial and energy clusters. These clustered CCS projects require linking multiple industries via one or more forms of transport to different storage sites. On a next level, the integration of CCS infrastructure into energy and industry systems and markets raises technical and economic challenges.

Given this complexity, designing and operating CCS chains needs a system approach of technologies and organisation: in terms of technologies, efficiency, economics, safety and legislation. For instance, how will CCS technologies interact with the power system, where security of supply and flexibility are prerequisites? What are the costs? How does CCS interfere with industrial production? CATO2 assessed solutions for connecting the different parts of CCS into a consistent chain and identified the best techno-economic options as well as the practical issues that would need to be solved for implementation.

As a part of this puzzle, CATO2 dedicated quite some research effort to understanding the connective piece of 'transport'. CATO2 investigated the technical and safety aspects of transport of CO_2, the way the infrastructure needs to be organised. This research ranged from technical questions about the behaviour of CO_2 in the pipelines to optimisation methods for the infrastructure that links clusters of CO_2 sources to various sinks.

Large-scale implementation of CCS will meet different barriers in time. Particularly the integration studies within CATO2 explicitly take into account the dimension of time, differentiating between the requirements between the short term (2015-'20), the medium term ('30) and the long term ('50). Roadmaps and local and (inter)national strategies and roadmaps resulted from CATO2 work, designating the possible role of different stakeholders and institutions and opportunities for The Netherlands.

SP3: Exploring the subsurface for reliable CO_2 storage

In the Netherlands, underground storage of CO_2 largely implies: using depleted gas fields, both onshore and offshore. Built on the data available from natural gas production, fundamental and applied CATO2 research has increased the knowledge to a level that it can be applied in practice.

Regarding underground storage, CATO2 had the objective to demonstrate technical feasibility. The most important R&D work concerns increasing the knowledge on injection and storage, exploring safety issues and developing a sound monitoring of CO_2 injection and storage. For this purpose, sub-programme 3 Storage (in close cooperation with other SPs) joined together the forces of a broad range of science disciplines such as geology, geochemistry, petrophysics and geophysics, geomechanical engineering, mathematics and reservoir engineering.

CATO2 built on the extensive knowledge about the subsurface that was collected along with the production of Dutch natural gas over the last 50 years. The presence of many smaller, almost depleted gas fields justifies the priority in CATO2 research to study such fields and makes the Dutch situation quite unique. In addition, also research on (geothermal) aquifers, coal seams and CO_2-enhanced oil/gas recovery was performed.

During the last decade, several Dutch locations have been identified and investigated as opportunities for demonstrating injection and storage. Although most sites were cancelled as a candidate for CCS demonstration, the preparations of these demos yielded much knowledge. In general, research and experiments have provided a much better understanding of the geological and mechanical processes in the subsurface, and hence of the stability and the safety risks of CO_2 storage.

Various (geo)physical, geochemical, biotechnical and remote sensing techniques have been developed and implemented as CO_2-monitoring tools, both for shallow and deep sub-surface geology, for pre- and post-injection time spans and for onshore and offshore fields.

SP4: Effective legislation and quantified risks

When the EU issued its Directive on CCS storage in 2009, the impact on the Dutch situation was largely unknown. Based on analysis, models and data, CATO2 research delivered knowledge on how Dutch regulation and permitting procedures can become compatible, safeguarding that applications along the CCS chain (including capture and transport) will be safe for humans and for the environment.

Without a considerable track record, especially in storage, CCS stakeholders and authorities are in need of transparent rules, based on the right information. The CCS Directive (2009/31/EC) on geological storage is the foundation of legislation for storage of CO_2 across the EU. It covers all CO_2 storage in geological formations in the EU, during the entire lifetime of a storage site. Also, the Directive lays the foundation for standards and criteria for storage site selection, in order to prevent significant risks or to remediate adverse effects. However, its actual impact on national legislation still had to be found out.

With the EU CCS Directive as a starting point, CATO2 contributed to painting a clearer picture of regulatory storage issues by:

- Analysing and providing recommendations for an effective regulation design, based on EU legislation;
- Providing recommendations for practical ways of putting national regulation and licensing procedures into practice;
- Clarifying the rules for site operators;
- Quantifying the risks.

The research and development were executed within sub-programme 4 for Regulation and Safety, with an interface to the data and knowledge from other sub-programmes. Research institutes and academia led the research, with considerable input and advice from industry and authorities. Also, international links to developments abroad have been crucial. In addition to the storage issues, also capture and transport asked for specific knowledge and legislation.

With respect to regulations, CATO2 kept in mind that regulations are not only for authorities. Regulations also guide project developers and other stakeholders on how to design their installations. Moreover, a sound and clear set of regulations is a prerequisite for public acceptance of CCS.

SP5: Understanding public attitudes, perceptions and misconceptions

Understanding the mechanisms that determine the attitudes, perceptions and sometimes misconceptions of the public is key for every stakeholder. CATO2 combined quantitative and qualitative research to get more insights into public perception and the role of knowledge, experts and expertise, the decision-making process, communication frames, community compensation and many other factors.

As with any other technology with considerable impact and large investments, CCS projects have to deal with public opinions. If CCS is ever to play a major role in the energy and industry systems, knowledge about public perception and its underlying factors is important. CATO2 research provides more insight into the mechanisms and trends in public knowledge, awareness, perception and opinion about CCS.

CATO2 research not only delivered on different elements in public perception of CCS, but also on misconceptions. Adjacent to this, the effectiveness of communication strategies was investigated. Likewise, local decision-making was examined. One special topic – also interesting for other sectors and technologies – involved the possible role of compensation for local communities.

Whereas public awareness of CCS has grown in the past years, the general public's level of knowledge of CCS, climate change, the energy system and the role of CO_2 remains low. Few people understand how much fossil fuels are still used in the Netherlands and how this links to climate change.

Research into the mechanisms between knowledge, perception and opinion shows that public opinions on

CCS are not necessarily and solely explained by the level of knowledge or by misconceptions. These studies revealed how opinions are built up from perceptions and arguments. This information provides a good starting point for information and communication, but also challenge the assumption that fighting 'illiteracy' on CO_2, climate change and CCS will necessarily make people more positive on average about CCS. When well-informed, the Dutch public proves to be more in favour of energy efficiency, offshore wind energy or biomass.

Regarding the occurrence of local opposition, research provided the insight that several social, institutional and political dynamics also play a role in how CCS is perceived. The actual cases of Barendrecht and North Netherlands added some interesting contributions here. In Barendrecht for instance, perceptions of the 'democratic procedure' that was followed proved important, in addition to the perceived safety issue related to CO_2 leakage.

Research also identified several pitfalls in the communication about CCS. An important recommendation for companies is: Create trust by connecting your message to the actual goals of your organisation and preferably not by sending messages that may be perceived as 'greenwashing'.

The offering of compensation to local communities may help to create a fairer distribution of local risks and benefits, and in this way has the potential to prevent or solve siting controversies. CATO2 compensation research delivered fundamental insights in factors that would matter for project developers and authorities in offering effective compensation regimes.

CATO2 research provides knowledge that can be applied in actual projects, by stakeholders such as (local) authorities, companies, project developers, NGOs and local residents. No blueprint or decision tree is supplied, but it provides dos and don'ts, building blocks, lessons learned and clues how to be credible and trustworthy in public debates and public policy-making processes. These building blocks can be applied in information and communication campaigns and in decision-making regarding CCS, and are also interesting for stakeholders in other sectors and technologies.

Capture: reduce costs, improve and demonstrate performance

The basic technologies for separating CO_2 from gases have been applied for decades, for instance in cleaning natural gas from CO_2-rich sources or in hydrogen production. However, capturing CO_2 for the purpose of reducing greenhouse gas emissions at industry or power stations is still quite a young technology, facing some large challenges. Cost reduction is the main challenge, because capture represents a large part of the costs in the whole CCS chain. In this respect, CATO2 made considerable progress, by improving and upscaling current processes, supporting the preparation of demos and developing next generation technologies.

Cost reduction: where's the potential?

The main cost of CCS using post- combustion capture, measured in € per tonne CO_2 or € cents per kilowatt-hour, lies in capturing the CO_2. A large-scale amine-based post-combustion capture process at a coal-fired power plant requires significant investment costs. However, operational costs dominate. Typically, 70% of the total costs originates from the operational cost. This is due to the high energy demand of the first generation systems for the regeneration of the amine solution. The use of steam for the regeneration leads to a reduction of the power plant efficiency, the so-called 'energy penalty'.

Basically, this penalty is caused by the fact that CO_2 first has to be absorbed from the flue gas by a chemical compound, and then in a subsequent desorption step the CO_2 has to be released from the compound again. For this de-sorption a lot of heat is needed, which is generally supplied in the form of steam. When applied to capture of CO_2 from power station flue gases, the overall gross electrical efficiency decreases (e.g. from 57 to 46%), resulting in an 'energy penalty' of in this case 11%-points. As an effect, the power plant has become significantly less efficient, resulting in a higher cost of power generation and lower capacity.

Four years of CATO2 research and development have reduced the costs of capture with a ballpark figure of around 20%, or in terms of the energy penalty in the power plant mentioned above: from 11 to below 9%-points loss in efficiency. This reduction has been confirmed in models, experiments and pilots. To deliver the ultimate proof that this reduction will really be a fact, full-scale demonstration is needed.

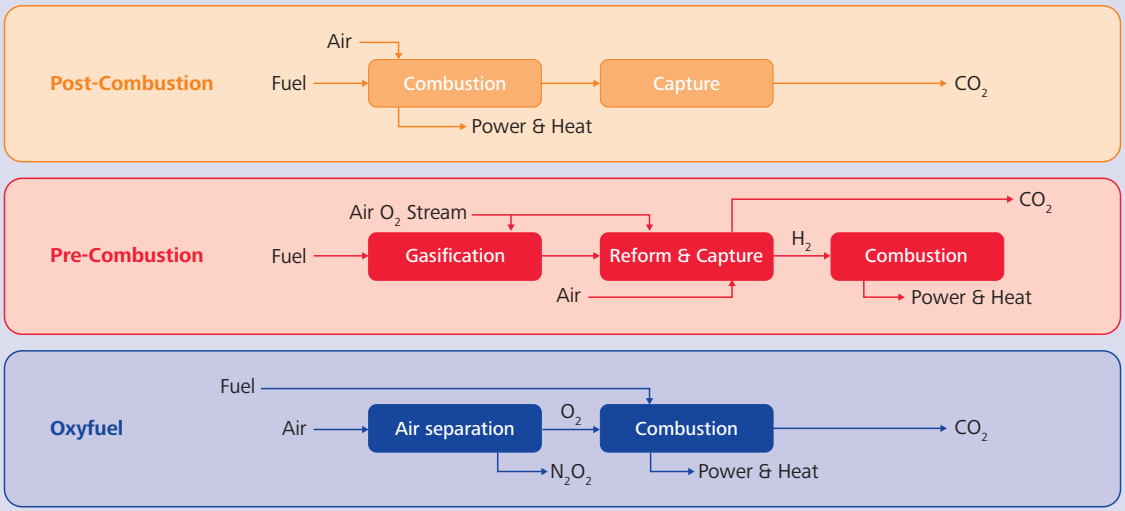
Experimental data to improve modelling

There are many factors that determine the costs, for instance the thermodynamic and chemical properties of the solvent and the equipment that is used. CATO2 paid considerable attention to characterising the solvent: how easily does it bind the CO_2 and release it again, what are other features with respect to safety and health aspects, toxicity and corrosion?

Three capture methods

There are three basic methods for capturing CO_2 from processing fossil fuels (in combustion or in chemical processes):

- **Post-combustion**: capturing CO_2 from the flue gases after the combustion process;
- **Pre-combustion**: extracting the carbon in the form of CO_2 from the hydrocarbons, before the hydrogen will be combusted.
- **Oxyfuel** solutions: by using pure oxygen (O_2, captured from the air), combustion of hydrocarbons provides only water and almost pure CO_2. Limited separation is needed before storing it.



Picture TNO.

CATO2 paid even more attention to optimising the whole process, because of the large opportunities in cost reduction. This work started with lab experiments, followed by a scale-up to pilots where processes are tested for a longer period of time, up to some months. By performing pilots under realistic circumstances, also characteristics concerning health, safety and environment (HSE), wearing out of the solvents and corrosion can be included in the results.

Performance of capture technologies cannot be evaluated without considering the technology it is applied to. Combining a capture technology with a power plant also requires physical modification and changed operation for the power plant. Because of these interactions, CATO2 evaluated the overall performance of capture and power plants, next to the energy requirement of the capture technologies itself.

These data were used in detailed modelling of the capture process. Nowadays, many chemical industries use complex modelling programs such as ASPEN for designing their processes and optimising them. These models cover thermodynamics, chemical reactions and other fundamental features of any process. Similarly, for modelling power generation cycles, modelling programs

such as SPENCE, Thermoflow and Modelica are used. But when it comes to capture processes, these models fall short, simply because the models did not have enough data input to cover these processes. CATO2 largely solved that issue, as experiments and pilots provided many relevant data. These data are the foundations under validated, accurate process and economical models, ready for use by designers and operators of capture plants. Also, the models for power plant and capture plant have been connected in order to optimise the efficiency of an integrated power plant and capture plant. Both power plant and capture plant models have been improved and extended to include dynamic effects such as start-up and shut-down procedures, both for post-combustion and pre-combustion capture technologies.

Matured processes

The planned ROAD demo in the Rotterdam harbour was in more than one way inspirational for this kind of research, even more so when the project increased its envisioned capture capacity, covering the equivalent flue gases of 250 MW instead of 50-100 MW). 'First-generation' capture technology is now ready to be applied on such a large scale.

The modelling and the underpinning data from laboratory and pilot plant investigation provide good confidence in the first generation post-combustion capture process, which culminates in a high accuracy in estimating the costs: 50 to 60 €/tonne CO_2, with a 25% margin. Figures with such accuracy are quite comparable to ball park figures for other CO_2 capture processes.

A higher accuracy and more certainty can only be achieved with very long test runs in pilots or demonstrations, for many years. Test campaigns of this size are a 'missing link'; they will fine-tune the figures, for instance regarding the lifetime of the solvents, any contamination of the solvents by impurities or other long-term effects. This type of data will provide even more accuracy.

Next generation solvents and processes

The perspective for next generation solvents and processes is encouraging, but their distance to commercial application on a future CCS market is still quite far away.

Within CATO2 research, the next generation technologies are an important topic. A considerable number of PhD students are working on different aspects. New combinations of solvents, and processes, the use of phase change solvents, adsorption and maybe even enzymes may hold the promise of capturing CO_2 at relatively low energy penalties (see also highlight **Developing a new low-cost capture technology**, on page 74). Another example of a new generation system is pre-combustion capture using hydrogen permeable membranes. By selectively separating hydrogen during the decarbonisation of the fuel, a significantly higher efficiency can be obtained.

Post-combustion

Post-combustion capture has been a major subject in CATO2 capture research, especially directed by the planned ROAD demonstration plant in Rotterdam harbour. For the same reason, capture combined with coal combustion received the most attention. CATO2 research considerably contributed to knowledge that made the ROAD technology ready to start up. In addition and with an eye on the future in Dutch power generation, also CCS with natural gas combustion was subject of research, given the importance of natural gas as an energy source in the Netherlands.

The applied post-combustion research focused on optimising processes and integration with the power plant, instead of optimising solvents. This choice was justified because of the bigger opportunities for improving the business case – which was proven by the result of 20% reduction of the energy penalty – and also because process improvement is more or less complementary to the effort into the development of solvents being conducted abroad.

Pilot measuring campaigns of typically one month revealed many data on the performance of different types of solvents. The experiments focused on the thermodynamic conditions (pressure and temperature) that determine how much and how fast solvents can absorb CO_2, and especially how much and how fast the CO_2 can be taken out again with the regeneration of the solvent. Also the dynamic behaviour and the operational flexibility within the power plant and capture plant are key components, because processes should easily be adjusted, switched on and off, without large problems or large energy use. CATO2 developed knowledge and operational concepts to minimise the energy consumption and solvent emissions.

At the start of CATO2 in 2009, demonstration projects were intended to be established around 2015. Obviously, the delay in the planning is the main reason why CATO2 did not meet some of its initial goals. But while scaling-up was postponed, research in mini-plants in the laboratories and in some pilots provided even more results and, therefore, delivered the progress.

The CATO CO_2 Catcher pilot plant, launched in 2008 at the E.ON coal-fired power plant in Rotterdam Maasvlakte, was crucial for the applied research in post-combustion capture. This pilot plant can be regarded as a predecessor of ROAD. In this installation 250 kg CO_2 per hour is captured from flue gases, testing different solvents and different process modifications. Since the launch, the CO_2 Catcher pilot operated for more than 6000 hours.

Other emissions

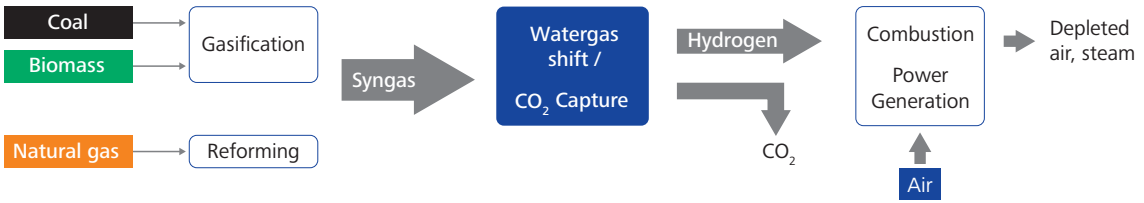
Besides looking for efficient processes, solvent degradation and emissions are important issues, not only for operational reasons, but also as a part of the overall environmental performance of CO_2 capture. Especially in coal-fired power plants, capture does not only reduce emissions that affect the climate, but also reduces other damaging emissions, such as sulphur oxide and small particulates. Meanwhile nitrogen oxides emissions largely stay at the same absolute levels, which means they increase relative to the amount of power produced.

CATO2 research also bumped into unexpected and unforeseen subjects, but proved to be flexible. One illustrative example of CATO2's flexibility was the nitrosamine question that received major attention from the large Mongstad CCS demonstration project in Norway. Nitrosamines originate from the amine solvents and are a product of atmospheric reactions between amines and nitrogen oxides or from a side reaction between nitrogen oxides with the solvent itself. Some of these nitrosamines can be carcinogenic. Testing at the CATO CO_2 Catcher proved that the levels of nitrosamines were extremely small. Based on the toxicity data available, the possible emission levels of nitrosamines are several orders of magnitude below the maximum emission thresholds that are allowed.

Experiments within CATO2 showed that nitrosamine emissions are not a real hazardous threat within the conglomerate of HSE (Health, Safety and Environment) issues. Normal cleaning of flue gases will reduce emissions practically to zero, and anyway far under legal standards or hazardous levels. The conclusion may be justified that the Mongstad project lacked some knowledge. This missing information may have inspired authorities and operators to stay on the safe side. Last year, the large-scale Mongstad project was completely cancelled for economic reasons.

Pre-combustion capture

When the CATO2 programme started, particularly in the Netherlands capturing the carbon components before combusting the fuels was a technology with good perspectives, with maybe even good chances in export. The 250 MW integrated gasification combined cycle (IGCC) plant in Buggenum, Limburg, was seen as a first-of-a-kind of many IGCC plants elsewhere. The Magnum power plant that is planned in the Eemshaven (North Netherlands) was originally intended to be built as a



Schematic representation of the watergas-shift reaction that leads to pre-combustion CO_2 capture.

multifuel IGCC. CATO2 was involved in preparing CCS technologies, ready for take-off.

Pre-combustion capture works differently from post-combustion capture. In pre-combustion, the capture and basic processes in the power plant are much more integrated than in post-combustion, where capture is more or less at the end of the pipe. The capture process takes place early in the power plant processes, namely right after the gasification of the fuel, and before the combustion and steam generation processes that generate the power. Consequently, retrofitting a power plant with pre-combustion CO_2 capture is less attractive.

In an IGCC power plant, the gasifier basically produces syngas from hydrocarbons like coal or biomass. The syngas primarily consists of hydrogen and carbon monoxide. Two modifications are needed to include pre-combustion CO_2 capture in an IGCC power plant. First, a catalytic water-gas-shift section is needed. This section includes a water-gas shift reactor to convert CO with steam (hot H_2O) into H_2 and CO_2. Second, the resulting H_2/CO_2 stream needs to be cooled down and sent to a $H2/CO_2$ separation unit. Here, a physical solvent absorbs the CO_2, and the hydrogen is used as a fuel in the gas turbines. After drying, the remaining CO_2 is ready for transport and storage.

In CATO2 two innovative pre-combustion technologies have been developed and improved, with the aim to make the processes more efficient and meanwhile to reduce capture costs.

Developing the ideal palladium membrane

Similarly to the post-combustion route, pre-combustion capture processes also gain a lot from fine-tuning and technological detailing. In this case, the use and performance of membranes are essential to efficiently 'shift' the reaction towards the end products CO_2 and H_2. CATO2 research covered the whole chain of technological development of palladium (Pd) membranes, from fundamental testing to long-term testing in a specially designed Process Development Unit (PDU). Models for designing membrane reactors have been developed, while several Pd membranes from different membrane manufacturers have been tested. The PDU, already constructed in CATO, has also been used in many international projects for long-term testing of membranes.

CATO2 united many key players in the field of Pd membrane development in a benchmark exercise, comparing the usefulness of different Pd membranes for pre-combustion CO_2 capture in natural gas fuelled combined cycle power plants (also known as NGCC plants). The present status of this technology justifies demonstration at the larger scale, necessary for subsequent scaling-up to (pre)commercial capacities.

Breakthrough in the reduction of capture costs

An important breakthrough in capture cost has also been accomplished with a new process for CO_2 capture in an IGCC power plant, which can also be applied in industrial processes such as the Blast Furnace Gas fuelled combined cycle such as the IJmond 1 power plant in the Netherlands. The Sorption-Enhanced Water-Gas Shift (SEWGS) technology integrates the water-gas-shift step with a hot CO_2

separation step using a solid adsorbent, which leads to considerable efficiency improvements of the entire CO_2 capture process. The adsorbents are essentially alkali-promoted synthetic clay-like materials, and the tonne-scale production by a commercial manufacturer has been realised in the CATO2 program. A new sorbent discovered in CATO2 (Alkasorb+), together with process optimisation, led to a 50% smaller loss of efficiency (the so-called energy penalty') and a 40% cost reduction. In four years of lab work, the development of SEWGS technology has progressed to the stage that it is ready for scale-up and validation in a pilot plant.

Overview of the installation for researching the SEWGS innovation for pre-combustion capture of CO_2. Picture ECN.

Oxyfuel developments

Since the cancellation of the SEQ demonstration project in Drachten (Groningen, N-Netherlands) in 2008, oxyfuel development for the short term did not have a large priority in CATO2 work. This provided the opportunity to do research on oxyfuel subjects that still are distant from the market, but hold a promise for the medium term (beyond ten years from now).

Such a promising option is chemical looping combustion (see also highlight **Chemical looping combustion** on page 77). In short, this possible breakthrough technology is based on using an oxidised solid metal to react with a fuel (e.g. syngas, natural gas) to produce CO_2, water and (solid) metal, like nickel or iron. The water can easily condensate from the flue gas, which leaves a CO_2 stream that can be utilised or stored. The metal is oxidised again and returns to the combustion loop.

The working principle for this chemical looping combustion has been proven in practice, for both gaseous and solid fuels. Basically, efficiencies larger than 50% can be achieved, while producing a mixture of CO_2 and water. The capture of CO_2 from this off-gas is fairly straightforward. However, the technology is still at the start of its development. Many features still have to be figured out. For instance, how do streams of heat from the oxidation combine with the actual power generation in an optimal way? How would a reactor based on this principle work, including the tuning of valves, in order to achieve sufficient efficiencies? What capacities can be achieved?

Choosing the adequate capture technology

A wide range of opportunities exist for combining capture technologies with industrial or power plants. Within CATO only, some 100 cases have been studied. How to choose the capture technology that is best suited for a plant?

DNV GL (the former KEMA) developed a methodology for benchmarking capture technologies (post-combustion, pre-combustion or oxyfuel), linking them to the desired

application in a power or industrial plant. The structured approach of a technology assessment facilitates the decision-making process to find the optimal technology for decarbonizing the power industry or industrial activities. For instance, the methodology has been supportive to designing and preparing the ROAD project.

The focus of the methodology is on energy performance, as this is a main cost feature in the operational costs of CO_2 capture. As an input, different parameters and performance indicators of the technologies are used. Also the desired conditions are included, such as a sufficient quality of the resulting CO_2, ready for storage. The method is applicable across many levels of maturity, and can deal with limited or not very accurate data of the (technical) performance of capture technologies. Also, the multiple insights contribute to further development of a capture technology.

Health and safety

Health, safety and environment (HSE) measures are an important aspect of the different capture processes, the transportation and the storage of CO_2. This is important because of the costs incurred for taking the necessary countermeasures. A separate part of CATO2 research was dedicated to the impact of post-combustion CO_2 capture and transport on human health (toxicity) and the environment (ecotoxicity). Until recently, sound impact data were sparse. This research, coordinated by Shell within the CATO2 framework, aimed at two specific hazards: the impact of CO_2 itself, e.g. in case of leakage, and the impact of by-products from the capture processes.

Regarding CO_2, much more data have been acquired from experiments with rats and with humans (volunteers). At the time of writing this book, two scientific articles have been submitted about these experiments. The general conclusion may be drawn that dangerous effects with people do not occur with concentrations under 10% CO_2 in air and exposure times of less than an hour. The other side of the spectrum is that rats start to die when CO_2 concentrations exceed 40%. The last CATO2 year will pay special attention to the zone between 10 and 40% CO_2 concentration in air, to define more precise at what level concentrations start to become dangerous (see also highlight **Post-combustion capture: from lab towards implementation** on page 79).

The HSE studies regarding health impacts of by-products of capture concentrates on nitrosamines, which originate from using amines in the capture process are limited and data are few. Hence, guidelines for nitrosamines originating from post-combustion capture were based on the most potent and toxic nitrosamines (N-Nitrosodimethylamine, NDMA) in order to stay on the safe side.

First, nitrosamines are not that exotic. They show up in several food products, especially in baked or smoked food products, and for instance in tobacco smoke. CATO2 investigations show that most nitrosamines originating from capture (in the process or in air) are less potent than NDMA. In more detail, carcinogenic and ecotoxic impacts have been scrutinised. Among other results, it was found that nitrosamines quickly break up under the influence of ultraviolet light. This limits the influence of nitrosamines in the surroundings of a capture plant. Overall, health risks from nitrosamines substantially stay under the normal Dutch health risk threshold.

HIGHLIGHT

Developing a new low-cost capture technology

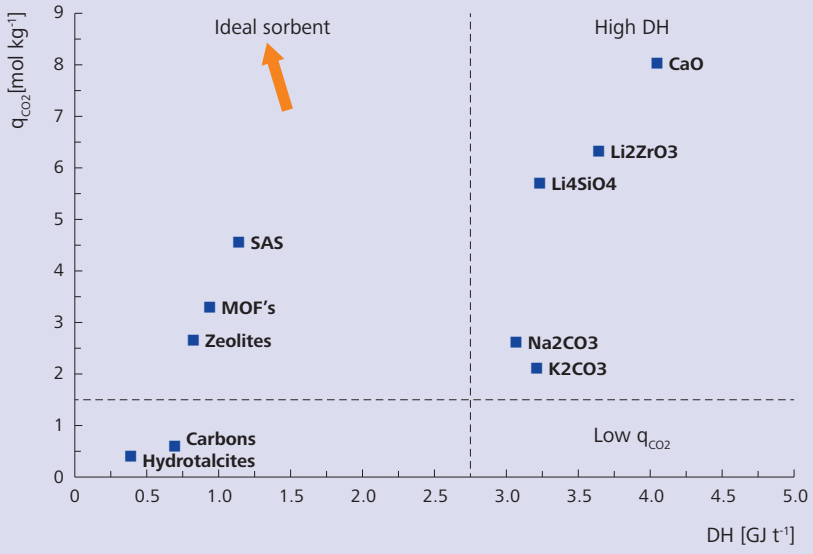
Calculations predict that using the current state-of-the-art technology in CO_2 capture and storage at power plants results in a 35-80% increase in the production costs (part of the market price) of electricity. This increase is mainly attributed to the high costs of CO_2 capture. Therefore, the development of a more cost-effective capture technology is a main objective of CO_2 capture research. Applying newly developed solid sorbents may offer a low-cost capture technology.

The conventional capture process utilises a mixture of amine molecules, typically MEA, and water to selectively absorb CO_2 from flue gases. Already at low temperatures, CO_2 dissolves in this absorption liquid (or solvent). By bringing the CO_2-containing gas in contact with this solvent in an absorber column, the absorption liquid 'captures' the CO_2. Subsequently, the liquid with the dissolved CO_2 is transported to a second column, the desorber. Here, the liquid is heated, which causes the solvent to release the CO_2 again. This supplies a stream of pure CO_2, which is compressed and stored, while the regenerated solvent is pumped back to the adsorber column to capture more CO_2.

The main cost driver of the process is the high energy demand, mainly associated with heating the aqueous amine solution from the absorption temperature to the desorption temperature.

From absorption to adsorption

One particular piece of work in CATO2 aims to develop a new capture process with a lower energy demand than the conventional process. The idea is to replace the liquid solvent by a solid sorbent. In chemical terms, this is equivalent to changing from absorption (to a liquid) to adsorption (to a solid).



Plot of the CO_2 adsorption capacity at post-combustion conditions versus the desorption heat for the most studied CO_2 sorbents.

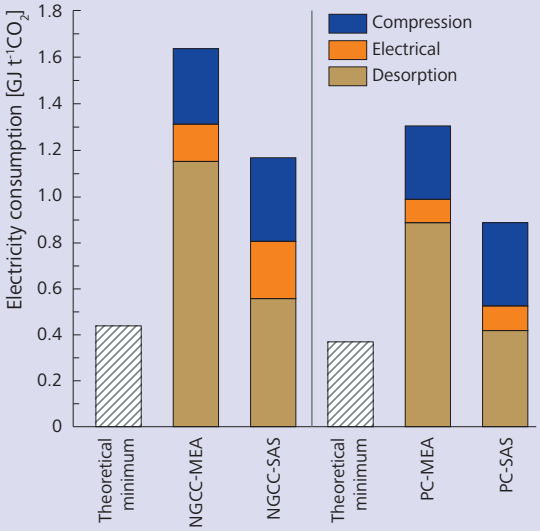
Switching from an aqueous solvent to a solid sorbent will greatly reduce the energy required for CO_2 capture, as the energy required for heating up a sorbent is much lower than the energy required for heating the solvent. This is due to the lower heat capacity of solids compared to liquids. The envisioned savings in energy will significantly reduce the CO_2 capture costs.

The main research activities in this research included preparation and optimisation of sorbent materials as well as the selection, design and experimental validation of different process concepts. The key objective is to examine the feasibility of adsorptive systems in post-combustion CO_2 capture.

Capacity

An ideal sorbent is capable of adsorbing large quantities of CO_2 while desorption of adsorbed CO_2 is easy. In other words, the adsorption capacity (qCO_2) should be high but the regeneration energy (ΔH) should be low (see Figure 1). From the solid sorbents studied in literature research identified Supported Amine Sorbents (SAS) as the most promising sorbent materials, as these sorbents possess relatively high capacities and require less energy for regeneration than most other sorbents.

For further investigation, different types of supported amine sorbents have been prepared, by physical impregnation of silica and of polymer-based materials such as tetraethylenepentamine (TEPA) and polyethylenimine's (PEI's). The sorbent CO_2 capacity was found to be strongly dependent on amine loading and pore volume. Significant improvement of the sorbent CO_2 adsorption capacity was achieved by tuning these variables. The cyclic capacity of the prepared sorbent material was measured to be roughly three times as high (3.2 mol of CO_2 per kilogramme) as of the conventional MEA solvent. This leads to a reduction in the thermal energy demand for CO_2 capture from roughly 3 gigajoules per tonne for the MEA-based process to 1.7 GJ/t for this novel capture process.



| First estimates of the net power losses of CO_2 capture by solid sorbents (SAS) compared to MEA absorbents, split into desorption losses (heat), electricity for compression and power needed for other devices (pumps, blowers, etcetera). NGCC stands for natural gas-fired combined cycle, PC for powder coal. MEA-estimates are usually more secure, because much more practical experiences are available than with SAS sorbents. Veneman et al. (2013).

Lab facility

A lab-scale capture facility has been built, in order to test the sorbents under process conditions. The capture plant consists of a gas-solid 'trickle flow' adsorber column and a staged 'fluid bed' desorber column.

The adsorber column type was selected because of its optimal contacting between the upward gas flow and the dropping solid. The column allows for high operating gas velocities. It also shows a relatively low drop in adsorber pressure. This saves quite some energy for compression, which is required for the large amounts of flue gases to flow against this pressure drop. Hence, the pressure drop in the reactor directly 'eats up' part of the pressure difference that drives the gas turbines of the power plant.

| Comparison of aqueous amine solvents and supported amine sorbents

Parameter/feature	Aqueous amine solvent (reference)	Supported amine sorbent
Energy consumption	+/-	++
Potential for further energy savings	+/-	+ (high pressure regeneration)
Solvents/sorbents handling	+/-	-
Solvent/sorbent degradation	+/-	?
Bare equipment costs (CapEx)	+/-	+ (higher mass transfer rates)
Emissions of toxic nitrosamines/nitramines	+/-	?

So basically, a lower pressure drop in the column increases the net power yields of the power plant.

The fluid bed desorber has been designed in at least five stages. Staging the fluid beds proves to be beneficial, because it combines good heat exchange characteristics with relatively small dimensions of the desorber column.

The experimental work, which is still continuing at the time of publication of this book, focuses on evaluating the performance of the capture process in terms of adsorber pressure drop, system productivity and energy efficiency. Moreover, the effect of the presence of H_2O and O_2 on sorbent stability and process performance will be identified.

Economics

The techno-economic comparison concludes that the adsorption-based capture process has the potential to lower both the operational costs and the capital investment, compared with the conventional MEA based process (Table 1). The Spence® software tool, developed by DNV-KEMA, shows the gains in energy efficiency of a power plant equipped with this novel capture system (Figure 2). A Supported Amine Sorbents (SAS)-based capture facility at a gas-fired power plant is 19% more efficient than a MEA-based capture facility. With pulverised coal a sorbent-based capture plant is even 33% more efficient [2].

These savings in energy translate into savings in operational costs. In addition, higher mass transfer rates in the adsorption column compared to the mass transfer rates typical for MEA scrubbers is expected to reduce the size of the scrubber with a factor three. This results in lower equipment costs, and hence a lower capital investment. Also here, all aspects are taken into account, but further investigations have to reduce the uncertainty in the results.

The main challenge is now to investigate and if necessary improve the stability of these supported amine sorbents. Especially, O_2 and H_2S, which are also present in flue gas, might cause sorbent deactivation. Research on this topic is on-going. The development of a small-scale pilot, capturing CO_2 from a flue gas slipstream, can play a big role in this as it will be the ideal way to test the stability of commercially available sorbent materials and that of newly developed sorbents under process conditions.

This research is conducted by Rens Veneman, who is a PhD student at the Faculty of Science and Technology of the University of Twente. The research is carried out under the supervision of Wim Brilman and Sascha Kersten.

Chemical looping combustion: efficient power production with integrated CO_2 capture

Conventional technologies for CO_2 capture in power production substantially reduce the efficiency of the power plant, driving up CCS costs. Usually, this 'efficiency penalty' ranges from 10 to 14%-points, which is about a quarter of typical efficiency. Chemical-looping combustion (CLC) has the potential to reduce the energy penalty substantially. CLC uses a solid oxygen carrier for fuel combustion, directly obtaining a highly concentrated CO_2 stream. CATO2 investigated CLC as applied in an integrated gasification-combined cycle coal power plant.

Fossil fuel combustion does not necessarily require gaseous oxygen (or air), but can be done with a solid oxygen carrier, like a metal oxide. This type of combustion is the principle of chemical looping combustion. In this technology, the fuel combustion is chemically equivalent to stripping the oxygen from the metal oxide (reduction) and reacting with the hydrocarbons in the fuel, which results in almost pure CO_2 and water. The metal oxide is recovered again by the reaction of the metal with air (oxidation), thus providing the heat for power generation and allowing the oxygen carrier to be used again for combustion. The secret of the higher efficiency lies in the fact that the air and fuel are never mixed, which avoids energy-intensive separation steps.

However, some specific process conditions should be met in order to reach high process efficiency. The whole power generation system, based on combined cycles of gas and steam turbines, has to be operated at high pressures, around 20 bar. In the case of coal-based power plants, so-called 'packed bed' reactors are more suitable than fluidised beds, because in fluidised beds, the gas and solids continuously have to be separated, which is a challenge at elevated pressures and high temperatures.

Experiments

CATO2 investigated a set-up with two packed beds operated in parallel, alternatingly fed with fuel (reduction of the metal oxide) and air (oxidation of the metal). In this packed bed configuration, the oxygen carrier reacts alternatingly with the fuel and the air. The operation of a packed bed CLC process has been experimentally demonstrated using methane and syngas as fuels. For integration with a coal-fired power plant, currently a system is studied with gasified coal (syngas) as a fuel. Because of the larger reduction of CO_2 emissions, reducing emissions from a coal plant offers a better business case.

The ideal oxygen carrier should be highly reactive at low temperatures and stable at very high temperatures, providing sufficient oxygen transfer capacity. Nickel, copper, iron and manganese based oxygen carriers are the particles that have been studied the most. From a technical point of view, a nickel-based oxygen carrier could be used, but costs are relatively high. Moreover, nickel oxides are toxic and have a relatively low CO_2 selectivity at high temperatures. Copper-based carriers are very reactive for the reduction at low temperatures, but cannot be applied at high temperatures, because they would melt. The CO_2 selectivity is a problem for iron oxide carriers and with Fe_3O_4, the oxygen transfer capacity is too low. Manganese-based carriers also show a low oxygen transfer capacity.

CATO2 concentrated on finding the right oxygen carrier for chemical looping combustion in packed bed reactors, but the ideal carrier is yet to be found.

Two-stage process

A novel plant configuration to be operated on a large scale and integrated with a power plant was designed in CATO2.

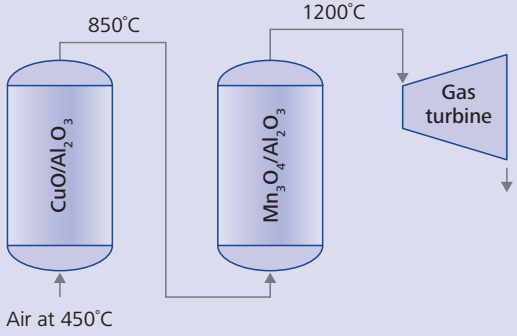
The configuration consists of a two-stage (two-stage CLC, or TS-CLC) production of hot air from the oxidation process (that is used to feed the gas turbine for power production). In the first oxidation bed, air is produced at a maximum temperature of 900 °C. The final temperature of 1200 °C is achieved in the second bed. To achieve this, both reactors operate with a different oxygen carrier. The first reactor operates with an oxygen carrier that has a high reactivity at low temperatures, for example CuO. The second reactor contains a material that is stable and selective at high temperatures, for example Mn_3O_4 (see figure). This configuration has been tested theoretically, using numerical models and process simulations on power plant scales. The models demonstrate that the gain in power plant efficiency is about 5% points (close to 41% of low heating value) compared with conventional CO_2 capture using Selexol.

In addition to developing the two-stage CLC configuration, CATO2 also demonstrated the feasibility of the copper-based oxygen carrier in a (one-stage) lab scale packed bed reactor at 2 bar, operated at temperatures below 900 °C. Here, the model proved to be a good predictor of the experimental results of the packed bed reactor.

Further steps

Chemical looping combustion processes hold a promise for efficient integration of CO_2 capture and power production, and hence for reducing the costs of CO_2 capture. Following these early results, in the last CATO2 year, other topics will be studied. For instance, CATO2 provided the proof-of-principle of TS-CLC, but the concept still has to be demonstrated in an experimental configuration with two reactor beds actually positioned in series. Also, operating the process at 20 bar has to be tested, as most of the tests up until now were at lower pressures (1-2 bar). The influence of the higher operating pressure will be studied in detail on both the particle scale and the reactor scale.

In this packed-bed reactor, experiments on the reactor scale at elevated pressures (up to 10 bar) will be executed. Picture TUE.



The TS-CLC configuration.

Martin van Sint Annaland of the Technical University Eindhoven supervised the work on Chemical Looping, assisted by Fausto Gallucci (also TUE). The research was conducted by PhD student Paul Hamers.

Post-combustion capture: from lab towards implementation

At the start of CATO2, it was envisaged that in 2015 the first demonstration projects related to large scale post-combustion capture would start. Post-combustion capture is quite often seen as the most mature capture technology available for retrofitting to existing power plants. CATO2 research lifted this technology up to a technological level where demonstration is a logical next step.

The basic principles of post-combustion capture of CO_2 have been known already from the 1930's. Looking at the first patent, the resemblance of the current methodology for capture with the patent is evident: the absorption process taking place in a packed absorber, a 'stripper' to regenerate the absorber and strip off the CO_2 under higher temperatures, with heat exchangers in between, in order to transport the heat from the place of production to where it is used. Even the absorption liquid which is nowadays considered as state of the art – the chemical group of compounds called 'amines' – was mentioned in this patent.

Given this history, at the start of CATO-2 research the main focus was on the scale-up of the amine systems which would be applied in the first demonstration project and meanwhile on improving the systems. For the scale-up, the CATO 'CO_2 Catcher' was an essential pilot project. With an output of 250 kg CO_2 per hour (originating from the coal-fired power plant) the capture pilot plant at the Maasvlakte facilitates several long measurement campaigns that added to a better understanding of the capture process.

Nitrosamines

Nitrosamines are one of the identified degradation products of the absorber liquid, the amines. Given the potential carcinogenic character of certain nitrosamines, identified in other research, it is of high importance to determine which nitrosamines are emitted, how much and what emission levels are allowed. To answer these questions, CATO2 performed detailed lab studies and additional pilot measurement campaigns. These studies were done also in connection with Norwegian programs, leading to a European alignment how to address the nitrosamine issue. Based on detailed CATO measurement, it can be stated that although nitrosamines are formed, the amount emitted will be very small if the capture plant is designed accordingly.

Aerosols

The first values of aerosol-based emissions of amines were higher than expected on the basis of detailed modeling and previous experiences. More detailed investigations showed that the measured values were not directly connected to the CO_2 Catcher, but directly linked to the quality of the flue gas coming from the power plant. The research revealed that the presence of small particles in the flue gas (e.g. sulfuric acid aerosols) can lead to a further growth of these particles inside the absorber, due to condensation of amine and water. The principle is equivalent to the condensation trails formed by airplanes at high altitudes. Due to an extensive collaboration within CATO2 between GDF, E.ON, University of Karlsruhe and TNO, mechanistic research confirmed this hypothesis and pointed towards possible countermeasures.

Countermeasures

In the final year of CATO2, the countermeasures will be researched in lab pilots and ultimately also in the Maasvlakte pilot plant. When using moderate volatile amine solutions, wet electrostatic precipitators and Brownian demister units can be used to reduce aerosol emissions.

Moreover, by changing operating parameters within the absorber, significant reductions of aerosol-based amine emission can be obtained. TNO and E.ON have patented an innovative alternative countermeasure, working on the principle of having a heated acid wash to remove aerosol particles after the CO_2 absorption section.

Apart from the technological solution itself, the four years of CATO2 research also shows that modeling is one thing, but can only be confirmed by doing things in real life, with real materials and at real conditions. This is a crucial CATO2 finding and an important reason for pilots and demonstration on the way towards large scale implementation.

CO_2 Catcher

A research topic that was added later on was the management of the capture solvent. During the CO_2 Catcher campaigns, it became apparent that a change in the programme was necessary. Two important findings from the pilot plant studies were the reason for that change. First, the formation of nitrosamine became an issue that had not been obvious before. Second, the emission of amine aerosols also was identified as a topic that needs further research.

| CO_2 Catcher at the E.ON power plant on the Maasvlakte (near Rotterdam). Picture TNO.

The nitrosamines and aerosol-based amine emission research was led by Earl Goetheer, science director with TNO, in close cooperation with Laborelec and E.ON from within CATO2 partners, and Karlsruhe Institute of Technology from Germany.

Integrating the CCS chain

At the start of CATO2, most of the individual elements of CCS (capture, transport, storage) were already in an advanced stage of development. However, an effective application of CCS also asks for robust knowledge on how these elements link together and on how CCS chains fit within the energy system and in the economy. CATO2 dedicated a substantial part of its research to optimising these chains and to model the integration of CCS into the economy. The results of the research are useful for improving the performance of systems with CCS and for developing policies and strategies for large-scale implementation of CCS.

Capturing, transporting and storing CO_2 may seem rather straightforward, but even at a small scale, linking the separate CCS elements to an effective and efficient chain is not trivial. This is mostly due to the fact that CCS connects domains that do not automatically match in a technical way, neither in organisation nor communication. For instance, building a CO_2 capture unit at a power plant means that chemical engineers enter the domain of electrical engineers. Connecting an industrial CO_2 emitter to a storage site of an oil and gas operator also means matching different working cultures. This may result in a reluctance of the emitter to accept the full responsibility or liability for storage activities, since he or she does not have the competence to evaluate the storage risks.

The picture becomes even more complex in the case of large-scale, multi-source CCS in industrial and energy clusters. These clustered CCS projects require linking multiple industries via one or more modes of transport to different storage sites. Not to mention the integration of CCS infrastructures into future energy and industry systems and markets, which raises technical and economic challenges that are not easy to solve.

Given this complexity, designing and operating CCS chains needs a system approach that includes technologies, organisation, economics, safety and legislation. For instance, how will power plants with CCS interact with the energy system, where security of supply and flexibility are prerequisites? How will CCS impact the position of renewables and how will further penetration of renewables affect the operation and economics of power plants with CCS? Or how does CCS interfere with industrial production?

CATO2 investigated how to connect the different parts of the chain in the most efficient techno-economic way. As a part of this puzzle, CATO2 dedicated quite some research effort to understanding the connective piece of 'transport': the technical and safety aspects of transport of CO_2, the way the infrastructure needs to be organised, how networks can be designed and how regulatory aspects have to be arranged. CATO2 also investigated local

and (inter)national strategies for CCS deployment, the role of different stakeholders and institutions in developing CCS and the opportunities for the Netherlands. CATO extensively collaborated with the Rotterdam Climate Initiative to evaluate CCS developments in the Rotterdam area and drafted guidelines for regional CCS developers, which are accessible online.

These integrative studies explicitly differentiate the requirements between the short term (2015-2020), the medium term (2020-2030) and the long term (2020-2050), thereby revealing the subsequent barriers in organisation, policies and incentives and how these barriers need to be addressed in order for deploying CCS.

Reliable data on costs

As with many other economic activities, one important rationale behind CCS research is to understand better the benefits and costs.

The benefits of CCS particularly lie in the mitigation of emissions of the greenhouse gas CO_2, in order to avoid severe climate change. These benefits are crucial to assess the social impact of CCS. However, CATO2 did not investigate (the monetisation of) these benefits, since these benefits are more general and depend on the overall global emission mitigation. Specific CCS benefits, such as stimulating economic activities around CCS, are covered by CATO2 research.

Not only the benefits but also the costs are important for CCS implementation. CATO2 researchers have spent a lot of effort into improving the quality of the cost data. Why was such an improvement necessary? Governments and industries need reliable estimates of the costs and their development over time, because they underpin decisions on policy measures or investments. Governments also need to understand which instruments speed up cost reductions in different sectors and thereby deliver progress in CCS implementation. At the start of CATO2, the uncertainty in CCS cost data was still large. For instance, the first actual business case studies revealed costs at much higher levels than literature data indicated. Although this can partly be explained by the demonstration character of the business cases, the lack of reliable data makes it difficult for investors, policy makers and industry to build their CCS strategies.

By combining and improving the data on the different technologies and by fitting these figures into more representative 'real life' scenarios for CCS chains, CATO2 increased the understanding of the structure and reduced the uncertainty of cost data, thereby substantially improving the insights into the overall CCS economics. This is a key achievement, because a cost comparison is the foundation of a feasibility study which is used to determine company and government strategies.

Research in CATO2 has also looked at how CCS is incorporated in the process of decision-making. CATO2 also provides better data on (system) costs and perspectives on cost reductions, which leads to more reliable assessments.

Understanding and improving the transport of CO_2

Transport is an essential topic in CATO2. Transportation is not only important from a technical point of view. Designing an optimal transport system for CO_2 also can reduce overall CCS costs. CATO2 confirmed earlier research: pipeline transport is the cheapest option to transport large volumes of CO_2. The research also indicates that ship transport has added value elements for smaller volumes: although it has higher operational costs, it also holds some key advantages, such as lower investments costs, flexibility in trajectory choice, and lower financial risks for the investors.

Selecting the transport conditions

Transporting CO_2 through pipelines is existing practice in different parts of the world. Especially oil and gas companies in the United States are quite experienced with this practice. For the purpose of enhanced oil recovery

(EOR) with CO_2, millions of tonnes of CO_2 have been transported for decades, through pipelines of thousands of kilometres in length. However, long distance CO_2 transport in Europe is quite new. Moreover, the spatial conditions for transport differ: the US pipelines are in deserted areas onshore, while pipelines in Europe will often be offshore or pass near to densely populated areas. CO_2 streams under CCS conditions provide additional challenges, because they have different compositions than in the case of EOR, where CO_2 usually is extracted from natural sources.

CATO2 contributed to the general understanding of how transport conditions with CCS can be optimised. Impurities in the CO_2 flows (e.g., hydrogen sulphide H_2S, nitrogen, water) require that higher operational pressures are used. Furthermore, the presence of free water in the pipeline, even in very small concentrations, may have unfavourable effects on corrosion, thereby affecting and weakening the pipeline steel. This will require anti-corrosion measures, which leads to increasing costs. To understand the conditions (temperature and pressure) required to safely operate the pipeline, CATO2 has conducted a series of experiments to determine and validate such conditions with different combinations and concentrations of impurities in the flow (see also the highlight **Safeguarding the carbon dioxide transport network** on page 127).

Choosing the best pipeline

Economic optimisation of pipeline transport depends on many parameters, such as the grade of steel that is required for the pipes, the CO_2 inlet conditions (temperature, pressure, impurities), or the necessity for booster stations to keep the flow running at the right speed and pressure.

Regarding the design of pipelines, CATO2 succeeded in developing cost optimisation models. These models enable a comparison of transport of liquid versus gaseous CO_2, both onshore and offshore for different steel grades. Using high-grade steel, which allows for smaller wall thickness and higher pressures, especially pays off in liquid transport. Gaseous transport occurs at lower pressures, which allows for lower grades of steel. Furthermore, savings in compression energy can compensate the cost related with bigger pipelines when CO_2 is transported as gas.

Contrary to the literature, CATO2 has shown that transporting CO_2 as gas can be cost-competitive with liquid CO_2 and should not be disregarded in advance. For instance, transporting gaseous CO_2 over 100 kilometres of flat agricultural terrain for onshore storage, with a flow of about 5 million tonnes per year, would cost around 11 Euro a tonne. Under the same terrain conditions, liquid transport is about 10% more expensive. Whether CO_2 should be transported as gas or liquid is highly dependent on the storage field, the transport distance and the amount of CO_2 (see also highlight **Costs, design and safety of CO_2 pipeline transport** on page 88).

Connecting multiple sources to multiple sinks

Part of the system approach of CATO2 was exploring how CCS chains can be built on the local scale. In an industrial park, different companies that emit CO_2 can join forces, in for instance designing an optimal configuration of a CO_2 transport infrastructure, in sharing CO_2 storage sites or by sharing CO_2 separation units. Obviously, this cooperation should enable lowering the average CO_2 emission avoidance costs.

CATO2 supported the Rotterdam Climate Initiative by filling in some knowledge and understanding gaps in its drastic plan for CO_2 emission reduction in and around the Rotterdam harbour. Three linked studies were conducted examining the potential of implementing CCS in clusters of industrial sources in the Rotterdam area, both in the mid and long term. The results provide good insights into potential operational problems, risks, profits, and trade-offs for companies of different sizes (see also highlight **Designing cost-optimal CCS configurations for an industrial cluster** on page 91).

Tools for assessing the costs of infrastructures

Developing infrastructures is not an easy task as there can be many combinations and alternatives to connect sinks to sources. One of the best examples of the practical application of CATO2 knowledge on CO_2 transport is the online tool 'Connect'. This tool visualises relevant economic characteristics of a particular pipeline. By playing the role of a virtual designer, any stakeholder can build a CO_2 pipeline infrastructure. By adapting the design, stakeholders can learn how important parameters such as the length of the network, the economics and the required pipeline transport capacity interact.

The tool shows that small adjustments in the trajectory can have large cost consequences. As the network is drawn in Google Maps, it also visualises how other nearby sources or sinks can be cost-effectively connected. 'Connect' is a strong tool for communication purposes, because it shows which parameters determine the costs of a network.

Another example is a tool developed at CATO2 together with the Global CCS Institute, the Rotterdam Climate Initiative and the Clinton Climate Initiative. This tool assesses the economics and financial risks of CO_2 transport and storage. For a set of plausible scenarios, the tool assesses the economic and financial impacts of connecting CO_2 sources in the Rotterdam area and the Eemshaven (North Netherlands) to possible sinks in the North Sea. The tool shows the costs for transport and storage, and also for industries that have to pay the transporter that will manage the common infrastructure (by ship or by pipeline). The analysis and the tool together provide a useful framework for discussing common networks by key stakeholders in the North Sea, including those in the Netherlands, Belgium and the UK.

Optimal infrastructure – conclusions and remarks

Designing an optimal infrastructure may pose technical challenges, but that is only one aspect of organising cooperation. Many other issues occur and many risk/benefit trade-offs exist. Important questions are for instance how big are the financial risks and the benefits for companies connected to such a shared infrastructure, and how do the participants share these risks and benefits? For instance, a risk of 'stranded investment' exists. A capture unit or transport network may be designed with a specific number of candidate CO_2 suppliers in mind, but those candidates could change their commitments along the way, thus affecting the business case of the companies that committed to the initial investment. Furthermore, for the individual plant manager it is important to know if and how the operations of the plant will be influenced by disruptive events inside and outside the shared network. Eventually, companies have proven to be open for shared solutions, but they are also very cautious not to affect their primary production processes.

A perfect foresight into such an infrastructure is impossible. But by investigating these issues CATO2 has provided a much better insight into how such an infrastructure can organically grow.

Knowledge on links of the CCS chain is ready to be applied. This knowledge has already been helpful in the preparations of the CCS chain around the Rotterdam CCS demo ROAD, especially in the design of the pipelines and the compressors (see also The ROAD ahead, page 35).

Fitting CCS into the power system

CCS is regarded as an important CO_2 mitigation option, but it needs to fit into the energy and industrial systems, technically as well as economically. Flexibility is an important issue here, both in power systems and in industry. CATO2 research focused on the integration into the power system.

What demands and constraints does the power system have for a proper integration? The competition in the power market requires that capacity is tuned to market demand. Sometimes demand changes rapidly and fast adjustment of production capacity is required: continuous security of supply is a prerequisite. An important system

integration issue is therefore: How does CCS interact with this need for production flexibility? By including such issues as flexibility and its impact, CATO2 research results contribute to reliable estimates of the potential and costs of CCS.

How can we assess the suitability of CCS in the power system? Fossil fuel (in the Netherlands particularly gas) fired power plants are regarded as a stabilising factor in a system where intermittent low-carbon energy sources such as wind and solar energy increase their input. The fossil power plants thus improve the overall security of supply of the whole power system. Applying CCS serves in making these plants compliant to low-carbon requirements.

This only works if CCS is no barrier to flexibility. CATO2 research shows the possibilities to operate CCS while improving the power system's security of supply. On the scale of an individual power plant, this flexibility can be provided by adjusting the CO_2 capture cycle to the power market conditions.

How does it work? In one basic capture technology (post-combustion capture, see page 68), a solvent absorbs the CO_2 from the flue gases. Subsequently, the CO_2-rich solvent goes into regeneration, where CO_2 is taken out again for disposal. This solvent regeneration process requires considerable amounts of energy and is largely responsible for the 'energy penalty', i.e. the reduction of the overall efficiency of a power plant. It therefore represents a large part of overall CCS costs.

Adjusting the regeneration process to the fluctuating electricity prices on the power market can decrease the costs of the 'energy penalty'. If prices on the market are high, skipping the regeneration (while temporarily storing the CO_2-rich solvent) will increase the power production and thereby the plant revenues. When power prices are low again, regeneration can be re-started at a relatively lower cost. In effect, the energy penalty may be reduced.

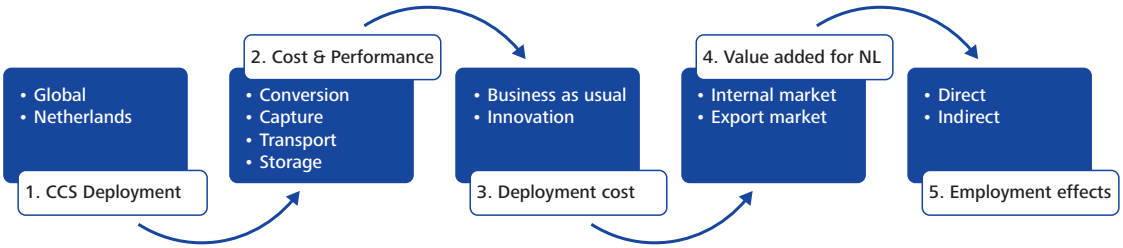
CATO2 simulations indeed have shown this solution is feasible on a timescale of one or two hours, which is comparable to the time-scale of current peaks in market price fluctuations. However, the operational profits of the plant only modestly improve, as this system requires additional investments and may be used only during a limited amount of hours per year.

However, seen from the broader perspective of the whole power system, CCS flexibility can be a profitable option. Making CO_2 capture flexible basically provides extra power capacity at peak hours, when kilowatt-hours are most expensive. In effect, this extra capacity is 10 to 40% cheaper than capacity that would otherwise be required to maintain the supply's security. If this 'system benefit' is translated into a financial reward for this mechanism, this makes investments in solvent storage more feasible.

As an alternative to solvent storage, the entire capture process could stop, venting the CO_2 into the atmosphere. Comparing CO_2 prices to power prices and the costs for storing the CO_2-rich solvent, this is generally not an advantageous option. In this comparison CO_2 prices are assumed high enough to cover CCS costs. In that case the fine for venting the CO_2 – in the form of the obligation to surrender (and buy) the equivalent amount of emission allowances – is also relatively high.

CCS competing with other low-carbon options

The integration of CCS in the energy system goes beyond analysing the impact of its implementation in the grid. In the power sector, but also in industry, CCS competes with other low-carbon options, such as improvement of energy efficiency, renewable or nuclear energy, fundamental breakthrough technologies in industrial production, or any combination of these options. For instance, the steel industry might consider applying new blast furnace technologies or other technologies that decrease the use of fossil fuels (and reduce CO_2 emissions). Studies in CATO2 have shown that CCS can complement (instead of compete with) other mitigations options helping industrial



Model 'Fortuna' has been used for calculating the economic values of CCS deployment for the Netherlands. Based on the S-curve for deployment of a young technology such as CCS, the model calculates the development and cost reductions in CCS, resulting in an estimation of commercial activities and employment in the Netherlands.

sectors to achieve ambitious CO_2 mitigation targets in a cost-effective way.

Prospects for the Dutch economy

While investigating the match of CCS to the Dutch economy, CATO2 studies show that the Netherlands has a good starting point in developing added value through global CCS business. For example, the Netherlands has a strategic position between the large CO_2 sources of Germany and France and the storage reservoirs in the North Sea. This position is further backed up by a large track record in exploration and production of (offshore) gas fields, which are considered as good candidates for CO_2 storage in the region. In addition, the availability of some significant amounts of CO_2 flows from intensive industrial production capacity within its borders, and some amounts just outside of the borders, may provide a good basis for further activities. Last but not least, the high level of CCS research in the Netherlands is acknowledged and renowned. In addition to business opportunities in transport and from service providers, these are excellent starting points that can develop into real business opportunities, economic value and additional employment.

To further understand the role of CCS, CATO2 has compared costs and benefits of different mitigation pathways with or without CCS. The study concludes that including CCS in the electricity generation portfolio has quite a positive impact on overall employment, seen from both a European and a global perspective. Compared to a scenario that meets the 2° C target without applying CCS, the study concludes that the equivalent scenario including CCS will increase the social costs by more than 10% (in Europe and globally) by 2030. Most of this increase originates from increased fuel expenditures. The models, however, do not include the consequences on other economic activities (and subsequent employment).

A study focusing on the Netherlands concludes that under advantageous circumstances, CCS can bring the Netherlands an added value of about € 20 billion and some 300,000 man-years of work until the year 2050. Promising figures, but the conditions to realise these numbers are also demanding:

- A continuously high level of RD&D input is required on a national level;
- Ambitious market activities by (Dutch) stakeholders are a prerequisite.
- The overall global goal not to accept any mean global temperature increase exceeding 2° C should be continued.

Another study also shows that Dutch industry is well-equipped to become an important player on the global CCS market. The main part of the added value and export opportunities lies in services, for example engineering, consultancy, and project management, especially in

transport and storage, and also in post-combustion capture and in offshore activities concerning gas fields. The manufacturing of CCS equipment seems not particularly a strong item in Dutch industrial perspectives.

Exploring pathways to large-scale implementation

One of the more integrative topics of CATO2 research was finding out how CCS can develop into a technology that is broadly implemented in energy and industry in the Netherlands and abroad. Of course no blueprint is available here, but different pathways connected to diverging perspectives have been explored.

Why do we use diverging perspectives? The perspectives on climate change, energy and CCS have not been exactly stable in the last decades. To illustrate the change in perspectives: at the start of CATO2 in 2009, starting the implementation of demos in the Netherlands and elsewhere in the EU seemed quite likely to happen within the timeframe of the four-year programme. However, developments proved to be quite different. Subsequently, the design of a roadmap and implementation plan in CATO2 was adapted to this variability in perspectives, especially on short-term actions, while keeping the long-term horizon still set on large-scale implementation.

CCS has been acknowledged by renowned institutions such as the International Energy Agency and the Global Energy Assessment as an important piece of the climate change mitigation puzzle. The development of CCS has experienced some hiccups in the last years, especially in Europe. However, if at a certain moment we do decide that CCS has to play an important role, the technology will not be immediately ready to roll. A roadmap identifying milestones and important barriers is a prerequisite to know how and where to start the large-scale application of CCS in the next decades.

CATO2 meets that requirement by presenting a roadmap and implementation plan identifying all relevant barriers, milestones and actions that are necessary to take next steps (see the highlight **Implementation Plan as a guidance to the future of CCS** on page 94). Moreover, the roadmap links each of these steps to the outcome of CATO2 research and technical reports.

HIGHLIGHT

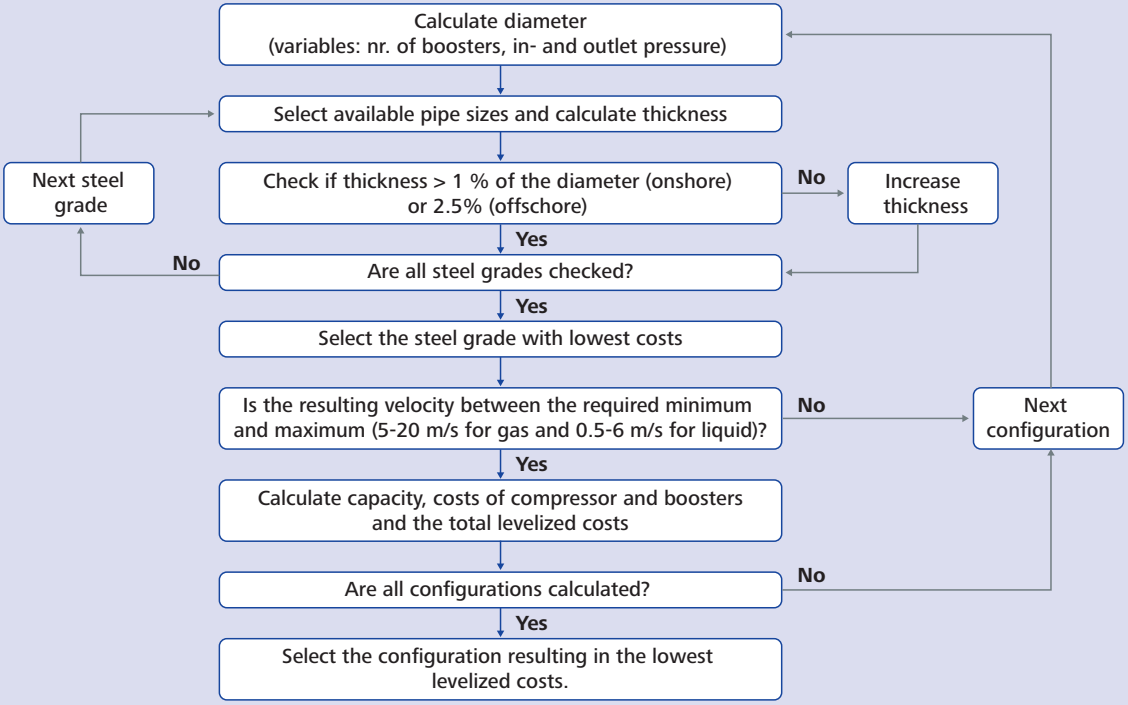
Costs, design and safety of CO_2 pipeline transport

For the purpose of designing CO_2 infrastructure, CATO2 supplies a new model for CO_2 pipeline transport, based on the physical properties of CO_2 and material and construction costs. This model serves as input for a risk and safety analysis, which reveals that gaseous CO_2 transport leads to higher safety risks than pipelines transporting liquid CO_2.

There is broad consensus that pipelines will play a major role in the transportation of CO_2. Estimations from the International Energy Agency indicate that a network of 200,000 to 360,000 km would be needed by 2050, in order to accommodate the required amount of CCS projects. But no large networks are yet known. Moreover, the knowledge required for designing the configuration is not yet complete.

Knowledge gaps

At this moment, there are three main knowledge gaps associated with CO_2 pipeline transport. Firstly, there is lack of insight into the actual costs of a CO_2 pipeline infrastructure. For instance, costs for a pipeline with 0.61 m diameter range from € 0.47 to 3.4 million per kilometre (see the figure). Secondly, multiple pipeline configurations can transport a given amount of CO_2 over a certain distance. However, until now the most



| This flow diagram allows for a selection of the cheapest pipeline among different steel grades and configurations of gaseous or liquid CO2 transport. With this model, 8 different steel grades and 191 configurations have been compared. Adapted from Knoope et al. (2014).

cost-effective configuration, in terms of inlet pressure, diameter and the distance between booster stations, is yet unknown. Thirdly, concerns exist regarding safety of CO_2 pipeline transport, especially close to densely populated areas like in the Netherlands.

Costs of pipelines

Many of the existing cost models are based on natural gas pipelines constructed in the 1990s and early 2000s. However, these models don't take into account the higher operation pressures needed for CO_2. As part of a PhD project within CATO2, a specific cost model for CO_2 pipeline transport was developed, in cooperation with several stakeholders such as Shell. The model incorporates the required wall thickness, different kinds of steel, and uses up-to-date material and construction costs.

The newly developed cost model estimates are in the upper end of the range predicted by other cost models. Moreover, the cost estimations of the new model are confirmed by the cost assessments made for some realised and planned CO_2 pipelines.

This cost model is a considerable improvement compared to many of the existing cost models in literature, because it takes explicitly into account the amount of steel required and correct thereby for the higher operation pressure of CO_2 compared to natural gas. Moreover, it is the only known cost model that compares steel of different qualities and selects the most cost-effective solution. The resulting material costs are added to costs for labour, right-of-way (priority) costs and miscellaneous costs. These last three cost categories are based on the up-to-date costs of natural gas pipelines constructed in the period 2008-2012.

Configuration

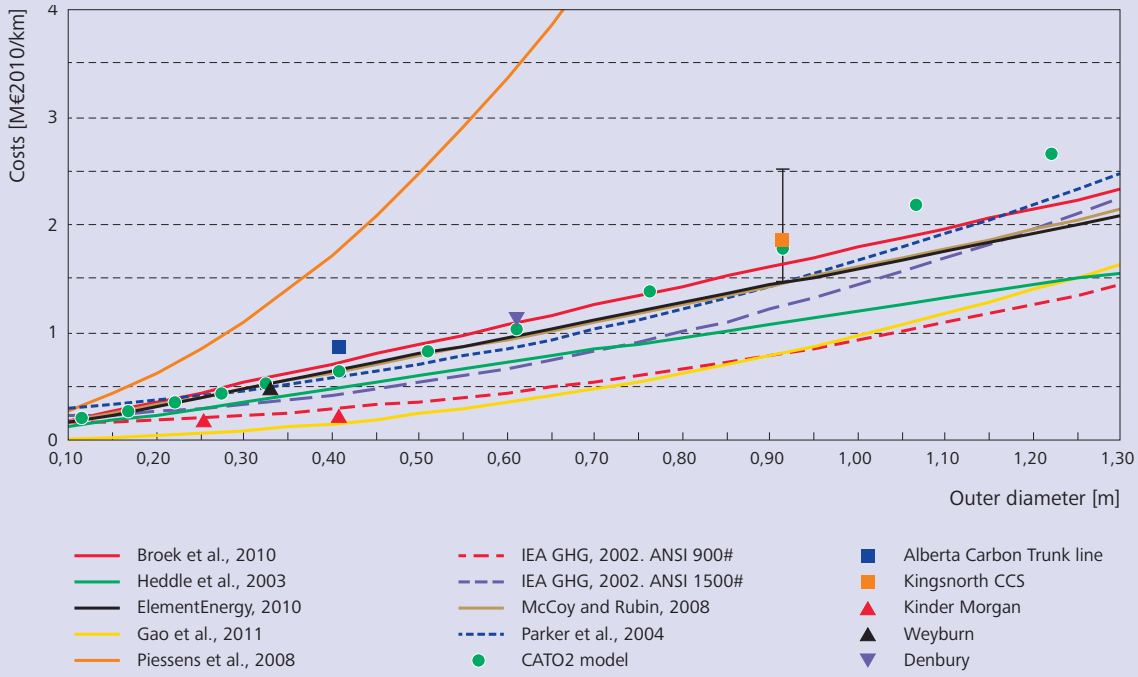
Together with a cost model for initial compression and pumping stations, the new cost model serves as an input for analysing the most cost-effective configuration of a CO_2 transportation system: in terms of inlet pressure, diameter and number of pumping stations. From calculation of the costs of many different configurations, the model reveals that the optimal inlet pressure for onshore CO_2 pipeline transport is 9 to 12 million Pascal (MPa), with supporting pumping stations installed at roughly every 100 km. Furthermore, the costs calculations show that gaseous CO_2 transport can be cost-effective if a small CO_2 stream is stored in a nearby reservoir with a low reservoir pressure, such as depleted natural gas fields. In contrast, liquid CO_2 transport is the most cost-effective option if large volumes are transported over large distances or if the CO_2 is stored in fields with a high reservoir pressure, such as aquifers.

Safety

In addition to material costs, also risk and safety considerations influence the optimal configuration of a CO_2 transportation system. Several risk mitigation measures can reduce the probability of a failure (e.g. concrete slabs, burying the pipeline to protect it) or limit the consequences of a failure (e.g. installing additional block valves). These measures bring along costs, so a balance has to be found between risks and economics.

Starting point for this balance is the current national policy on risks and safety. Current Dutch regulation prescribes that a person permanently living near (< 5 meter) a pipeline transporting natural gas or other flammable liquids should run no risk exceeding 10^{-6}, which means: one casualty in a million (years). By applying the same risk standard to CO_2 pipelines, and applying and using specific knowledge on safety and CO_2 spreading in case of leakage developed within CATO2, this model analyses the locational risks resulting from CO_2 pipelines. It also assesses how much the risk is reduced by risk mitigation measures. By incorporating the costs of risk mitigation measures, the model balances risks and economics.

The results show that for a pipeline of 71 km transporting 150 kg CO_2 per second, the 10^{-6} locational risk is located 770 m from the pipeline in the case of gaseous transport. In the case of liquid CO_2 pipeline transport, the risk never



Comparison of the developed pipeline cost model with cost models given in literature as well as some cost estimations for planned and existing CO_2 pipelines. Adapted from Knoope et al. (2014).

exceeds 10^{-6}. This large difference is due to the limited force behind a release of gaseous CO_2, which implies that CO_2 mixes with the surrounding air to CO_2 concentrations that have a higher risk for inhabitants. Liquid CO_2 would blow out at a much stronger force and dilutes at greater distances, causing lower concentrations at ground level.

With gaseous CO_2 transport, relatively cheap measures such as additional surveillance and marker tape, with costs less than 1% of the whole project, reduces the 10^{-6} distance to 650 m. Concrete slabs on top of the pipeline even reduces the distance to 100 m, but increases the investment costs with about 10%.

The CATO2 model has proven to be very successful in predicting the real costs of CO_2 pipeline infrastructure. The next step is to use the cost model for making projections of the CO_2 infrastructure development over time. This will be done for the Netherlands in the coming year. Furthermore, research should focus on how the transport system can be linked with different kinds of storage fields, especially in relation to the required temperature and the required injection pressure of CO_2.

Marlinde Knoope plans to achieve her PhD based on this research. She is supported by her co-promoter Andrea Ramirez (UU) and her promoter André Faaij (UU). Furthermore, Wim Guijt (Shell) provided input on pipeline engineering and Ingrid Raben (TNO) supported with the risks modelling.

Designing cost-optimal CCS configurations for an industrial cluster

Costs are a major issue in CCS, also when applied to industrial processes. An optimal CO_2 capture configuration is needed to reduce costs. A techno-economic feasibility study within CATO2 modelled different CO_2 capture configurations for a cluster of 16 industrial plants in the industrial Botlek area. In general, centralised configurations prove to be cost-effective, which is particularly interesting for the smaller emitters.

CCS is an option for deep CO_2 emissions reduction in industry. However, in order to become a realistic option, reduction in costs is very important. Previous research has indicated that applying CCS to a cluster of industrial plants can be more cost-effective than a collection of individual CCS initiatives. However, the performance of different cluster configurations has, so far, hardly been evaluated.

Within CATO2, research focused on the technical feasibility and costs of several CO_2 capture configurations for a cluster of 16 industrial plants – together emitting around 7 Mt CO_2 yearly – in the Dutch industrial Botlek area. The research distinguishes between two types of capture technology: post-combustion capture and oxyfuel (combustion with pure oxygen, resulting in pure CO_2 and water; see also page 68).

In both capture routes, the CO_2 stream is purified and compressed to a pressure of 110 bar before being transported through pipelines to a CO_2 storage site. The bulk CO_2 pipeline transport and storage sites would be shared, so these infrastructure parts don't make a difference in the cost optimisation analysis.

Possible configurations

There are several cluster configurations, which differ regarding the locations of the system elements, such as the CO_2 capture units (CO_2 absorption tower, desorption tower, CO_2 purification units, CO_2 compressors), oxygen production plant and energy plants. Regarding this last item, the required steam and electricity can be produced in a steam boiler and purchased from the electricity grid, or in an in-situ energy plant that generates both steam and electricity.

Two specific cases are investigated: One configuration with the units placed at each industrial plant site (the 'decentralised' configuration); and one with centralised units, where CO_2 from all 16 plants is jointly captured, purified and compressed ('centralised' configuration). As a consequence, the capture units and energy plant in the decentralised configuration are relatively small compared to the same elements in a centralised location.

Also, the local pipelines – transporting flue gases, oxygen gas and CO_2 – within the area differ per configuration. In total, three main post-combustion and two main oxyfuel combustion configurations were investigated. The figure shows one of the post-combustion configurations, representing the absorption tower placed at the plant site and the desorption tower positioned at a centralised location.

Centralised options are cheaper

The costs are calculated based on studies presenting detailed cost data on capture equipment and pipelines. Average CO_2 emission mitigation costs for both capture technologies prove to be around 20% lower in the case of centralised CO_2 capture equipment. Average costs with centralised post-combustion capture are about 70 €/tonne CO_2, while with oxyfuel combustion costs are reduced by another 5 €/tonne.


Locations
Chemical absorption units
Strippers, CO_2 treatment units & Compressors
CO_2 emission point sources
NGCC-CHP unit
Pipelines / Ducts
Flue gas
CO_2 rich & CO_2 lean amine solution
Local CO_2
Trunk CO_2
0
500 m
N
AVR Rijnmond
Cabot
Air Liquide
Enecal
Eurogen
DSM
Biopetrol
Cargill
Evonik Carbon Black
Lyondell
Air products
Akzo Nobel
Esso
Shin Etsu
Rotterdam Aromatic Plant
Air Products HyCo4

Aerial photograph of the industrial Botlek area. The picture presents the post-combustion CO_2 capture-network configuration. Depicted are the chemical absorption towers, desorption towers and compressors, and CO_2 emission point sources. The coloured lines represent the flue gas ducts, CO_2-rich and CO_2-lean amine solution pipelines, low-pressure CO_2 pipelines and the high-pressure CO_2 trunk pipeline that transports the CO_2 to the storage sites. Berghout et al. (forthcoming).

However, the analysis also reveals that CO_2 emission mitigation costs can differ a lot per industrial plant. The lower average costs that are linked to the centralised cluster configurations are mainly due to economies of scale obtained by building large centralised capture units, oxygen production plants and energy plants. Centralizing CO_2 capture equipment is particularly interesting for industrial plants with low annual CO_2 emissions (i.e. less than 200,000 tonnes per year), particularly because of economies of scale. Furthermore, large energy plants are able to generate steam and electricity more efficiently, resulting in lower energy production costs.

The study also shows that using a combined heat and power plant (producing both steam and electricity) is more cost-effective for centralised cluster configurations, whereas a separate boiler for steam production and purchasing electricity from the electricity grid are preferred options for the decentralised configurations.

Cost allocation needed

A shared infrastructure is a preferred option because of cost reduction, but is still far from actual realisation, even in the Botlek area. Building on the cost optimisation studies, further research should focus on the optimal deployment pathways for the CO_2 capture configurations. Also, development of tools that allocate the costs of CO_2 capture infrastructure among the participating plants is an issue for future research.

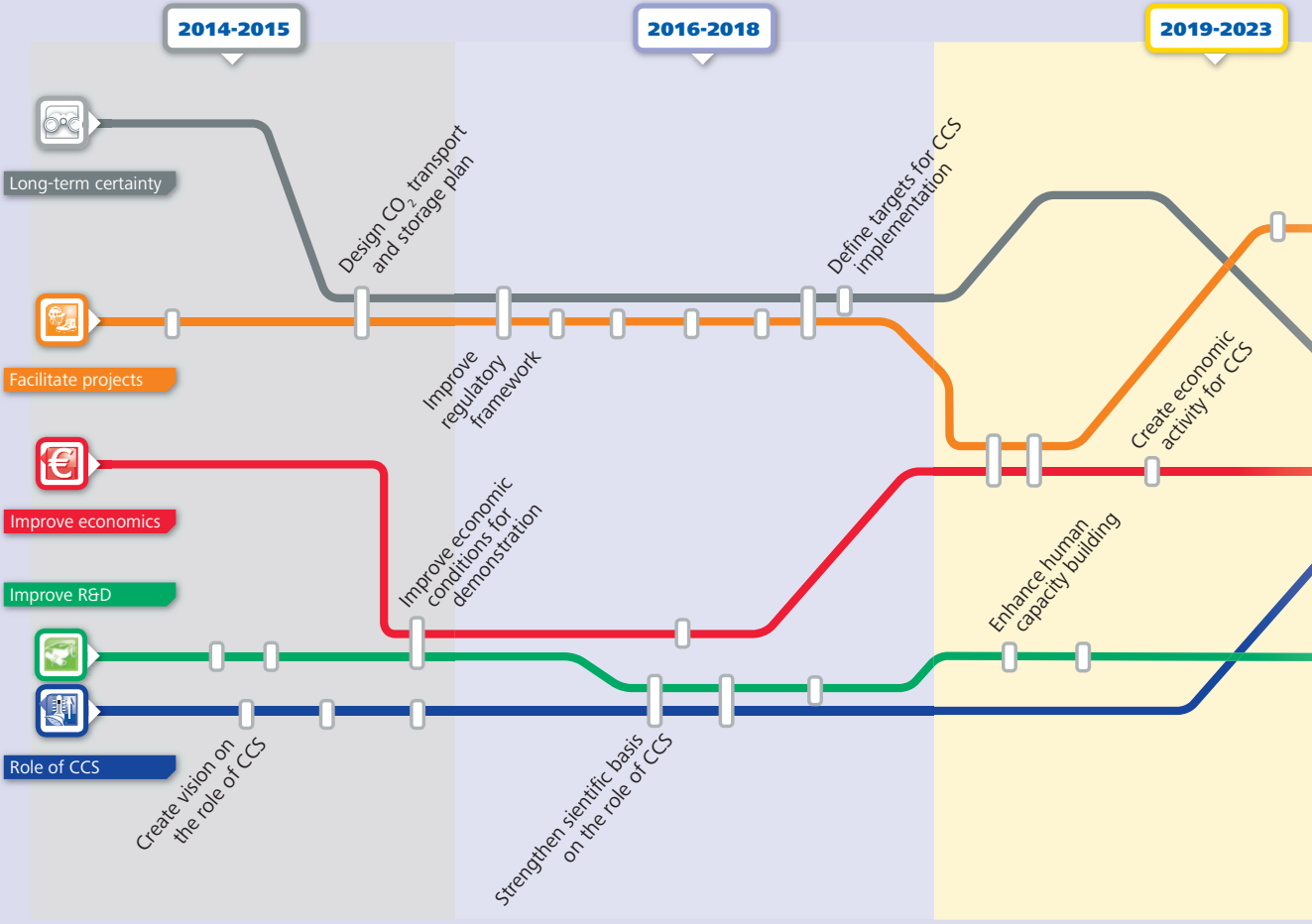
The cost optimisation study is part of a PhD study at Utrecht University by Niels Berghout, with support of Dr. ir. Machteld van den Broek and Prof. dr. André Faaij.

HIGHLIGHT

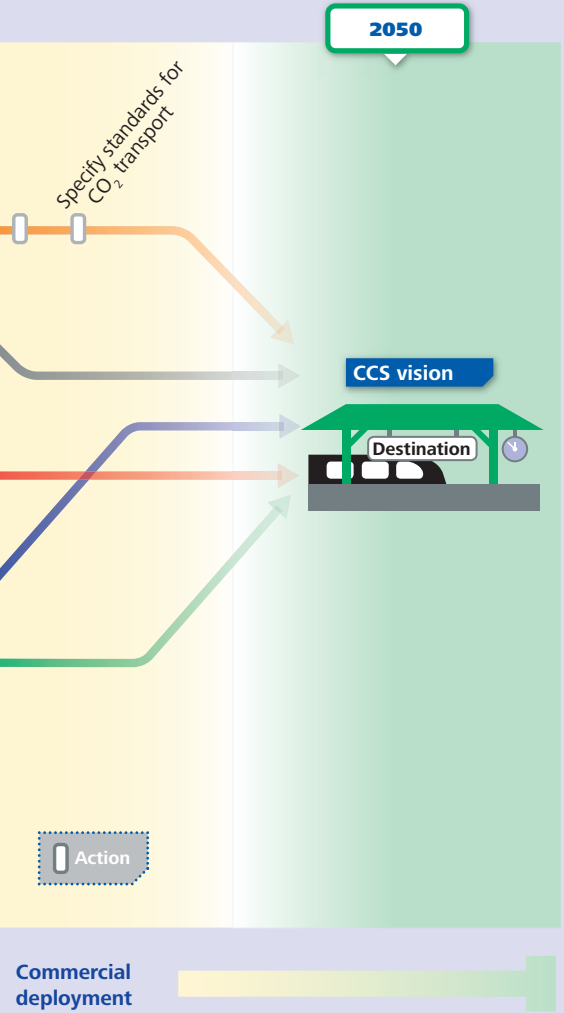
Implementation Plan as a guidance to the future of CCS

In close collaboration with the CCS community and based on research, CATO2 created the 'CCS Implementation Plan'. This plan sketches historical developments and the current situation in CCS. By providing a vision and a Roadmap towards 2050, the Implementation Plan offers guidance for future strategies by policy makers and other stakeholders.

So far, the Dutch government has taken several steps towards a large-scale roll out of CCS in the Netherlands.



Co-funding the CATO and CATO2 programmes is one of those steps; subsidising small-scale capture projects another. On several occasions, the Dutch government also has indicated the need for a long-term strategy to organise transport and storage of CO_2 in the Netherlands. Considerable attention has been paid to using Dutch gas and oil fields for CO_2 storage, how to design a cost-effective transport and storage infrastructure and how the Dutch government can manage these developments.



The Implementation Plan, represented by a map for required CCS actions.
Source: adaptation of the CCS Roadmap graph, Ecofys.

Demonstration is regarded essential for gaining practical experience in technical, organisational, financial and legal aspects of the entire CCS chain. Currently, one small-scale pilot for CO_2 storage exists: in the offshore gas field K12B storage combined with enhanced gas recovery is tested. Other pilots for CO_2 capture and a CCS demonstration project might start in the next years. The Dutch government reserved budgets for co-funding large-scale demonstration (i.e. the ROAD project).

Accelerate progress

But at present, progress of CCS in the Netherlands and in Europe is slowing down. Even in this pre-demonstration phase, CCS faces several barriers in financing, integrating the full capture-transport-storage chain, public acceptance, developing transport infrastructure and creating a regulatory framework. Without strong coordination and leadership, CCS risks a progress that is too slow for a timely contribution to reducing greenhouse gas emissions.

As the only rationale – besides some small economic benefits – for implementing CCS is combating severe climate change, progress of CCS heavily depends on policies. To justify their investments in CCS, market parties need to be convinced that policy focus will be stable and will not depreciate their investments. This requires transparent and firm policies, as well as well-defined strategies to develop and deploy CCS in the Netherlands. The CATO Implementation Plan answers the question: Which steps do the government and market parties have to make to fully exploit CCS opportunities in reducing CO_2 emissions?

Shared strategies needed

The Implementation Plan concludes that development and large-scale deployment of CCS are only possible if government and stakeholders share a strategy. The Implementation Plan supports the Dutch government and other

stakeholders by defining their roles and responsibilities and by identifying the major actions required for shaping the right market conditions.

According to the analysis, progress is required on five issues:

1. Understand the role of CCS in the entire portfolio of abatement measures.
2. Stimulate research and development to improve performance and increase confidence in CCS.
3. Improve economic conditions.
4. Create efficient project conditions to shorten project implementation.
5. Provide long-term certainty.

If CCS is indeed recognised as necessary, it is of the utmost importance that the demonstration phase of one or more individual projects will smoothly develop into a well-coordinated large-scale implementation phase. Deploying large-scale CCS in time asks for coordinated ways of regulating, organizing and financing CCS. Timing of decisions on the five themes will be crucial.

Currently, a common understanding of the position of CCS in the portfolio of greenhouse gas mitigation strategies is missing. The basis of the Implementation Plan is a common vision of the role of CCS in 2050, collected from the input of CATO partners and other stakeholders. This vision reveals high ambitions for CCS in both the industrial and power sector and, to a lesser extent, the transport sector. This ambition is complemented with specific views on the social dimensions, economics, technologies, spatial planning and public perception. These views have been used to frame which actions are required.

The Implementation Plan

The main element of the Implementation Plan is a CCS roadmap, covering the main actions that should stimulate the development of CCS and create the right conditions for its large-scale deployment in the Netherlands.

The Implementation Plan provides consistent pathways of CCS towards 2050. It subsequently addresses the five themes by formulating over 25 actions, varying from creating coalitions for public communication, the need for a transport and storage plan and specifying (inter) national standards for CO_2 transport. For each action the initiator or responsible actor is indicated, the timing and the required results. Each action is also linked to CATO2 results, which support the implementation of the action. The CCS roadmap addresses key policy actions and key R&D development that are required for achieving the 2050 vision.

The Implementation Plan supports policy makers to develop CCS into an economically and technically mature technology. The government and other stakeholders can use this information for defining further strategies and actions. The Implementation Plan focuses on CCS in the Netherlands. However, it also takes into account the developments abroad, especially those in the European context, because quite often they have a direct impact on developments in the Netherlands.

Implementation Website

At the time of writing of this book, the Implementation Plan was still under construction. The final Implementation Plan, including the roadmap, is displayed online. The website contains the Implementation Plan, the 2050 vision and a visual of the roadmap, hyperlinking to all relevant background information, including the CCS pathways towards 2050.

The implementation plan is coordinated by Chris Hendriks and Joris Koornneef of Ecofys, supported by Utrecht University, TNO, ECN and with contributions from other CCS stakeholders in the Netherlands (ministries, NGOs, industry).

Exploring the subsurface for reliable CO_2 storage

In the Netherlands, underground storage of CO_2 largely implies: using depleted gas fields. These fields are abundant, both onshore and offshore. Many data about these geological formations are available from natural gas production. However, for reliable and safe permanent storage of CO_2, this knowledge needs to be adapted and extended. In addition, alternatives such as aquifers and depleted oil fields are also under consideration. Fundamental and applied CATO2 research has increased the knowledge to a level that was applied in practice in the ROAD demo preparations.

Concerning CO_2 storage, CATO2 had the objective to demonstrate technical feasibility and monitoring of underground CO_2 storage, mainly in depleted gas fields, but also in aquifers, coal seams and oil fields. This chapter describes the most important R&D work, which concerns increasing the knowledge on injection and storage, exploring safety issues and developing a sound monitoring of CO_2 injection and storage. Most of this work was executed within Sub-Programme 3 Storage, in close cooperation with other SPs, while some of the knowledge was already used in the preparation of Dutch demonstration projects.

CATO2 joined forces of a broad range of science disciplines such as geology, geochemistry, petrophysics, geophysics, geomechanical engineering, mathematics and reservoir engineering. Basically, they searched for the answer to the question: What happens when CO_2 is stored underground? This question may be regarded as the scientific equivalent of the broader question from society: can CO_2 be stored safely and permanently?

Building on existing gas reservoir knowledge

Since the sixties of the last century, the Netherlands produced natural gas, initially from the large gas field of Slochteren, and later on from other, smaller fields onshore and offshore. This brought about a great deal of knowledge about the subsurface, though still not fully covering the specific application of CO_2 storage.

The presence of many almost depleted gas fields justifies the focus in CATO2 research and makes the Dutch situation quite unique. CATO2 also performed research on (geothermal) aquifers, as well as on other opportunities such as CO_2-enhanced oil/gas recovery and application of coal seams. This links to other parts of the world, where CO_2 storage in aquifers (underground layers containing warm water) has a large potential and is a priority in research and validation activities.

A changing scene of storage demonstration

During the last decade, several Dutch locations have been identified and investigated as opportunities for including them in projects demonstrating injection and storage.

At different periods of time, different locations reached different stages, such as Barendrecht, the offshore gas production site K12-B, Geleen, Delft, several sites in the Northern Netherlands, and ROAD/TAQA. Other locations (such as in the Northern Netherlands) were about to become selected for further research.

However, most of the candidate sites have been skipped, for various reasons. At present, two sites are still on track: K12B, operated by GDF Suez, where CO_2 is actually captured from locally produced natural gas and stored, and P18-4 operated by TAQA, which is the offshore gas field that will be a complementary part of the ROAD project. For this site, site operator TAQA recently received a permit for CO_2 storage from the government.

Although many sites were dropped as candidates for CCS demonstration, the evaluations of all sites yielded much knowledge. In general, research and experiments provided a much better understanding of the geological configuration and mechanical processes in the subsurface, and hence of the stability and the risks of CO_2 storage.

Simulating storage in models

The process of storing CO_2 starts with injecting dry CO_2 gas into the reservoir. The depleted gas reservoirs under consideration in the Netherlands consist of sandstone, where most of the natural gas has been extracted from the pore space. Very generally speaking, the process after injection will look as follows. Initially, the CO_2 will remain in the pore space in gaseous form or, if pressure rises sufficiently, in a dense (supercritical or liquid) form. After this initial phase, part of the CO_2 will dissolve in the water present in the reservoir, but as there is little water present, dissolution usually will not play a major role. Part of the CO_2 will also react with the reservoir rock and gradually mineralise. Most of the CO_2 will remain as a gas in the pores.

Obviously, injection of CO_2 will increase the pressure in the reservoir again, potentially up to the conditions of the original gas field, levelling with the pressure of the surrounding subsurface again. This suggests that the reservoir becomes more and more stable.

Models are essential for representing what happens in the reservoirs at in-situ conditions. These models provide the various scenarios about CO_2 storage under various conditions and through time. Predictions are made regarding the CO_2 injection, its physical state and its effects on the rock structure and behaviour of geological formations. But even with large demos, models are indispensable, because direct observations at depths of several kilometres are hard and expensive. However, observations at comparable rock outcrops at the surface, in boreholes and from geophysical (seismic) interpretation, will allow for further calibration and improvement of the models.

- Different types of models can be distinguished and are more or less complementary in describing the reservoirs and the effect of CO_2. *Geological* models describe the reservoir: the geometry, the type of rocks, the different layers, the porosity and the permeability)
- *Flow* models mimic how CO_2 spreads in the reservoir, where CO_2 and also hydrocarbons may flow and how the pressure will rise. Dissolution is often taken into account in these models.
- *Geochemical* models describe what type of reactions and interactions take place. In principle, these can be fully coupled to reservoir simulations resulting from the geological and flow models, but these would take a huge amount of super computer calculation time because of the amount of interactions and parameters that have to be taken into account. However, CATO2 contributed to several smart ways of combining the models and the simulations and to produce fine grid results at higher speed.
- *Geophysical* models describe pressure changes and stress changes in the subsurface, how the rock behaves and how the faults in the subsurface will behave. Also here, smart methods are needed to couple these models to the geochemical and flow models. For instance, geochemistry affects the strength of a rock

and therefore changes the geomechanical response. This might change porosity again, and therefore the flow in a reservoir.

Much of CATO2 research aimed at a smart combination of all these types of models in a smart way, ensuring that calculations are feasible and are representative. A strong focus of CATO2 has been on combining the effects of chemical reactions (geochemistry) on fault zones and on geomechanical properties of the reservoir. Simulations of the flow of CO_2 are essential here, because this flow determines the pressure evolution. Within CATO2, quite a few models have also been tested at small scale in the laboratory.

For developing models of CO_2 injection and storage, researchers were allowed access to the commercial models that underpinned natural gas production from the commercial oil and gas industry participating in CATO2. CATO2 experiments, data and more fundamental research have now resulted in a set of models that can provide answers to different scientific questions about CO_2 storage, with different resolutions and at different scales. For instance, details of flow processes around the well bore hole ask for different scales and models than seismicity issues that possibly affect the residential housing at the surface.

Different scales

CATO2 research underpinning the models is organised around two classes of lab experiments, on two different scales and under pseudo in-situ conditions. Utrecht University provided experimental results on processes on a scale of centimetres to millimetres. These lab tests are complemented by the Delft University of Technology, which was able to experiment on a scale of centimetres to about one meter. Together, the experiments provided essential insight in flow processes, chemical reactions, solution of CO_2 and water (H_2O), the effects of CO_2 on the salt water in the reservoir (called brine), physical-chemical rock-fluid-gas interaction and CO_2-water phase determinations. This enables modelling these processes.

The best validation of the models is of course practical application of CO_2 storage, but that has not been executed substantially as yet. However, in certain cases the models were validated with figures from real life. For instance, the natural gas reservoir near Werkendam (Province of South-Holland) contains over 70% of CO_2 from natural origin. Examination of cores collected near the production site provided numerous data on how CO_2 intruded in different reservoir rock samples during this 'multi-million-years experiment'. These data have been used to validate model parameters and find the most relevant geochemical reactions (see also highlight **A natural lab for long-term CO_2 behaviour** on page 105).

Storage sets 'envelope' for CO_2 flow conditions

One important issue that should be solved is the required condition of the input gas. In most cases, the captured CO_2 gas streams already contain more than 95% CO_2. Direct storage of these high CO_2 content streams may seem to be a cheap and simple way of taking the CO_2 out of the atmosphere. EU regulations effectively allow direct storage of such streams because in most cases they meet the EU requirement that the gas should 'overwhelmingly' consist of CO_2. But there are reasons why such 'rough' gas streams should not be directly stored.

For instance, flue gases that are captured from industrial activities or from fossil fuel combustion can contain impurities that may be heavily corrosive, affecting the transport and injection installations.

Another risk that should be avoided is 'clogging' of the injection wells and reservoirs at the injection points. Principally, injecting CO_2 into the reservoir especially may clog if it locally de-hydrates the pores around the bottom end of the well and creates salts which plug the pores. These barriers prevent gases from the well bore hole entering the deeper regions of the reservoir. Too many

wells would be required and storage cannot be executed cost-efficiently. So irregular fresh water injections and fine-tuning of the thermodynamic conditions of injected CO_2 streams are prerequisites.

In order to prevent clogging and to optimise the processes, models now enable optimisation of the flow in the pipelines and in the wellbore, accounting for the optimal trade-off between process improvement and costs. For example, multi-phase flows are probably to be avoided. They are sub-optimal in an exergetic way and lead to higher transport costs. Following the whole chain from capture to transport and permanent storage, CATO2 delivered an 'envelope' of conditions (temperature, pressure, volume, impurities) that CO_2 capture gas streams have to meet.

For instance, transport pipelines require that no more than 0.5% (in weight) of all gases consist of sulphur and nitrogen oxides, and no more than 3% of oxygen, because of the corrosion impact. Only very low concentrations of other impurities are tolerated. Depending on the mix of gases, super-critical or fluid phases of the flow into the well-bore are preferred. Compression has to be executed at the beginning of the pipeline; placing compressors along the way is not a cost-efficient option.

Wellbore integrity

Before discussing the geological system as a whole in this section, also man-made, engineered systems are of major importance when investigating the long-term integrity of CO_2 storage sites: the wellbores. CATO2 put much effort in assessing the processes and parameters that determine the long term stability and performance of wellbore materials, namely steel, cement and polymers.

Wellbore materials have to withstand both chemical and mechanical loads over extended periods of time. Combined approaches of experimental and simulation studies helped understanding the behaviour of well materials, particularly of the steel casing and cement, how they react on chemical and mechanical forces and how to construct and evaluate (monitor) wellbores with respect to long-term safety.

Special focus was put on the sealing behaviour of the interfaces of wellbore materials, which represent the weakest link in the systems. In particular the older plugged and abandoned wells are considered as the major potential leakage pathways for CO_2. This is because often not much is known about their actual sealing performance in case injected CO_2 increases the pressure in the field. A qualitative well integrity assessment of the P18 gas fields has been performed, evaluating the quality and long-term safety of all seven wells in the potential storage area. The study shows how the safety of old wells could be assessed. This study provides important input for assessing the ecologic and economic feasibility of storing CO_2 in the P18 gas fields.

Cap rock integrity

As the stored CO_2 has to stay underground for ages, models are also a prerequisite in understanding how CO_2 and the reservoir will behave. More specific: will the integrity of the faults, the cap rock and the reservoir as a whole be maintained?

CO_2 injection will change the characteristics of these systems. Fluid pressure in the pores, changing temperatures, chemical reactions such as salt precipitation, water uptake by CO_2 or buoyancy effects may all have an impact, especially on the integrity of faults and the covering cap rock. Models simulate the effect of injected CO_2 on the stability and transport properties of geological faults, possible leakage pathways and long-term effects.

To start with the latter: on the very long term (millennia), most of the stored CO_2 will remain in supercritical (fluid) form. Parts will be dissolved in water, while a little will be mineralised and thus permanently trapped.

During injection in a nearly depleted gas field, the risk of leakage is small but not zero (because risks never are

zero). Given the fact that the pressure of CO_2 injected into the reservoir formation will always be kept well below the fluid pressure in the surrounding rocks of typically 350 bars, it is hard to imagine scenarios in which the CO_2 could escape through the surrounding formations. The counter pressure will simply push back any CO_2 trying to escape.

However, geological CO_2 storage returns reservoirs back to higher pressure again, potentially resembling their initial state. Refilling them may affect the sealing capacities of faults and the cap rock. Obviously, all boundaries have to withstand these changing conditions.

In case of geological 'faults' in the reservoir, other scenarios might occur (see the highlight **Assessing risks posed by faults** on page 108).

Monitoring

Monitoring the condition of the storage reservoir itself and of its direct environment is essential for CO_2 storage. Monitoring needs to show the answers to questions such as: Is there any CO_2 leaking from the subsurface? What impact did the storage of CO_2 have on the subsurface and the surroundings?

Monitoring essentially means: measuring the conditions, collecting the relevant data through time, analysing those and drawing the conclusions about the status of the storage site and its environment. Monitoring is always mentioned together with 'verification', because verifying the monitoring results against models and lab results is needed to prove its reliability and relevance.

Monitoring is the concluding piece of CCS, for the safety of CO_2 storage has to be assured and confirmed for a long time. For this reason, monitoring is – next to the environmental impact assessment – an essential part of CCS regulation, legislation and licensing. The EU CCS Directive (2009) specifically defines which parameters and processes should be part of monitoring. The CCS Directive also states that without proper and approved monitoring, a company is not allowed to subtract the amount of stored CO_2 from the emissions for which it has to buy and submit emission allowances under the EU Emissions Trading Scheme. Here, a direct economic liability is at stake, for if leakage occurs, monitoring should be able to define how many emission allowances a site operator has to submit.

Monitoring has to deal with the fact that different locations and characteristics demand different methods for measuring. Moreover, developing methods for measuring CO_2 leakage is difficult if demonstration sites do not substantially leak in practice. CATO2 found some solutions for these problems and delivered on many monitoring issues. Finally, CATO2 contributed a large part to development of Dutch monitoring concepts up to the level that was appropriate for the licensing procedure (and actual licensing) of the storage part of the ROAD project (see also page 35). In general, CATO2 has developed many monitoring methods that are ready to be applied in specific site monitoring.

Monitoring should confirm the (long-term) containment of CO_2 and should measure any leakage. This can be done either by direct measuring methods, or by indirectly verifying that the CO_2 and the reservoirs behave as predicted by the models. In many cases, the monitoring strategy for a particular site will be a combination of the two.

Basically, monitoring can be executed at two levels: in the deep and shallow subsurface (including the surface). Deep underground monitoring, in the Dutch case of a gas field, can be applied to the gas field itself (in order to confirm the models) or to the overburden (e.g. to check on any leakage). It aims at observing any changes in the subsurface of up to two kilometres depth by continuous recording of measurements. Measurements can be executed with several devices and with different methods.

A renowned method in deep underground monitoring in oil and gas production is the seismic method. Seismic

methods have been successfully applied at the Sleipner field, off the Norwegian coast, which is the longest running large-scale CO_2 storage demonstration in the world. There, seismic data have monitored the CO_2 migration in the reservoir in eight time-lapse measurement campaigns, confirming that no upward migration of CO_2 – consequently no leakage – occurs. The data are used for creating a full 3D simulation model. CATO2 built on these methods.

Most of the seismic methods are based on acoustic imaging: producing sound waves at different places and detect them at other places. By tracing the distortions and interference between different signals, these devices track and position any geological anomalies. Acoustic imaging experiments with so-called 'geophones' (microphones up to a depth of 50 m underground) also detect saturation levels of the CO_2 storage on different places, which is a welcome addition to storage modelling.

Many data have been extracted from monitoring experiments in the German project at Ketzin, where CO_2 has been injected into a saline aquifer. There, geophones have

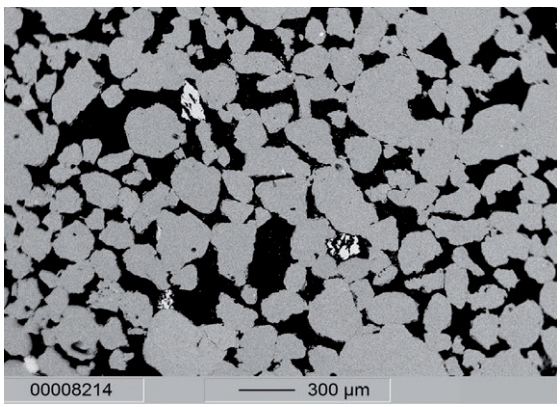


Image of a sample of sandstone, taken with the electron probe micro analyzer, which clearly shows the framework of pores and grains. The quartz grains (grey, typically 100 to 200 µm large) and the pore space (black) dominate, with some K-feldspar spots (grey-white) in between. Salimi et al. (2012).

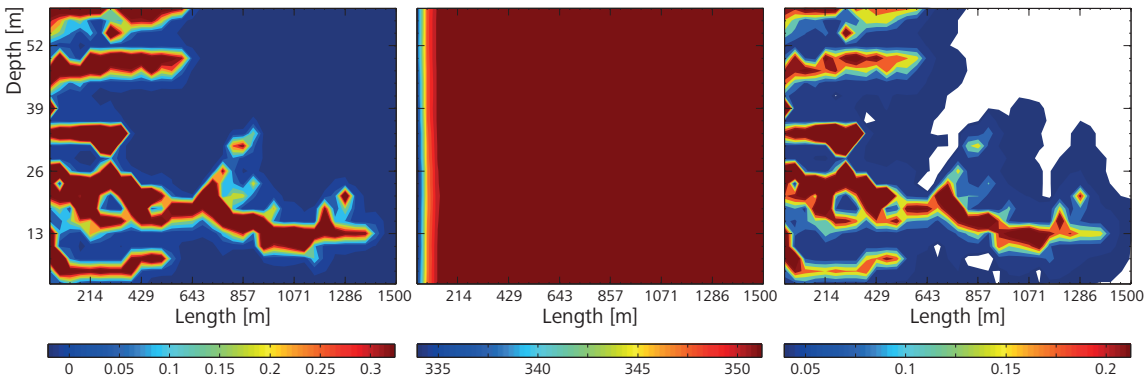
'listened' to sounds for four years (see also highlight **Improving seismic monitoring** on page 112). Many existing measuring methods have been investigated and new techniques have been developed, such as seismic ambient noise interferometry. This method gains information about the propagation of seismic waves from the cross-correlation of noise recordings such as traffic, industry, wind, sub-surface rock repositioning, et cetera.

CATO2 analysis of Ketzin measurements and data led to information about pressure falls, zones of small 'cracks' or fractures, and other characteristics of the underground reservoir and surrounding rocks. In addition, devices were upgraded to achieve a high signal/noise ratio. In effect, the permanent monitoring configuration of Ketzin has been tested and is ready to be adapted and used at any storage site, preferably onshore, but also offshore. CATO2 has added an important dimension to the knowledge on CCS monitoring by designing and calibrating monitoring configurations up to levels that are demanded by EU legislation.

Surface measurements of CO_2 are supposed to detect any leakage. Commercial devices for direct CO_2 detection are already available. The challenge is how to decide when and where monitoring is needed, to be (almost) sure that no leakage occurs during injection. The strategy is based on identifying the risk of a leakage with a large certainty, for instance by identifying deviations (for instance pressure drops) from expected situations such as in natural gas production, volcanic vents, et cetera.

CATO2 research also adapted, improved and developed other types of monitoring devices and configurations, which subsequently delivered data for increasing the accuracy of the models. Some examples:

- The use of (commercially available) infrared sensors for atmospheric CO_2 measurements, as extensively tested in Cabauw (Province of Utrecht). At that rural grassland spot, high natural fluctuations of CO_2 concentrations occur, which are measured by IR (reflection) sensors.



These three false-color pictures are the result of modelling of injection of CO_2 in a sandstone aquifer at 2.7 kilometers depth. On the bottom in horizontal, the scales are representing the saturation, temperature and gas-distribution. The left picture shows the extended gas saturation distribution of CO_2 gas (mol/mol) in the reservoir from the injection side (left). The middle picture shows the temperature distribution in K, which is clearly a few degrees lower next to the injection side. The right one shows the overall-CO_2-mole fraction distribution for all the CO_2 injected after a certain time. The brown 'fingers' show the corridors where CO_2 is faster distributed into the aquifer. Salimi et al. (2012).

- Fiberoptics: Glass fibre coatings that are sensitive to acidity and CO_2 concentrations. By sending light into the fibre and detecting it at the end, any changes in the coating can be measured and interpreted.
- Remote sensing techniques with satellites that are able to detect small surface changes.
- In case of offshore storage, biological monitoring of subsea locations has been developed, in order to track any impacts of leakages from the storage site.

Also in offshore monitoring of CO_2 leakage from the sea bottom, CATO2 delivered specific solutions.

Utilisation combined with storage

One way of isolating human-made CO_2 from the atmosphere is utilising the CO_2 in products where it will stay (almost) permanently. In one particular type of technologies, called CO_2 enhanced oil or gas recovery (CO_2-EOR/EGR), storage and utilisation are combined. North-America has stored millions of tonnes of CO_2 with EOR. CATO2 spent some research of this opportunity too, and also to its equivalent for gas recovery (EGR).

EOR/EGR is based on injecting CO_2 to produce additional oil and natural gas from partly depleted reservoirs, after primary and secondary recovery. From a business perspective, particularly EOR is profitable, because it can recover considerable amounts of additional oil. Under regular circumstances a reservoir will only release some 40 to 60% of all oil that is available. By injecting CO_2 (injecting nitrogen is an alternative) a part of the remaining oil is effectively 'pushed out', while CO_2 stays in the reservoir.

CO_2-EGR uses a different concept. A natural gas field not connected to an aquifer produces about 90% of all its resources before reservoir pressures do not produce any more natural gas. With EGR, injecting CO_2 slows down the pressure decrease during production, although the gases mix. EGR with CO_2 is not proven by economically viable large-scale production sites yet. CATO2 calculated a small benefit in particular cases, relying on existing infrastructural measures and provided that a legal framework removes regulatory obstacles that exist now.

Another innovative idea investigated within CATO2 involves combining CO_2 injection in aquifers while harvesting geothermal heat. Some scientific work has been conducted into the opportunity to use an aquifer at 2.5 km depth. Modelling of an underground structure near Delft indicates that the potential storage amounts to some 30 million tonnes of CO_2, while energy yields can be profitable. The study shows that in the classical type of Dutch clastic reservoirs one may expect a mixture of pure supercritical CO_2 to pure water, depending on the heterogeneity in porosity and permeability and temperature of the reservoir (see the figures on pages 102 and 103). Research on this case is still pending. This Delft project requires indentification of a geothermal well pair, before the discussion of the second stage, i.e. capture and co-injection can be restarted.

A third option, seasonal storage of CO_2 from a refinery for later use in greenhouses and by soft drink producers, was analysed by a CATO2 research project. The CO_2 stored in a depleted gas field acts as a solvent for water, hydrocarbons and even radioactive elements. CATO2 concluded that it is impossible to use the reproduced CO_2 in greenhouses or soft drinks because of contamination of the gas in the reservoir.

A natural lab for long-term CO_2 behaviour: Werkendam

EU regulations for CO_2 storage require an assessment of the long-term fate of CO_2 in the reservoir. Assuming that CO_2 has been successfully contained, the long-term effects depend on the gas-water-rock reactions within the storage reservoir. One way to investigate these long-term effects is provided by the natural gas field of Werkendam, which contains over 70% of CO_2. Investigations into this 'natural lab' supplied much insight on the gas-water-rock interactions, resulting in a model on the long-term fate of CO_2.

The principal processes that occur after injection are largely known. Directly after injection, the CO_2 is generally present in the reservoir in a phase that is called 'supercritical' (which is: not liquid, not gaseous, perhaps best described as a compressible liquid). Over time it partially dissolves in the formation water, thereby increasing the acidity of the water. As a consequence, some minerals in the rocks will partially dissolve, while in return part of the dissolved CO_2 reacts and becomes mineralized in carbonates.

Mineralized CO_2 is immobile and highly beneficial in terms of efficient storage. On the other hand, the dissolution of minerals into the acid, CO_2-saturated pore water potentially has negative side effects. Particularly in fault zones, dissolution of the minerals can affect the strength of the rock and therefore the geomechanical stability of the reservoir.

The potential of a reservoir to form carbonates from CO_2 and the time frames of the geochemical reactions described above prove to be highly case-specific. Hence, the complete assessment of the gas-water-rock interactions over the long-term is an important part of CO_2 storage evaluation.

Calibrating models on a geological time frame

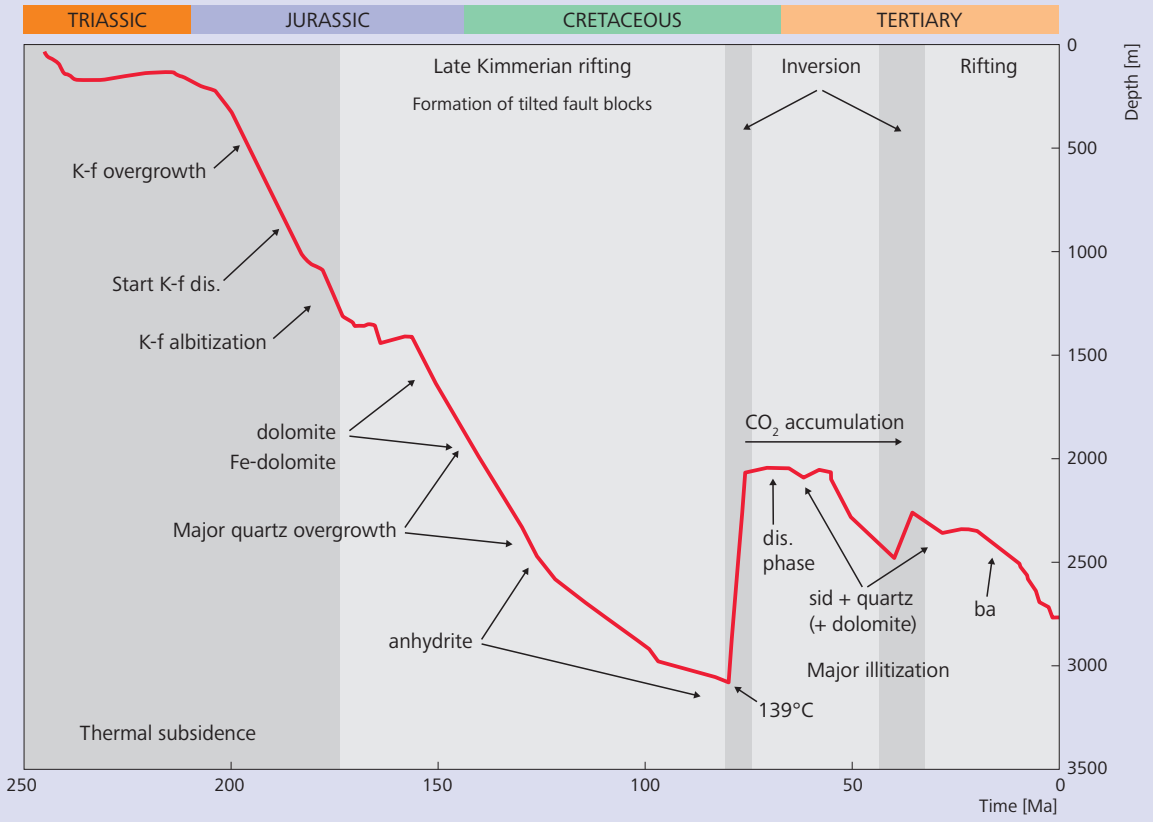
In principle mineral reactions due to CO_2 storage can be studied in the laboratory, with experiments that simulate CO_2-storage conditions. A major drawback of these lab tests is that these experiments can never be extended to geological periods of time – say millions of years. So geochemical models are necessary to build upon these experimental data and extrapolate them, in order to assess the long-term geochemical reactions.

Geochemical modelling is frequently applied for CO_2 storage evaluation. However, these models are necessarily simplified with respect to natural systems. Therefore they deal with large uncertainties. To circumvent these limitations of lab experiments and modelling, studies of natural CO_2-containing gas fields complement these tests and increase our understanding of the gas-water-rock reactions over geological time scales. The observed processes and chemical reactions, assessed in hindsight, are used to calibrate and further improve the geochemical models.

The natural CO_2 field of Werkendam is representative for numerous potential Dutch storage locations, both on- and offshore. These potential storage sites, including the P18-4 reservoir of the ROAD project, are mostly (future) depleted hydrocarbon reservoirs, located in the Triassic sandstone formation in the Dutch subsurface.

Petrographic analysis

The Werkendam field was drilled and investigated for natural gas production in 1991. Core material was obtained, which provided the opportunity to perform a petrographic study on Werkendam drilling samples. Comparison with samples from a CO_2-free reference field



Observed mineral reactions integrated with the burial history for the Werkendam natural CO_2 field. CO_2 accumulation probably occurred around 70-80 Ma during or after major uplift of the formation. K-f = K-feldspar, dis = dissolution, sid = siderite, ba = barite.

allowed the determination of the mineral reactions that occurred in the Werkendam reservoir rock as a result of the high CO_2 concentrations. The results of this petrographic analysis have subsequently been used to assess the ability of applied geochemical models to simulate the observed complex mineral reactions.

Core samples from the Werkendam field were studied and compared to samples from a nearby natural gas (CH_4) field in the same sandstone formation: the Barendrecht-Ziedewij field, which was initially selected as a potential storage reservoir for a CO_2 storage pilot project.

After deposition of sediments, mineral reactions occur during burial, due to changes in fluid compositions and pressure and temperature conditions. Since these mineral reactions are very slow and often incomplete, traces of previous minerals and textures are left behind. They provide the opportunity to deduce which reactions occurred through time. X-ray diffraction and Scanning Electron Microscopy methods were applied to analyse mineral reactions and determine their successive and relative occurrence over time.

The analyses show that the early mineral reactions were very similar in both gas fields. Slight differences can be

attributed to deviations in burial history of the fields. Concerning the later stages (probably the last 70-80 million years), the Werkendam samples show mineral reactions which are not observed in the samples from the natural gas field. These reactions include the partial dissolution of feldspar minerals ($KAlSi_3O_8$ and $NaAlSi_3O_8$) and anhydrite cement ($CaSO_4$), and the formation of small amounts of Mg-rich siderite ($MgFe(CO_3)_2$), barite ($BaSO_4$) and quartz (SiO_2). In addition, all kaolinite clay is converted to illite (illitisation). Part of the CO_2 seems to be mineralised in siderite. However, petrographic analyses did not allow quantification of the amount of CO_2 trapped in siderite since the formation of siderite is very local and only limited core material was available.

On the basis of the Werkendam and Barendrecht-Ziedewij cases, a geochemical (batch) reaction model was developed. In the model, a high CO_2 partial pressure was applied to the natural gas field mineralogy of Barendrecht-Ziedewij, in order to check if the model is able to simulate the CO_2-induced reactions that occurred in the Werkendam field. For this purpose, assumptions needed to be made with regard to the initial mineralogy, as well as potential secondary minerals which might precipitate. These assumptions influence the model results and they are not easy to fine-tune. We were able to select a set of assumptions for the model to match the observed reactions. However, further insight in the assumptions is necessary.

Conclusions and future challenges

The petrographic analyses of the Werkendam natural analogue for CO_2 storage and comparison with a CO_2-free reference provided quite some insight into CO_2-induced mineral reactions on geological time scales. The analysis showed that, compared to other natural CO_2 fields around the world, the trapping of CO_2 in siderite at the Werkendam field is unique. Most often calcite or dolomite is the precipitating carbonate. The formation of siderite might be caused by the lack of calcium or by high concentrations of iron in the formation water.

Concluding, geochemical modelling proves to be able to simulate the observed mineral reactions that happen in real geological life. However, the observation that the selection of assumptions needs to be better understood calls for a broader study, in which more natural analogues of different formations provide data to assess processes of importance in CO_2-induced reactions.

This research is conducted by Mariëlle Koenen and Laura Wasch at TNO, in cooperation with Utrecht University.

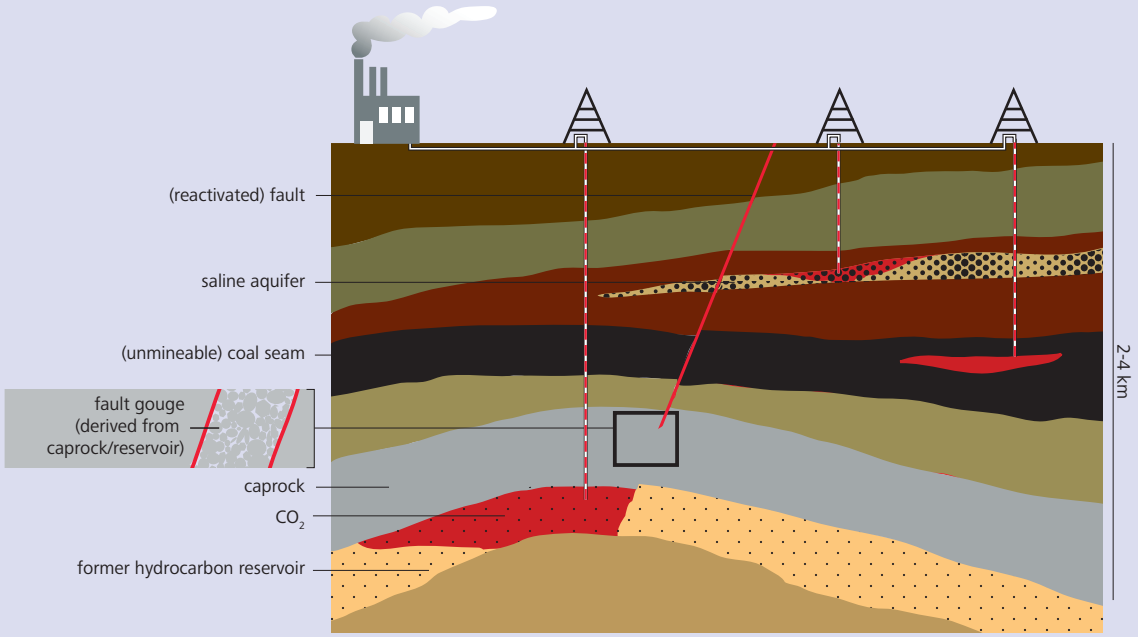
HIGHLIGHT

Assessing risks posed by faults

Geologically stored CO_2 will mainly reside in the pores of the reservoir rock as a highly compressed or 'supercritical' phase, with some dissolving in the pore water. To ensure successful trapping, the natural sealing capacity of overlying 'cap rocks' and cross-cutting faults must be maintained. A key risk here is that of fault activation and its potential for causing both leakage and induced seismicity. CATO2 research has evaluated these risks and indicates that CO_2 storage will have little to no effect on fault strength or stability for most rock types on the timescale of 10 to 100 years. Reassuringly, in the long-term, carbonate precipitation within faults will tend to increase fault strength and inhibit reactivation.

Geological faults consist of extinct, shear fracture zones containing finely crushed rock, called 'fault gouge'. Faults present in a CO_2 storage system, sited in a former gas or oil reservoir, contain gouge originating from the overlying 'cap rock' and from the reservoir rock itself (see the figure). Since such systems trapped hydrocarbons successfully for millions of years, the cap rocks and faults bounding the system must in theory continue to provide reliable sealing capacity.

However, reactivation of faults as a result of CO_2 injection or storage could lead to increased porosity and permeability, increasing the risk of CO_2 migration or leakage. CO_2 can potentially influence the frictional strength of faults through a variety of short-term effects during or in the years after injection, or through long-term mineral reactions during the subsequent decades to centuries. A decrease in frictional strength can potentially lead to fault



| A schematic impression of a storage site.

reactivation. Depending on the detailed mechanical properties of the fault gouge and the reservoir cap rock system, fault reactivation may result not only in CO_2 leakage but also in (micro)seismicity.

Lab experiments

Both short and long time scales have been investigated via laboratory experiments guided by modelling. Frictional stability was measured by determining how the frictional strength of the fault gouge depends on shearing velocity. This is important not only to determine fault strength, hence potential for reactivation, but also because fault gouge must become frictionally weaker with increasing velocity ('velocity weakening') for seismicity to be produced. If the gouge becomes stronger with increasing velocity ('velocity strengthening'), acceleration is impossible, impeding nucleation of seismic slip.

The HPT Laboratory at the Faculty of Geosciences at Utrecht University is a world leader in rock and fault mechanics and is well-equipped for research into the influence of CO_2 on the frictional properties of faults. In CATO2, fault gouge was simulated by crushing rock samples from key reservoirs and cap rocks from Dutch gas fields. A fault's motion is simulated by shearing a thin layer of rock powder between two L-shaped steel blocks, sealed inside a rubber jacket, located inside a heated pressure vessel (see figures on the next page), capable of simulating natural pressure and temperature conditions. This type of experiment generates data on the frictional strength of fault gouge as a function of host rock type, subsurface pressure, temperature, and fault sliding velocity. Dry and wet conditions can be investigated as well as the effects of varying pore fluid composition and of injected CO_2 (CO_2 in the supercritical phase, with or without water).

Short-term effects of CO_2

Experiments focusing on the short-term influence of CO_2 typically took several hours and involved rock types representative for the main Dutch gas reservoirs (Rotliegend and Bunter). The reservoir rock used was from the Hardegsen formation of the Bunter sandstone. Two types of typical cap rock were used: clay stones from the Röt and Solling Formations overlying the Bunter (W. Netherlands), and anhydrite from the Zechstein formation overlying the Rotliegend sandstones of NE Netherlands.

Short-term CO_2 exposure did not result in any significant changes in the frictional strength shown by fault gouges prepared from the above rocks, compared with normal subsurface (CO_2-free) conditions. Only Zechstein anhydrite gouges showed a 5 to 10% decrease in strength upon CO_2 exposure (wet and dry). This must be taken into account when determining allowable CO_2 injection pressures, to prevent fault reactivation.

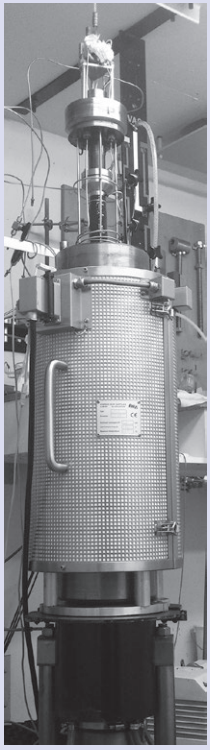
'Self-sealing' of faults

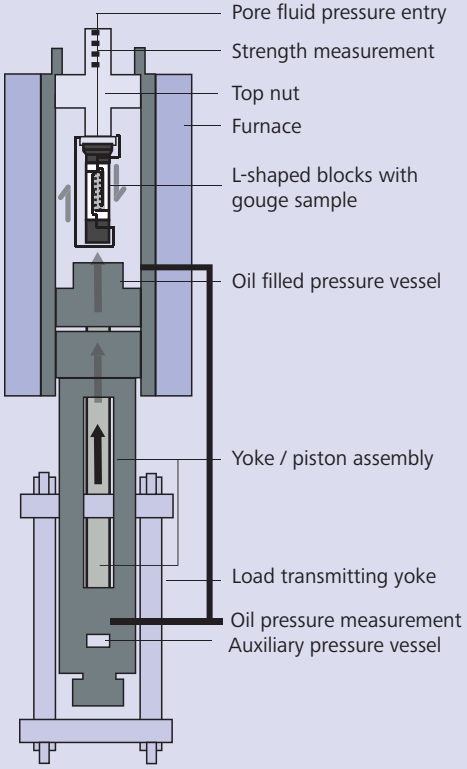
Other CATO-2 experiments on anhydrite-rich gouges investigated the effect of fault reactivation, hence gouge shearing, on gouge porosity and permeability, particularly the evolution of porosity with time after reactivation, and whether re-sealing occurs. Results showed that a reactivated fault in anhydrite is likely to compact to become impermeable again within a few decades upon cessation of fault movement, regardless of the presence of CO_2.

The behaviour in clay-rich fault gouges was found to be more complex. Some clay minerals (smectites) swell upon contact with water, but CATO-2 experiments showed that they also swell upon exposure to CO_2, though much less. This means that faults and fractures in smectite-rich cap rocks have the unexpected potential to seal through swelling of the mineral structure upon CO_2 penetration. These complex effects are being evaluated further.

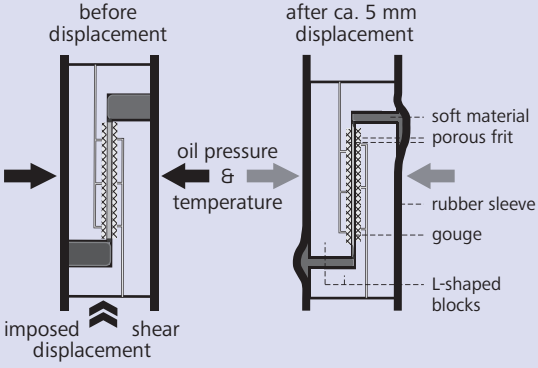
Potential for induced earthquakes

Under the conditions investigated, CO_2 injection had no effect on the velocity dependence of fault friction for any of the fault gouges studied. Therefore, assuming injection is engineered within normal safety margins, no (additional)





Apparatus used to simulate fault reactivation and motion at the pressures and temperatures pertaining in real CO_2 reservoir system at up to 4 km depth (left). It consists of a pressure vessel with a furnace. The L-shaped blocks pictured inside the schematic section of the pressure vessel (right) contain the fault gouge. Advancing the yoke/piston assembly slides the L-shaped blocks past each other, simulating fault motion. Under: L-shaped blocks with fault gouge. Gouge is pasted onto the blocks, and held together with a rubber sleeve before it is loaded into the pressure vessel. The movement then induced by the loading piston shears the gouge enabling its frictional properties to be measured. Picture A.H.M. Pluymakers, Utrecht University.



seismic activity is to be expected in association with CO_2 storage than in the case of injecting an inert gas. Zechstein anhydrite did reveal some potential for (micro-)seismicity under dry conditions above 120°C, but these conditions are not relevant for CO_2 storage in the Netherlands.

Long-term effects of CO_2

Long-term CO_2 storage (hundreds to thousands of years) is likely to influence the mineralogy of fault zones via chemical reactions, which will likely change fault frictional behaviour. First-order lab simulation of the mineralogical evolution of a generic fault zone suggests slight frictional strengthening, due to a bulk increase in frictionally strong minerals (quartz, feldspars, carbonates). However, site-specific modelling and lab simulation is needed to assess specific fault gouge types. In terms of (micro-)seismic potential. The lab simulations showed that carbonate precipitation related to CO_2-water-rock interaction can increase fault strength and hence reduce reactivation potential. On the other hand, if reactivation were to occur, the potential for induced (micro-)seismicity is also enhanced, but only at temperatures over 100°C and in fault gouges with carbonate content of 50% or more – which will only rarely result due to reaction with CO_2.

Anne Pluymakers is a PhD student and Jon Samuelson is a post-doctoral researcher at Utrecht University. They conducted these lab experiments, supported by Sander de Jong and Dr. Colin Peach and supervised by Prof. dr. Chris Spiers.

HIGHLIGHT

Improving seismic monitoring of CO_2 storage

One of the main challenges during and after the injection is to verify that CO_2 is behaving according to expectations. The spreading of the CO_2 and the changing pressure need to be monitored, for years or even decades. Obviously, any monitoring method at the surface has some benefits compared to methods that need (expensive) drilling. CATO2 research supplied some innovative ideas for improving seismic methods and demonstrated their feasibility, both in the laboratory and at the field pilot in Ketzin (Germany).

When monitoring CO_2 behaviour in a reservoir over time – particularly its pressure and saturation evolution – it is of the utmost importance that seismic recordings are of high quality and replicable. For monitoring, roughly two types of seismic techniques can be distinguished. *Active* seismic monitoring uses seismic sources and receivers at the surface; *passive* seismic monitoring only uses receivers for 'listening' to the subsurface events. CATO2 tested a smart combination of both to improve the existing methods.

Active seismic data acquisition at the Ketzin CO_2 storage site. Picture TNO.

The traditional methods are based on time-lapse seismic monitoring (with fixed intervals during a certain period of time) at the surface. However, this monitoring introduces many uncertainties. Both sources and receivers are positioned at the surface, far away from the target CO_2 reservoir at depths often much larger than 800 m. Changes in the layers above the reservoir, such as seasonal effects or changing water tables, can be misinterpreted as changes inside the reservoir. Similarly, the sources and the receivers may be differently located from one survey to another, which also may lead to misinterpretations.

In the Ketzin field, CATO2 researchers used permanently installed receiver arrays, in combination with a semi-permanent source. In addition, in scaled models the researchers developed and demonstrated new processing methods, based on so-called interferometry. CATO2 focused on two questions:

Can the repeatability of seismic experiments be improved, either by new processing techniques or by permanently installed data acquisition systems?

Can these seismic networks detect the subtle changes induced by pressure or saturation variations in the reservoir, including any micro-seismic activity induced by the injection of CO_2?

The seismic monitoring network at Ketzin

To demonstrate the added value of a permanent seismic network, in 2009 TNO installed a fixed monitoring network at the German Ketzin CO_2 injection pilot project. In this pilot near the town of Ketzin, CO_2 has been injected into a saline aquifer since July 2008. In 2013, when injection stopped, about 67 ktonnes of CO_2 had been injected in total.

The network consists of a two – dimensional seismic array of 120 meters length, with 3-component geophones at the surface, 4-component receivers buried at 50 meters depth and a central vertical array of 4-component receivers. The specific seismic test configuration has been applied for two purposes: the recording of high-quality *active* time-lapse seismic data to monitor the CO_2 migration; the recording of continuous *passive* seismic data to investigate to what extent the injection process creates micro-earthquakes.

During more than four years, passive seismic data have continuously been recorded and stored, available for research purposes. CATO2 researchers succeeded in creating an automated workflow that actually detected so-called 'micro-seismic' events. Particularly the buried hydrophones have demonstrated to be suitable for the detection and localisation of such small events. Compared with more traditional seismic surveys, these methods show an improved repeatability.

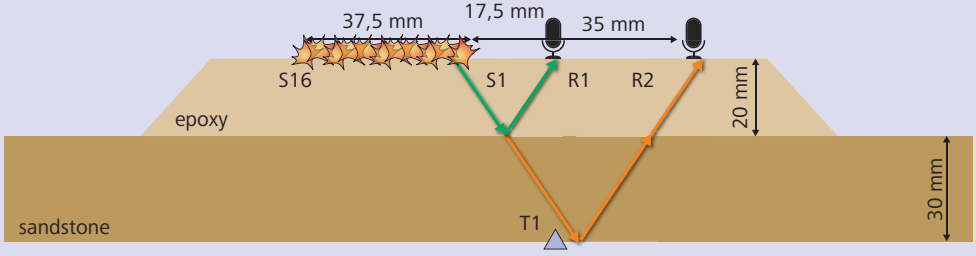
The added value of the Ketzin demo

For further exploring the potential of the network, an experiment was designed using a prototype fixed source during the period around the end of the injection. The source is a vibrator system driven by linear motors, a highly innovative prototype source under development at the Delft University of Technology.

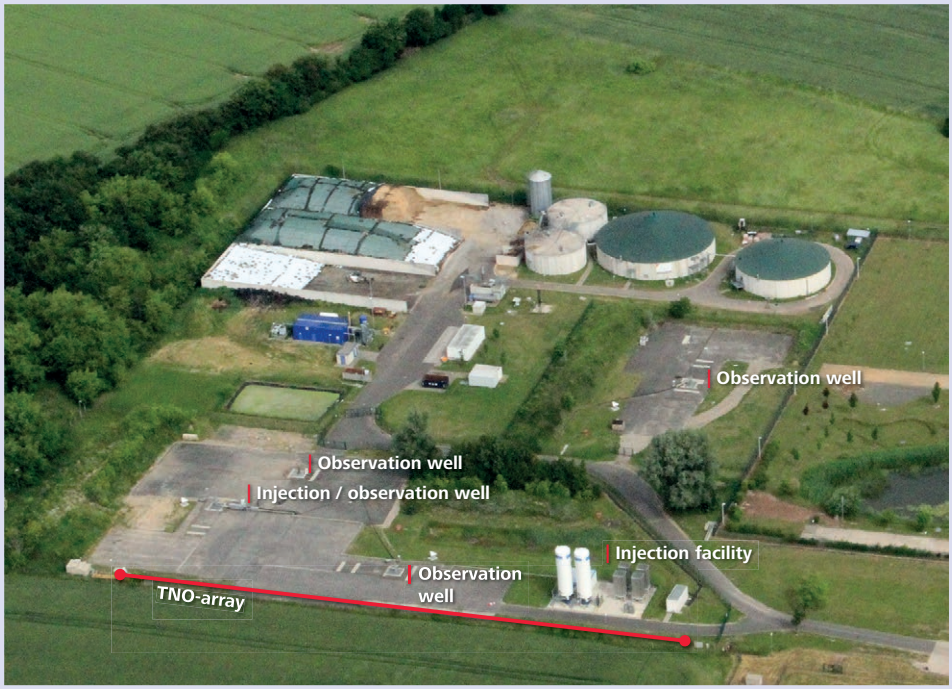
Around the end of the injection, one could expect to see a maximum effect in the vicinity of the injection well because of the decreasing pressure. Conventional systems would not be able to detect these effects. But the experiment with the permanent source and receiver system indeed showed a detectable time-lapse seismic response. Moreover, the 'shots' showed improved repeatability compared to a more traditional source and therefore detect changes that are much more subtle. The experiment indeed observed changes at the reservoir level, although more experiments are necessary to confirm these observations.

Processing technique using 'ghost arrivals'

In addition to the data acquisition methods, CATO2 also investigated innovative ways of processing the seismic data. 'Seismic interferometry' retrieves data by correlating the seismic response at two receivers. With sources positioned at the surface, the receivers (also at the surface) firstly monitor the physical reflections. In addition, interferometric processing of data from the receivers also supplies so-called 'ghost reflections'. These ghost reflections are obtained by eliminating the part of the signals that are due to the pathways through the overburden and are expectedly the same for both receivers anyway (see the figure underneath). By eliminating these pathways, the ghost reflections make it look as if (ghost)



The experimental setup, showing a twolayer sample used to monitor changes inside the reservoir. The bottom layer represents the (sandstone) reservoir, the top (epoxy) layer the cap rock. The ultrasonic data are recorded at the two receivers (microphones). By comparing the signals R1 and R2 and by applying seismic interferometry, the sources' nonrepeatability and the influence of the cap rock are suppressed. Draganov et al. (2012).



Picture of the installation of the permanent seismic source at Ketzin. Picture GFZ.

source and receiver were both placed directly on top of the CO_2 reservoir. This directly reduces the uncertainty caused by layers above the reservoir, and also increases repeatability.

The ghost-reflection method was validated in a specially built laboratory at Delft University of Technology. The ultrasonic measurements at two fixed receivers were simulated in a two-layer sample: the bottom layer was made of sandstone and represents the reservoir; the top layer was made from epoxy and represents the cap rock. Four measurements were made – one benchmark, three monitoring measurements – with changing saturation inside the reservoir. By deliberately moving the source, repeatability can be checked. The ghost-reflection method proved to be very accurate in estimating the changes in the seismic velocity.

More field testing

Although the combination of field testing and lab experiments show that the methods proposed are promising, more field testing is needed for confirmation. But CATO2 indicates that similar permanent seismic networks and innovative processing techniques are well-suited when real CO_2 storage is demonstrated. Fine-tuning of the system design will even further increase the possibilities for reliable monitoring.

The lab experiments were performed by Deyan Draganov (TU Delft) and Ranajit Ghose (TU Delft) assisted by Karel Heller (TU Delft). The Ketzin field tests were coordinated by Rob Arts (TNO).

Effective legislation, based on quantified risks

At the start of CATO2, the European Commission had just published its legal framework for safe and effective implementation of different CCS components. This CCS Directive set the social and legal boundaries, the responsibilities and liabilities for any CCS operation. However, the impact of the CCS Directive on the Dutch situation was largely unknown. Based on analysis, models and data, CATO2 research delivered knowledge on how Dutch regulation and permitting procedures can become compatible, safeguarding that CCS applications will be safe for humans and for the environment. In particular, CATO2 findings were applied in licensing the ROAD demo.

A license to operate

With a young chain of technologies without a considerable track record like CCS, a number of legal issues still have to become apparent. For instance, at this moment no large storage sites are in operation in the Netherlands, and hardly any in Europe. However, both stakeholders and authorities need to have a transparent set of rules, founded on the right data. Authorities need regulation to keep control of the CCS activities, within general social and legal boundaries for environment and safety. Meanwhile, investors and operators need them in order to be able to quantify risks and benefits in their business case and in designing the operation and maintenance of their activities.

The actual design and implementation of regulation and legislation are obviously a governmental responsibility. As a research programme, CATO2 contributed in four ways to a clearer picture of regulatory issues:

- Analysis and recommendations for an effective regulation design, based on EU legislation;
- Recommend practical ways of putting national regulation and licensing procedures into practice;
- Clarifying the rules for operators how to monitor and report on the performance of their site;
- Quantifying the risks for environment and humans.

The common interest in these issues resulted in research and development on a high level, mostly executed within sub-programme 4 for Regulation and Safety, with an interface to the data and knowledge from other sub-programmes. Most developments were led by research institutes and academia, with considerable input and advice from industry and authorities.

Also, international links to developments abroad have been crucial. Although legal issues may differ a lot from country to country, there is also some overlap, for instance in safety issues, validation of data or in monitoring and reporting about safety or environmental impacts.

Legislative framework ready to go

In April 2009 – just a few months before CATO2 was officially launched – the EU adopted the CCS Directive (2009/31/EC) on geological storage. This EU law is the foundation of legislation for storage of CO_2 across the EU. It covers all storage in geological formations in the EU, during the entire lifetime of a storage site. Also, the Directive lays the foundation of standards and criteria for storage site selection, in order to prevent significant risks or to remediate adverse effects.

Before 2009, storage of CO_2 was not well covered by legislation. The CCS Directive provided quite some guidance how to handle these issues. Further clarification on some issues resulted in extra guidance documents later on. But its actual impact on national legislation still had to be found out. The CCS Directive obligated national governments to have national legislation implemented by mid-2011, but many legal details still had to be solved.

With the EU CCS Directive as a starting point, CATO2 focused on developing a thorough understanding of the legal framework, and on making recommendations for the creation of regulations that are fit for the introduction of CCS in the Netherlands. It looked for answers on a wide range of questions. For instance, how to deal with offshore storage? How will monitoring and reporting of CO_2 leakage or safety issues look like? How can the access of third parties to storage sites be regulated?

In addition to these issues, which are directly related to storage, also the other components of CCS – particularly capture and transport – require specific knowledge and legislation.

With respect to regulations, it should be kept in mind that regulations are not only meant for control and management by authorities. They are also the guidance for both project developers and other stakeholders how to interpret and implement different aspects of legislation for capture, transport and storage and how to design their installations. Obviously, all these aspects affect any CCS business case. Moreover, a sound and clear set of regulations is a prerequisite for public acceptance of any industrial activity.

Long term climate liability

One particular characteristic of storing CO_2 is the need to keep the CO_2 from entering the atmosphere. Although there are some examples of natural underground fields where high concentrations of CO_2 have remained in place for millions of years, stored CO_2 from CCS projects may theoretically still leak to the atmosphere one day. CATO2 research into geographical conditions (see also the chapter on CO_2 storage) shed more light on the character and the size of possible leakage processes. This knowledge is

| Picture: © European Union 2010 PE-EP

also the basis of safety regulation, safety measures and monitoring and reporting measures.

The actual activities around CO_2 underground storage resemble some usual mining and industrial activities, but have some particular characteristics. One discriminating aspect is the long-term liability of storage of CO_2. This aspect is related to questions such as:

- What happens in the long term with stored CO_2?
- What are the chances of CO_2 leaks, and what would be their size?
- What is the impact of such CO_2 leaks for climate change, environment and humans?
- Who is liable?

When following the principle of 'the polluter pays', the producers of CO_2 should be held liable for what happens to their waste gas. This liability can be transferred to the operator of the storage site, who gets paid for taking over the responsibility. However, an eternal liability for the site operator is not practically feasible. The operator may not even exist anymore as a legal entity when something happens to the storage site. So other solutions are required.

Usually, very long-term liabilities are taken over by the collective or the state. Also in the case of CCS, the Directive has chosen to finally transfer this liability to national governments. In parallel, shared funds can be created that will allow compensation of any damage that might be caused by leaking CO_2.

Another problem that arises with long-term storage and obtaining a permit is related to the possible leakage of millions of tonnes of CO_2 from the storage. If large amounts of CO_2 leak to the atmosphere, the EU system for emissions trade will require the operator to submit the equivalent amount of emission allowances (European Union Allowances, EUAs). This contingent liability is potentially very large compared to the value of the storage activity, especially if prices of CO_2 allowances have substantially increased. It therefore creates an imbalance between the financial risk and the commercial opportunity expected for CCS storage.

Should an operator keep these emission allowances on his account, or do any better possibilities exist? CATO2 presents a number of structural solutions that keep the financial burdens for project developers at a feasible level. These scenarios include government re-insurance, reducing the liability period, pooling liability funds and temporary storage allowances (see also highlight **Overcoming the risks of climate liability** on page 122).

Impact on CCS business cases

Meeting any regulation has financial implications for the operator, as countermeasures and monitoring have a cost and can even become expensive. In general, severe regulations could increase costs. But first and foremost, knowledge of the risks is of great importance, in order to be able to quantify risks and liabilities and to base regulation upon this knowledge. In this respect, CATO2 achieved results that are important for the business case.

Knowledge that leads to fine-tuning of regulations reduces costs. One example is the way CO_2 storage is insured. Insurance companies base their premiums on the basis of data, experiences and models that are representative of the actual situation. If these data are missing, the best guess of insurance companies will always be on the safe side. Either they will not insure the activity, or premiums will be relatively high. However, knowing the risks lowers the insurance fees, and therefore improves the CCS business case.

Another way in which CATO2 improves the business case is that reliable data create a better mutual understanding of risks between operators and authorities. Having a shared set of risk data makes it easier to set fair permitting conditions, to manage risks, to meet conditions and to monitor in an effective way. This directly contributes to lower operation and maintenance costs.

Transboundary issues

Another unanswered regulatory question at the start of CATO2 concerned cross-border CCS activities. The first EU demos are likely to be point-to-point, with both source and sink within the boundaries of one EU member State. But in order to make a significant contribution to 2050 climate change goals, the EU will need massive deployment of CCS, and therefore extensive CO_2 transportation networks, which connect emitters to CO_2 storage sites, e.g. all around the North Sea. This development will lead to regular cross-border CO_2 transport.

This transboundary movement can only be realised if a number of legal issues have been resolved. CATO2 analysed a number of pending legal issues, including financing and ownership, third-party access of networks and financial liability. In addition to these legal issues, potential ownership and investment approaches for CO_2 transportation infrastructure have been investigated. Economic theories about how to organise this have been tested against the views among actual industrial stakeholders, using a survey.

This led to the conclusion that in order to take advantage of economies of scale and the equitable distribution of pipeline infrastructure, some form of governance will be essential. Government involvement may be necessary to help co-fund, or provide financial guarantees for the oversizing of pipeline capacity in anticipation for the broad deployment of CCS, once the fundamental incentive structure are in place.

Furthermore, the same survey suggests that unilateral support for national pipeline projects, through either direct financial support or the involvement of publicly owned entities in the development or operation of pipeline projects could cause conflicts when combining pipelines into transboundary networks. Therefore, a European support fund to support the development of cross-border transport infrastructure must be considered for future implementation, dependent on the progression of CCS as a climate mitigation technology.

In the case of a CO_2 pipeline spanning across multiple countries, each Member State has jurisdiction over the part of the pipeline situated on its territory. This means that several regulatory regimes may be applicable to one network. As Member States are allowed to have more stringent demands than issued in EU laws, potential operators may have to deal with multiple authorities with potentially conflicting permit demands. CATO2 recommends that a dialogue between national governments will be instrumental to reducing the risk of potential jurisdictional barriers and prolonged planning procedures concerned with CO_2 transport infrastructure.

This particular transboundary research is a good example of the international connection of CATO2 with researchers abroad, such as in the IEA Regulator Network on CCS.

Subsea legislation

An interesting test case for the adequacy of legislation is a CCS storage project in the North Sea (as planned in the ROAD project). The introduction of an enabling regulatory EU framework for CCS has provided clarity on many aspects, but it has also introduced questions regarding implementation of the regulation. Taking the perspective of a project developer, studies provide an overview of the legal issues that the initiative will encounter. A CATO2 comparison of the rules and legislation of the countries surrounding the North Sea reveals many differences with regard to these issues and identifies a number of salient legal barriers. As said above, the most pressing legal barrier relates to the obligation for storage operators to surrender CO_2 emissions allowances in case of leakages.

For environmental issues regarding North Sea transport and storage, the legal framework OSPAR exists, which is an agreement between fifteen countries around the North East Atlantic, protecting and conserving the marine environment and its resources. The OSPAR convention,

which in 1992 originated from the Oslo and Paris conventions, prohibits dumping, preserves biodiversity and ecosystems and essentially covers all human activities that can adversely affect the seas. Regarding CO_2, how would the OSPAR framework translate into implementation of regulation in order to prevent CO_2 'dumping'? For this purpose, CATO2 investigated the consequences of normal operation and possible leakage to the subsea environment.

The transportation of CO_2 by ship has also emerged as a potential alternative to CO_2 pipelines, because of the lower investment costs and flexibility that CO_2 carriers provide. However, little is understood about how CO_2 transport by ship is regulated, and how it fits into the EU regulatory framework for CCS. In order to assess how well-developed the existing legal framework is, CATO2 made a comparative analysis of the regulation of the ship transport of three substances which (as a reference) could cause damage: nuclear materials, oil, and liquefied natural gas (LNG). Based on this assessment, it is recommended that further legislative measures are required to pave the way for large-scale ship transport of CO_2 for permanent storage offshore. In order to explicitly envisage transport of CO_2 by ship, the EU CCS Directive, the ETS Directive and the Regulation on Monitoring and Reporting of greenhouse gas emissions should be considered for amendment.

Analysis of other legal issues

CATO2 analysed some other legal issues that were identified as crucial for further deployment of CCS projects, or at least of CCS demonstration projects. One issue is so-called 'third party access' (TPA). CATO2 analysed some modes of allowing other stakeholders to access infrastructure for transport and storage owned and operated by another party. Arranging TPA is essential within the liberalised EU market for energy, and is also crucial for sharing costs for large infrastructure among different parties.

CATO2 also analysed some organisational modes to share risks and investments, allowing for dimensioning the pipeline's capacity for future growth.

For example, long term contracts can be established between the project developer and secondary users that commit to capacity requirement at a given tariff. Similarly, the UK offshore oil and gas regimes oblige pipeline developers to 'market test' the demand for new capacity, thus encouraging the formation of investment coalitions that pool their pipeline capacity requirements. The US interstate pipeline regulations impose an obligation to hold 'open seasons', encouraging multilateral investment from the project outset. Joint implementation of a pipeline project designed to run at near full capacity, removes the incentives for a 'late comer', while still exploiting economies of scale.

In many parts of the world, Enhanced Oil Recovery has proven to be a first mover for CCS projects. EOR involves injecting CO_2 to increase the production from an oil field. This generates extra income, while a large part of the CO_2 stays in the field. A similar technique can be applied to empty gas fields, which are numerous in the Netherlands and at sea. However, Dutch mining legislation does not allow having a combined concession for both the production of oil and gas and for the storage of CO_2 within the framework of the European emissions trading scheme. Now, with the knowledge generated by CATO2 this barrier of non-existing regulation can be resolved.

Licensing procedures

Following the legislative framework, CATO2 developed knowledge about regulation that allows particular operators to apply for and get a permit. Much attention was paid to the underlying data on environmental and safety performances and to monitoring and reporting guidelines.

CATO2 identified some best practices from licensing and certifying CCS activities at designated CCS sites in the

Netherlands (offshore as well as onshore urban and rural areas). The results of these investigations culminated in two features:

- The ROAD demonstration plant was able to go through an entire procedure and finally get a permit. So far, EU laws had not been tested in practice, because no demo was realised yet. Laws are in place (CCS Directive), but with CATO2 knowledge, the authorities have now actually translated this into Dutch legislation and applied to the ROAD case. ROAD is the first CCS project in the EU where a complete permitting procedure has been finished.
- A decision tree has been designed, showing all best cases and clarifying to applicants which authority to approach for which permit or element of a permit at what moment in the procedure. Permitting roadblocks have been identified, different requirements for different legislation (Law on Environmental Impact Assessment, Spatial Planning Act, other laws) have been mapped.

Measuring environmental impact

Life cycle inventory, analysis, and valuation of the environmental performance of CCS chains are an important input to both authorities and companies in order to avoid environmental damage. However, at the start of CATO2 environmental performance assessments of CCS chains were not satisfactory. They covered only a few capture solvents, they missed out on many toxic emissions and waste and had large uncertainties, due to a lack of measurements.

CATO2 developed a tool for analysis of the environmental impact of different CCS configurations. For this Life Cycle Analysis tool, CATO2 first collected the relevant data and models on the environmental performance of CCS technologies. Along with this data collection, CATO2 developed different methods for ranking environmental impacts for the most relevant chains of CCS technologies, such as solvent emissions, waste by-products, emissions, and water consumption. For this ranking, CATO2 applied literature studies, but also (confidential) monitoring data from partners.

This research led to the development of the environmental performance tool, valuing different types of impacts in a simple and transparent way. The tool includes the opportunity to design different variants of complete CCS chains, from fuel extraction to electricity generation and CO_2 capture and storage. Meanwhile, also a first screening of the environmental performance of second generation CCS technology chains was performed (see also highlight **Environmental performance tool** on page 124).

Monitoring and reporting

In the application for a permit, the operator has to show his plan for monitoring the important parameters of its activities, and for reporting on this monitoring. CATO2 provides the practical guidance on monitoring plans for CCS.

For instance, capturing CO_2 should be monitored, in order to be eligible for the exemption of submitting emission allowances under the EU Emissions Trading System. The EU ETS Directive allows operators of industrial installations or power stations not to submit EUAs for the amount of captured CO_2, but as this represents large amounts of money, the monitoring should be highly reliable. Based on research, CATO2 provides guidance on quantification approaches and suitable technologies for EU ETS Monitoring and Reporting Guidelines for CCS.

One important outcome of this type of CATO2 research is a tool for developing the right and efficient monitoring plan. In principle, this tool leads the applicant through the process of designing the monitoring plan, starting at the major issues and the major risks, and after that descending to smaller risks. Many stakeholders from many countries have shown interest in this tool, which has been downloaded from the CATO website more than 2500 times.

Analysing and modelling safety risks

Existing risk models for natural gas – often used as a benchmark – do not always apply to the case of CO_2, because of chemical and physical differences. Before, it was not always known which model can be applied in which situation (capture, transport, storage). But experiments have led to the adaptation of risk models and analysis.

The risk assessment model for CO_2 pipelines was developed with a view to support risk management and licensing of CO_2 pipelines, and to facilitate spatial planning. Very important input came from the so-called tank experiments. These experiments delivered the data on the possible release of CO_2 in case of a pipe rupture, and how the CO_2 would disperse in the local surroundings. The experimental variables were for instance pipe pressures (80, 120, 150 bar), impurities and simulated rupture sizes, which provided data on volume of CO_2, outflow, pressure, temperature, droplet sizes, and other data. Basically, these data are used to validate and improve the risk models (see also highlight **Safeguarding the CO_2 transport network** on page 127).

HIGHLIGHT

Overcoming the risks of climate liability with CO_2 storage

'Climate liability' refers to the financial risk associated with geologically storing CO_2 in regions where CO_2 emissions have a market price. In the EU, potential CCS storage operators have underlined climate liability as a significant and internally unmanageable risk. CATO2 investigated the issue in detail, and provides possible solutions to overcome the risks of climate liability to CCS operators.

The EU Directive on the geological storage of carbon dioxide sets out a comprehensive framework to mitigate the environmental and health impacts of CO_2 storage. It also provides an economic incentive for CCS: captured CO_2 stored in accordance with this CCS Directive counts as not-emitted within the framework of the EU Emissions Trading System (ETS) Directive. If this CO_2 value is sufficiently high, CCS becomes interesting for private investors as a CO_2 abatement measure.

However, the CCS Directive also creates liabilities and obligations. The majority of these consist of environmental permitting arrangements and implementing the 'polluter pays' principle. They require storage site operators to monitor the storage site, implement corrective measures and remediate any damage to the environment in the event of unforeseen circumstances. This applies to the whole of the CCS chain.

Allowances in case of leakage

In addition, EU regulation creates an obligation to surrender CO_2 credits (European Union Allowances, EUAs) in case of leakages. This seems equitable. But a significant discrepancy may arise between the value of the permits at injection and the value at a leakage event in the future, when climate targets become more stringent and the price of emissions allowances increase. Hence, the climate liability potentially exceeds the value of the original storage activity.

This creates an imbalance between the risk of financial exposure and the commercial opportunity of CCS storage. Storage operators in the Netherlands have highlighted this climate liability as a significant and internally unmanageable risk which may act as a deterrent to attract investment for CCS projects.

The risk level

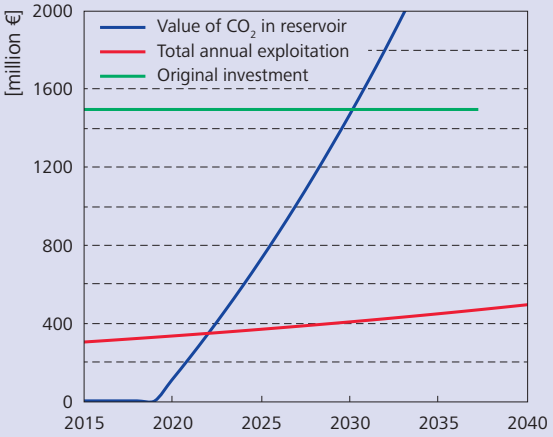
Work completed within CATO2 has quantified the level of financial risk associated with climate liability, through the use of a basic model calculation of a hypothetical CCS project: a 600 megawatt coal fired power plant, with an annual capture and storage of 3 million tonnes of CO_2 ($MtCO_2$).

The total investment costs of the power plant and capture unit are set to € 1,500 million, with an annual € 300 million for capital and operation and maintenance costs. The model shows that the value of the stored CO_2 in the reservoir rises rapidly over the annual exploitation budget for the combined power plant. Within a decade after the start of the project, the CO_2 value even exceeds the total investment costs for this unit (see the figure).

Reducing the climate liability risk

The example above demonstrates to what extent climate liability in the EU will be a concern for potential CCS project developers. CATO2 investigated what regulatory or policy mechanisms can be considered to reduce the risks of climate liability.

CATO2 organised an expert legal workshop to hear the views of stakeholders from businesses, the government,



The figure shows the increasing value of the accumulating CO_2 (+3 $MtCO_2$/year) in the reservoir in comparison with the original total investment and the annual exploitation budget. CO_2 injection starts in the year 2020 with an initial CO_2 price of € 36.6 per tonne. The CO_2 price is assumed to rise 2% annually, which results in a price of € 44.6 in 2030 and € 54.3 in 2040. Picture CATO2.

non-government organisations and academia to discuss the issue. The workshop was identified some possible solutions to address the issue:

• **Transfer of responsibility after a limited period.**
Currently, the responsibility for a CO_2 storage site is expected to be transferred to the authorities after a period of twenty years. Instead, the length of the period could be based on the performance of the storage site. As with the selection of the site, site characterisation and monitoring strategy are based on scientific insights, this principle should also be applied to the (post-)closure phase. Reducing the transfer period to three years for example requires an intensive post-closure monitoring survey under the supervision of the competent authority itself. This solution can be applied on a national level.

• **Liability cap based on historic EUA price**
Setting a maximum deviation from the EUA prices at the time of CO_2 injection, in the case of future CO_2 leakage does not necessarily reduce the liability for an operator, but 'caps' the liability upon which an investment decision can be made. This option requires significant alterations to current regulation, both the CCS Directive and the EU ETS.

• **Spreading the ETS liability over the whole chain**
The long term EU ETS liability can be distributed among capture, transport and storage operators, which reduces the risk faced by storage operators but increases risks for capture and transport. This would require a change in the CCS Directive. Also, this option could get very complicated in the case of multiple-use infrastructure.

• **Member State involvement**
The Member State can act as last-resort insurance for some of the EU ETS liability, for example when the EUA price or the cumulative value of the stored CO_2 exceeds a threshold. Other Member State involvement could include a contribution to a national financial security pool, also funded by operators. However, Member State involvement is contrary to the CCS Directive and will have to be assessed under state aid regulations.

• **EU Financial Security Support EU ETS**
The EU ETS liability of future demonstration projects could be covered by a reserve of EUAs, established by withholding an amount of EUAs each year from the EU ETS auction process. If no leakage occurs within the demonstration phase (say 5 years) EUAs can be auctioned.
The expert legal workshop did not identify one single favourable solution. However, a consensus did emerge about a split between the demonstration and the commercial stage. The demonstration phase needs additional support, whereas in the commercial phase more options are available.

Thomas Mikunda (ECN) investigated the subject of climate liability, together with Avelien Haas-Kamminga, Rieks Boekholt (RUG), Joost de Wolff (DNV-GL) and Manuel Nepveu (TNO)

HIGHLIGHT

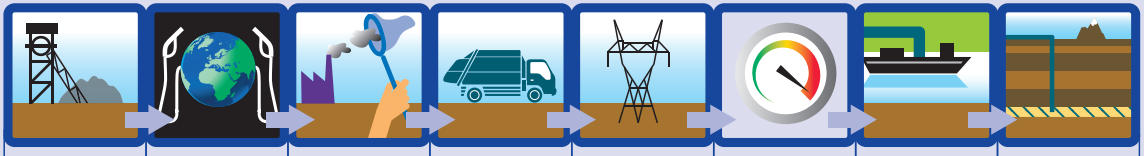
Environmental performance tool assesses the lifecycle of CCS chains

Decisions on the deployment of CCS require reliable data, for instance on CCS environmental performance. Within CATO2, much attention has been paid to developing a strategic tool that assesses the environmental performance of CCS chains over their life cycle. The tool offers stakeholders the ability to build, adapt and compare CCS chains. The tool proves to be a sound basis for both knowledge sharing and stakeholder engagement.

The overall environmental profile of a power plant – including its life cycle – changes if CCS is applied. This effect is positive for greenhouse gases, because emissions are lower per MWh for plants equipped with CCS compared with a similar plant without CCS. But regarding other environmental themes such as acidification and eutrophication, the balance may be positive or negative. Life cycle assessment (LCA) of CCS chains provides a better understanding of the full environmental benefits and trade-offs.

LCA tool limitations

Although LCA is a powerful tool, there are some limitations when using it for assessing CCS chains. For instance, decision makers or stakeholders will find it difficult to apply dedicated LCA software for constructing and analysing a life cycle for power plants with CCS. Comparison between existing LCA studies is also difficult, because major assumptions and methodologies (like system boundaries, unit of comparison, and impact assessment and methodologies) are not easily accessible and transparent. These assumptions have a large impact on the end-result, which in turn may result in mixed messages about the environmental performance of CCS technologies. Stakeholders may also have different viewpoints regarding the environmental theme they regard as most important. Weighing of results accordingly may result in very different results, which may complicate the debate.



Fuel extraction	Fuel logistics	Conversion and CO_2 capture	Waste from conversion & capture	Distribution of energy carrier	CO_2 compression	CO_2 transport	CO_2 storage
One possible chain of different options:							
Coal (Dutch supply mix)	Ship oceanic + inland	Pulverised coal + post combustion capture	Reclaimer waste from post combustion capture	General distribution	Electric (from power plant)	Pipeline onshore	Hydro-carbon (onshore)

Overview of steps of the life cycle for power generation with and without CCS.

The strategic environmental performance tool

CATO2 developed the Strategic Environmental Performance Tool, based on the following pillars:

Accessible: The user does not need to have specialised knowledge of environmental impact assessment or life cycle analysis and is able to assess the environmental performance of CCS chains in some simple steps.

Transparent & Traceable: Data on the environmental performance of CCS technologies have been collected in a central database. Comments and literature references have been added to track-and-trace the origin of the data.

Flexible: The tool is also flexible in the output in terms of graphs and data tables, so that the tool can be used for multiple purposes and perspectives. Major assumptions can easily be changed to show impacts on end-results.

Steps in building the tool

The tool has been constructed following a few subsequent steps. First, the CCS chain is unravelled by choosing a specific activity per step. The CCS chain consists in total of nine steps (see figure): Fuel extraction; Fuel logistics; Conversion and capture of CO_2; Waste from energy conversion; Waste from capture of CO_2; CO_2 compression; CO_2 transport; CO_2 storage; and Distribution of the energy carrier. The user can build one or multiple chains simultaneously to allow direct comparison.

In the next step, an environmental performance database is designed, consisting of data of energy conversion supply chains, including CO_2 capture and storage. The database has an (Excel) overlay for easy data entry, calculations and review. The database functions as a platform where environmental performance data of steps in the life cycle of a power plant with or without CCS are gathered, prepared and stored. The information feeding the database is gathered per step of the chain from LCA literature, existing life cycle inventory databases (for example Ecoinvent) and – where possible – results of international emission measurement programmes at CCS pilots and demonstration plants.

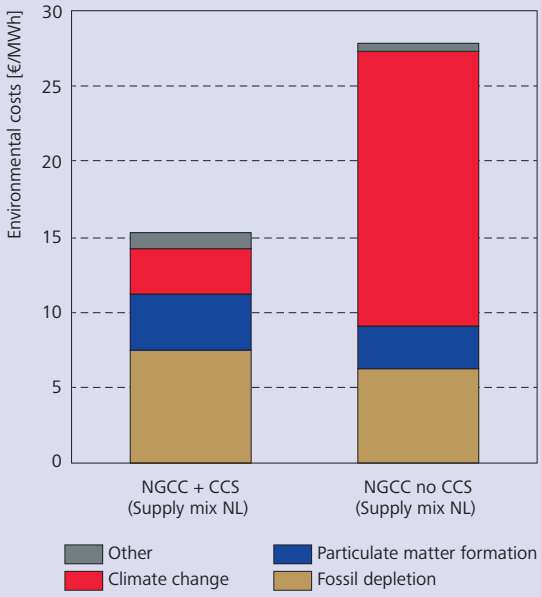
The tool uses a well-accepted methodology (ReCiPe) by default for calculating the environmental impacts from life cycle inventory data, such as data on emissions, water consumption, raw material use etc. With this methodology, the tool includes a set of eighteen environmental impact categories and five weighting sets. The user of the tool can add, change or review information on environmental performance of steps of the life cycle and add comments for further detail. The user can also add new (sets of) environmental categories.

In the next step, the tool calculates the impact scores for multiple environmental themes or categories. Additional insights can be obtained by grouping or weighing the different environmental impacts according to predefined set of weighting factors or to the preference of the user. Valuation or weighting allows translation of stakeholder perspectives. Monetisation of end-results is also possible to express the environmental damage costs across the life cycle. Such analyses may show under what conditions the benefits of CCS outweigh the trade-offs, from different stakeholder perspectives.

Accessible results

The results of the calculations are presented in an output Excel file. The file presents easy-to-review data on the selected chains. For the advanced user, it also includes the detailed data.

One example of an outcome is the environmental performance of a natural gas fired power plant with and without post-combustion capture of CO_2 (see figure) . The user can directly compare and change the information by modifying the functional unit of analysis (the power produced or the primary energy used), by changing the set of environmental themes, by selecting the amount of chains, by modifying the amount of steps of the life cycle and by changing the preferred weighing set. The ability to



Environmental damage costs of producing 1,000 kWh of electricity plus distribution of contributions from environmental themes for a natural gas fired power plant with and without post-combustion CCS. The 'other' costs are represented by many smaller issues like eutrophication or acidification.

create graphs allows the user to analyse the results from different perspectives and use the tool to create better insights and discuss these with other stakeholders.

Obviously, the data should be up-to-date, representing state of the art technologies. As a next step, the tool can become a web-based interface. Other suggestions for improvement are to enable the comparison with other sources of energy production, such as renewables. The research efforts can also be extended to CCS at industrial facilities, such as iron & steel, cement, refineries, and chemical plants.

TNO, Ecofys, ECN and Utrecht University performed this research: TNO (Arjan Horssen, Toon van Harmelen), Ecofys (Joris Koornneef, Ruut Brandsma), Utrecht University (Andrea Ramirez, Wouter Schakel, Mariëlle Corsten), ECN (Arjan Klomp, Koen Smekens).

Safeguarding the carbon dioxide transport network

From the start of CATO2, safety issues related to sudden CO_2 releases from transportation pipelines have been recognised as of high importance. By validating the models with experiments, CATO2 succeeded in upgrading the quality of Quantitative Risk Assessments (QRA's) and substantially reduce their uncertainties. This provides more confidence in safeguarding the CO_2 transport.

Safety is a crucial issue with every large-scale industrial activity, so also with transport of CO_2. In a commercial stage of CCS, millions of tonnes of CO_2 will have to be transported from capture plants to the storage sites. This CO_2 preferably is transported through pressurised pipelines, which may stretch for tens, maybe hundreds of kilometres through more or less densely populated areas. The need for safeguarding these pipelines is obvious, knowing that CO_2 in high concentrations may suffocate people and animals, and even the effects of toxicity of high concentrations may not be excluded.

Bearing this in mind, risk analysis with respect to CO_2 pipelines was an important research topic within the CATO2 programme. Not only the safety itself is important, but also the way in which the public perceives the safety of transportation pipelines, and how it judges the way the safety is guarded. For these reasons, risk analysis needs to be sound and transparent and data should not be disputable.

Improving risk analysis

Basically, any analysis of accidents regarding CO_2 releases from pipelines or pressurised containers is based on thermodynamic models of the subsequent event. Modelling the thermodynamic behaviour of CO_2 (thermodynamic) on its accidental release is not easy, given the substance's unique phase change characteristics.

One way in which risk analysis models can prove their value and reliability is by showing the same results every time the analysis is applied. At the start of the CATO programme, risk analysis of CO_2 transportation usually did not show much consistency in the results. CATO2 invested quite some effort in theoretical and experimental research activities, in order to improve the knowledge on CO_2 transport costs and transport safety.

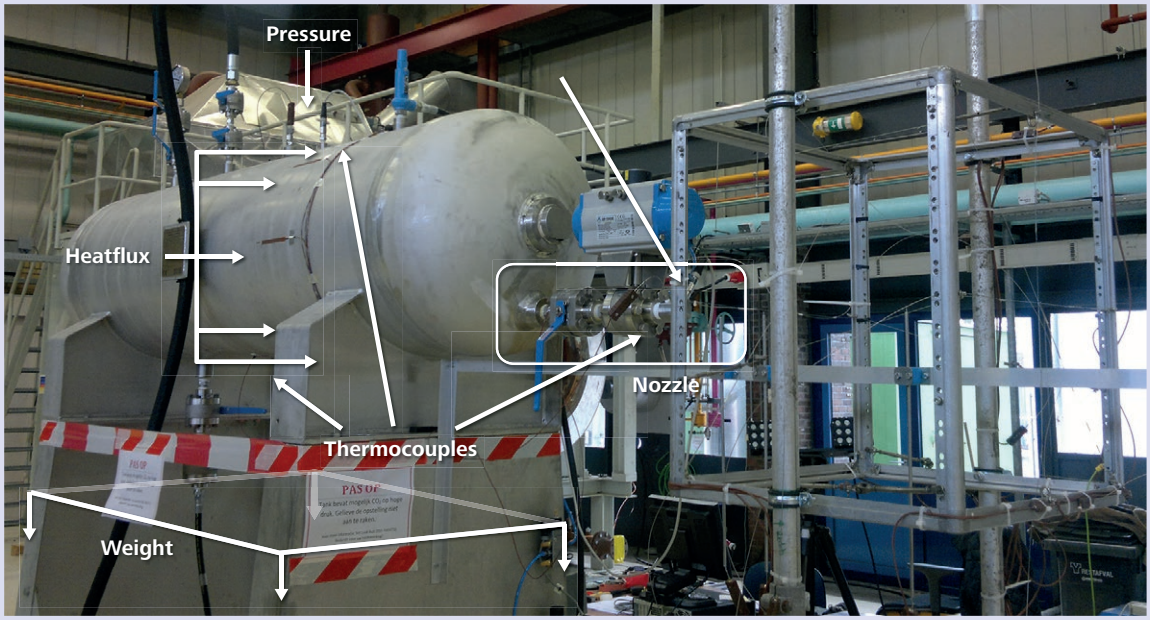
The experiments within CATO2 focused on gaining a better understanding of the thermodynamic behaviour of CO_2 after its release from a pressurised container or a high pressure pipeline. To a large extend, data from these experiments allowed to further develop and validate the existing outflow models.

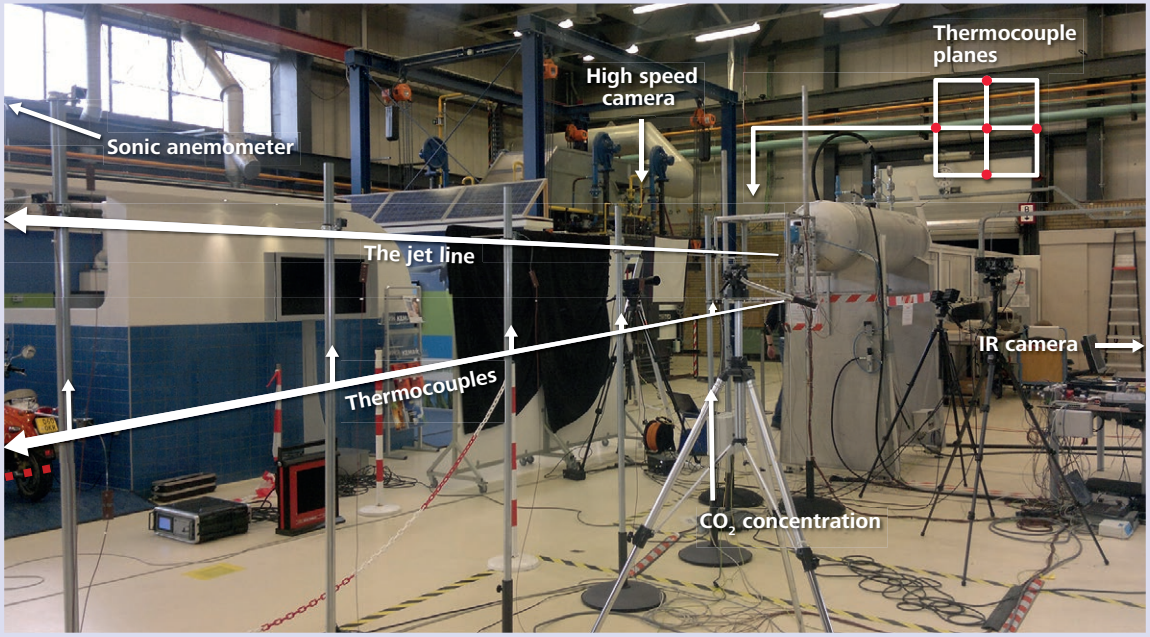
The experiments

Different scenarios for an accidental release of CO_2 from a high-pressure pipeline ('loss of containment') were experimentally simulated at two facilities. At the research facilities of DNV-GL Groningen (formerly Gasunie Research and DNVKema), CO_2 was released as a pressurised liquid or as a dense gas, representing different cases of CO_2 transportation (see figure on page 128). In particular, initial pressures and outflow nozzle sizes were varied to represent different scenarios.

These experiments acquired data on the following quantities:

- The temperature in different locations of the jet (the stream escaping from a ruptured pipeline or container);
- The physical phase of the jet (liquid, vapour or solid);
- The velocity of the jet at the orifice level (deduced from measurement data);
- The shape of the jet;
- CO_2 concentrations around the expansion zone.





| Experimental set-up 'Gasunie Research (presently DNV-GL) Groningen, Netherlands'. Picture TNO.

TNO and DNV-GL closely cooperated in designing and execution of the experiments, and also in the interpretation of the results. They co-authored a scientific article on the issue.

At a later stage, additional series of outdoors experiments were performed at the test site of INERIS at Montlaville, France. These experiments used a different tank layout and extended the Groningen experimental conditions by simulating a release of supercritical CO_2 and a full pipeline rupture. Interpretation of these data-sets was underway at the time of writing this book.

Deriving concentrations

In both the Groningen and French tests, a grid of thermo-couples, arranged along the release direction provided the distributions of temperature inside the jet. Starting from these data, a relationship between measured temperature and CO_2 concentration could be established. Subsequently, this delivered the data for building a picture of the concentration in the entire cloud.

As a conclusion of this experimenting and modelling, this work has reconfirmed that safety issues concerning CO_2 are closely linked to the specific transport conditions (gaseous or dense liquid), and when released to the topographic conditions of the surrounding terrains and the weather. As with any large-scale transport of gases, CO_2 transport will need a quantitative risk assessment in each specific case. However, CATO2 has largely improved the spray-release and dispersion modelling that is the basis of such risk assessment.

The improved models provide a more realistic repre-sentation of the safety issues. The experiments and the models also show a high rate of repeatability, which make the models more reliable and enable stakeholders to make reliable estimates of safety issues. For instance, they practically rule out the possibility that rupture of pipelines will have considerable risks at distances of kilometres

| Experimental set-up 'INERIS, Montlaville, France'. Picture TNO.

(which was a thought that was quite valid about five years ago).

Implementing the calibrated models into software will facilitate both transport system operators in designing and operating their systems, and the authorities in their permitting procedures. Partly due to CATO2 results, the models now have grown into a sound basis for developing a commonly shared view on safe CO_2 transport.

This research has been conducted by Mark Spruijt (TNO), with the help of TNO colleagues, University of Bologna, Saxion, DNV GL and Ineris.

Understanding public attitudes, perceptions and misconceptions

Understanding the mechanisms that determine the attitudes, perceptions and sometimes misconceptions of the public is key for every stakeholder. CATO2 combined quantitative and qualitative research to get more insight into public perception and the role of knowledge, experts and expertise, the decision-making process, communication frames, community compensation and many other factors. This knowledge is valuable for all stakeholders in future CCS projects.

In recent years, two planned onshore CCS projects in the Netherlands have been cancelled because of public opposition: Barendrecht and the North Netherlands. In Barendrecht, the worries of the public on the safety of storage of CO_2 led to abandoning an already well advanced storage project for CO_2 in a local nearly depleted gas field. Storage projects in North Netherlands did not even make it to that stage. The Dutch government withdrew its plans for storing CO_2 underground onshore, after public opposition around the first pre-selection of concession sites. Currently, the Dutch government only allows offshore underground storage.

Many people explain opposition by the NIMBY syndrome (Not In My Back Yard), which is a general principle that states that local people are opposed to any project in their neighbourhood for reasons of self-interest. But the NIMBY explanation is much too simple and much too superficial. CATO2 research shows that many social and psychological factors determine people's attitudes and perceptions regarding CCS.

CATO2 integrated the first CATO programme research into the factors behind public perception of CCS. The cancelation of Barendrecht and North-Netherlands and all debates in the same period added an interesting new chapter to this research. Meanwhile, the withdrawal also was a missed opportunity for further research within the CATO2 programme. Actual public perception research planned around these projects had to be adjusted or skipped.

Public perception research

As with any other technology with considerable impact and large investments, CCS projects have to deal with public opinions. If CCS is ever to play a major role in the energy and industry systems, knowledge about public perception and its underlying factors is important. CATO2 research provides more insight into the mechanisms and trends in public knowledge, awareness, perception and opinion about CCS.

CATO2 research not only delivered on understanding different elements in public perception of CCS, but also on misconceptions. Adjacent to this, the effectiveness of communication strategies was investigated. Likewise, the processes of decision-making have been investigated,

Some jargon in public perception

Definitions of key terms used in this chapter (as quoted from the Oxford English Dictionary).

Awareness: The quality or state of being aware, consciousness.
Perception: The process of becoming aware or conscious of a thing or things in general; the state of being aware; consciousness. The mental product or result of perceiving something.
Opinion: A view held about a particular issue; a judgement formed or a conclusion reached; a belief; a religious or political conviction.
Attitude: Settled behaviour or manner of acting, as representative of feeling or opinion.
Misconception: A view or opinion that is false or inaccurate because based on faulty thinking or understanding.
Knowledge: The fact or condition of knowing something.
Information: Knowledge communicated concerning some particular fact, subject, or event; that of which one is apprised or told; intelligence, news.
Communication: The transmission or exchange of information, knowledge, or ideas, by means of speech, writing, mechanical or electronic media, etc.

including the interactions between decision-makers on different governmental levels and with the public. One special topic – also interesting for other sectors and technologies – involves the possible role of compensation to local communities.

CATO2 research provides knowledge that can be applied in actual projects, by stakeholders such as (local) authorities, companies, project developers, NGOs and local residents. No blueprint or decision tree is supplied, because every project has its own characteristics. However, it does provide dos and don'ts, building blocks, lessons learned and clues how to be credible and trustworthy in public debates and public policy-making processes. These building blocks can be applied in information and communication campaigns and in decision-making regarding CCS, and are also interesting for other sectors and technologies.

Low initial awareness and knowledge

CATO research over time shows the development of awareness and knowledge concerning CCS. Before plans in Barendrecht became publicly known, very few people in the Netherlands were aware of the possibility of CO_2 capture and storage. In 2004, more than seven in ten people said they did not know what it was. However, public awareness quickly grew as the protest in Barendrecht against the storage plans was broadly covered in the media.

Unfortunately, what has not increased is the general public's level of knowledge regarding CCS, climate change, the energy system, and the role of CO_2. Although most people state that they know about global warming, only very few people understand how much fossil fuels are still used in the Netherlands, and how the combustion of these fuels leads to CO_2 emissions, and consequently to climate change. The fact that media reports are often about specific CCS projects, leaving out the underlying rationale for CCS, does not help to increase the knowledge levels on the link between CCS and climate change.

Trends in opinions

With or without knowledge, people tend to develop opinions on subjects relevant to them. The question is how predictive these opinions are of future general public

opinion about CCS. What kind of arguments do people use when forming their opinion, and is this different when more and better information is available to them? What kind of information is helpful for the public to be able to meaningfully participate in a discussion on our future energy system?

CATO2 applied a combination of methods to investigate the links and mechanisms between knowledge, perception and opinion: On the one hand, current knowledge, ideas and perceptions were measured, including possible misconceptions, via questionnaires based on open interviews with lay people. On the other hand, the so-called Information-Choice Questionnaire (ICQ) methodology was used. In the ICQ, people first receive balanced, validated expert information about our energy system and about the consequences of energy options for the future, including CCS. Subsequently, they are asked to evaluate these consequences. By comparing these measurements with previous ones, CATO2 drew some conclusions about the changes in uninformed and informed opinions over time.

In general, these measurements show that public opinion on CCS is not necessary solely explained by the level of knowledge or by misconceptions. The results falsify the assumption that fighting 'illiteracy' on CO_2, climate change and CCS will make people more positive on average about CCS. People develop a more stable opinion based on information, an opinion that is not easily changed and therefore more predictive of future opinion than opinions that are hardly based on information at all. But more information leads as much to more negative opinions as to more positive opinions. Overall, when people are well-informed about future options and their consequences for the whole energy system, they are not that enthusiastic about CCS and prefer more sustainable options such as wind turbines at sea, efficiency at home or in industry, or the use of biomass (see also highlight **Investigating the Rationale** on page 137). People were mostly ok with the combination of use of biomass and CCS but did not prefer it over these options.

The most informative result from these studies however is not the value of opinions, but how they are built up from perceptions and arguments, because this gives a starting point for information and communication. With that, it gives a starting point for enabling the public to participate meaningfully in a discussion on the role of CCS in our future energy system. The desire expressed by many people to base their definite opinion of CCS on valid, trustworthy information is strikingly common in these studies.

Lessons for campaigners

For project developers, it is important to know why people are in favour of or opposed to CCS. CATO2 research shows a positive attitude of the public is strongly linked to the perception that the CCS technologies are necessary in combatting severe climate change. On the other hand, a negative attitude often coincides with perceived high safety risks.

Given this knowledge about the links between awareness, knowledge level, perceptions and opinion on CCS, stakeholders may conclude some lessons on how they communicate and how this influences opinions. For instance, taking away misconceptions about leakage and safety may reduce worries and may prevent a more negative attitude. More importantly, knowing about awareness and knowledge levels and possible misconceptions makes it much easier to know where to start the discussion. This both enables the lay people to participate in the discussion instead of being talked down to, as well as prevents a lack of understanding between parties within that discussion.

The influence of experts and expertise

In modern society, CCS is just one of many complex matters about which people have to make up their minds. Often, people don't know much about a complex matter and still have an opinion on the matter. This opinion

| An example of where public perception turned into opposition: a protest against storage plans in the North of the Netherlands. "Boerakker CO_2 guinea pig? No thanks." Picture ANP XTRA Koen Suyk.

tends to be very wobbly and not stable. In a next phase, after having formed an opinion, people have a more or less 'closed attitude', which is much more stable. One interesting research question was: how do people come to a closed attitude regarding CCS (or in psychology terms: Cognitive closure)?

For instance: what role do experts play? CATO2 researched the importance of (the perceived) level of source expertise. Experimental research has led to some remarkable conclusions.

It is not a big surprise that the perceived level of expertise of the information source (experts such as geophysicists versus non-experts such as citizens) is one important factor. People expect to close their attitude more easily when they use expert sources.

However, in everyday life we also see that people sometimes base their attitudes on non-expert information. CATO2 research shows that under certain circumstances, non-expert information can be perceived as being even more helpful in forming definite opinions than expert information, for example when the non-experts agree to a large extent. It is surprising how important the role of consensus is in closing an attitude.

The closure of an attitude was measured by asking people several questions, and by testing their willingness to participate in a poll. The results show that especially in the case of non-expert information sources, consensus is an important factor (more than in the case of expert sources). Consensus among non-experts increases their perceived authority and makes it easier for people to close their attitude towards CCS.

In this respect, expert information, e.g. provided by CATO2 participants, may not always have the outreach and impact that lay information, as provided in the media or in informal communications, sometimes has. People that are responsible for informing the public about complex matters such as CCS should be well aware of the effect of communicating (non)consensus and should not underestimate the impact of non-experts.

Framing the message

In earlier stages, the CATO programme showed that the credibility of the information source is an important parameter in public perception. Consortia of stakeholders that are regarded as having different interests – e.g. NGOs, scientists and utilities – are more credible than a company only, or a single authority.

CATO2 followed up on these conclusions by further investigations, especially on the framing of the messages, and came up with some recommendations. For instance, side messages may distract the receiving public from the main reasons why CCS projects are necessary. Also, experiments show that when a company tells that investments are motivated by environmental concerns only, the company is often perceived as 'greenwashing' its business (See also highlight **Pitfalls in the communication** on page 140).

Both large companies and the authorities sometimes rely on their 'gut feeling' in communication challenges. CATO2 research justifies that testing communication and messages provides more insight and can improve the effectiveness of communication.

Local projects sharpen the edges

Bringing CCS projects to live comes with selecting locations and preparing the actual roll-out of the project, including communicating with the surrounding citizens and authorities. Several local projects that recently have been discussed in the Netherlands, such as the intention of storing CO_2 in an empty gas field in Barendrecht and in the North of the Netherlands, show that the debate may become really edgy. In the two cases mentioned, the debate ultimately led to dropping both projects.

The investigations that were executed around these cancelled projects show interesting results that also can be used for the future development of similar activities like gas production, shale gas production or other large-scale activities in which new technologies will be implemented in a complex societal environment.

Earlier research had shown that initial public reactions towards CCS do not necessarily differ between the general public and citizens that have a planned CCS project in their vicinity. But as projects are nearing their execution, opinions may change. This is not a one-way change towards opposition. One particular experience with the US FutureGen project is even referred to as an example of PIMBY (Please In My Back Yard) because communities ended up competing to hosting the project and its employment opportunities.

Barendrecht was quite a different case. In Barendrecht, a survey among 800 people held two years after the first announcements in local media, revealed that almost everybody in Barendrecht was aware of the project. A second important finding was: 86% of Barendrecht residents were negative about the planned storage project. That figure might come as a surprise to people who thought the opposition in the media was felt by a minority of the Barendrecht population.

Furthermore, the survey supplied much detailed information on the factors that played a role in the local opposition. How did the decision-making process affect the public opinion? How important was the safety issue of transport and storage of CO_2? Was there a strong fear of decreases in property values?

By applying a multiple regression method on the data, the researchers were able to deconstruct the underlying

aspects. In the end, the procedure proved important in addition to the (perceived) safety issue; the 'democratic process' was not perceived as particularly fair. Although not directly monitored within CATO2, the local history of Barendrecht, that became a host to large motorway routes and a rail track for goods (Betuwelijn) in the last ten years, probably gave the inhabitants the impression of becoming the 'dumping ground'of large Dutch infrastructure. They might have felt that they were again confronted with a fait accompli.

The research in Barendrecht provided insight into the relationship between the decision-making process and the opinions of the public, and there has also been research performed on the progress of the decision-making process in the North-Netherlands focusing on the involvement of and interrelationships between all different stakeholders involved. These investigations revealed that transparency is a prerequisite for decision-making processes and that the result of the final decision, the closure of the whole processes, is being influenced by several dynamics, both social, institutional and political (see also highlight **The U-turn in Barendrecht** on page 29).

Offering compensation

In cases where infrastructural works or large industrial activities need to be established near residential areas, compensation to the communities and citizens has become 'business-as-usual'. Companies and utilities have become well aware of the possible impact of their projects on citizens and offer to invest in projects to compensate for local burdens. This is a matter of 'social responsibility', but is of course also expected to influence the public and render a more positive attitude.

CATO2 generated quite some profound insight in the way compensation mechanisms work. This knowledge also applies to projects other than CCS. Although experiences by companies are abundant, empirical scientific literature on this topic was hardly available in general, and was completely lacking in CCS.

Many factors play a role in the compensation process: the perception of the process; the way residents are involved; the perceived trustworthiness of the stakeholders. Compensation can also have many forms, such as offering money or offering investments in things that can act as a trade-off (roads or other infrastructure, a hospital, a playing ground or a park).

Several studies investigated the links between different trade-offs and the acceptance level. Literature and theory were combined with experiments. Systematic variations in the studies revealed some dos and don'ts in compensation methods. Lessons are learned that can be applied in CCS project. (see also highlight **Community compensation for hosting a CCS site** on page 142).

Investigating the rationale behind people's opinions on CCS

In CATO research, the so-called 'Information-Choice Questionnaire' (ICQ) has proven to be a valuable instrument for investigating people's opinions on CCS as a climate change mitigation measure. CATO2 dedicated a new ICQ survey to zoom in on the arguments underlying the opinions. From this survey, the combination CCS and biomass proves to be regarded as somewhat positive, while most people are not in favour of CCS combined with coal and gas power stations. Furthermore, this study shows that factually incorrect beliefs can be debunked, but this does not change opinions.

Society does not always absorb new technologies, despite their technical feasibility and advantages. Emerging technologies always raise the question whether they fit into society. Sometimes, much time and effort are spent on developing new technologies that in the end are rejected, locally or even nationally.

When CCS started emerging as a possible technological solution for reducing CO_2 emissions about ten years ago, a logical next step was to investigate the public perception of this option. However, investigating public perception of technology is not straightforward, particularly if it is new and largely unknown. The first studies on public perception of CCS showed that very few people knew something about CCS. But even if they had just stated that they never heard of it, people were inclined to give their opinion. These 'uninformed opinions' turned out to be easily changed, by relevant or irrelevant factors.

For a serious discussion on the place of CCS in society, uninformed opinions are not very useful, so other methods have been developed to study public perception. In earlier projects in the Netherlands the Information-Choice Questionnaire (ICQ) method has been applied. The ICQ is essentially a decision aid that includes information.

It is essential that this information is accurate, reliable and balanced. Therefore, a range of experts decide first on the most relevant policy problem as well as the most relevant options to solve it. Together they gather background information of the problem, the options and the consequences of implementing the options. After translating into lay language, this offers people a structured and informed basis for their decision-making process.

Experiences

Until now, several ICQs on CCS as a climate change mitigation option have been developed and administrated to large population samples representative of the Dutch general public. The majority of the respondents is positive about the methodology and evaluated the ICQ as a good decision aid. Indeed, people tend to base their opinions for a large part on the information from experts, which was evaluated as reliable.

However, a substantial part of the opinions cannot be explained by the given expert information. This implies that other factors play a role, such as other arguments, ideas, feelings and possibly misconceptions (beliefs that are factually incorrect). Apparently, the ICQ information does not include all elements that people use to form their opinion. But a meaningful discussion on CCS requires that all arguments are known. Moreover, for the effectiveness of communication it is necessary to know the knowledge level and possible misconceptions of the group for which the communication is intended.

HIGHLIGHT

Question

CATO2 investigated which arguments people use to base their opinion of energy technology on. For instance, do they use other arguments than the ones experts deem important? And are there possible misconceptions of CCS or related topics and can these be rectified?

Solution

Several studies were executed to answer these questions. First, interviews with lay people were used to assess the range of possible beliefs and misconceptions. Subsequently, a questionnaire was designed to measure how many people actually have these beliefs and misconceptions.

Large numbers of respondents turned out to be unsure about the different topics. Many were unfamiliar with the characteristics, effects and sources of CO_2. For example, many of the respondents could not tell whether CO_2 causes cancer, or whether CO_2 is flammable, explosive or emits radiation. A substantial percentage of people was also in doubt of the effects of CO_2: whether it causes acid rain or smog.

Furthermore, much doubt existed about the sources of CO_2 emissions. A substantial percentage of respondents did not know whether CO_2 is released when electricity is produced using natural gas, or coal, or oil, or using nuclear power. Most striking though is that there was quite a bit of confusion among the Dutch public as to our current energy use and its relation to climate change. Although a majority of people stated that they have some idea of global warming and CO_2 emissions, few people were able to convey a reasonable estimate of the percentage of Dutch energy consumption that is based on fossil fuels. Also few could answer correctly that the use of gas, oil or coal for electricity production emits CO_2.

The next ICQ addressed doubts and misconceptions in the information included in the questionnaire. So in addition to the information that experts deemed important, also

| A Dutch cartoon (header: the citizen's pitfall) representing the fact that experts and their reports are not always convincing: "No, I don't have a good feeling about it." Picture Maarten Wolterink.

factual information regarding the most common lay beliefs was provided. The group of respondents was split in three:

- One part received an introduction to the ICQ comparable to an earlier ICQ;
- One part got an introduction were factual information was given negating the misconceptions, without mentioning the misconception itself ('implicit debunking').
- A third part received this introduction including statements that some people do not know about the particular facts ('explicit debunking').

Adding information to the introduction resulted in an increase of correct knowledge directly after the ICQ. Especially when misconceptions were explicitly

debunked, knowledge improved. However, though the misconceptions were corrected, this did not change the way people formed their opinion. How information about consequences was processed or used to form opinions about options did not differ between the three groups.

People's opinions proved to be largely based on the information from experts about the consequences of the different options for CO_2 emission reduction. Still, none of the specific consequences stood out as critical for acceptance or rejection of the options.

The ICQ resulted in positive opinions about biomass, offshore wind turbines and CO_2 emission reduction measures in households or industry, with hardly any rejections. Also the combination of biomass with CCS was received slightly positively. CCS combined with coal- and gas-fired power plants was not good enough for most people. Few respondents chose this option, while 10.7% of people found this option unacceptable. Nuclear energy was the most controversial. One in four preferred this option, but just as many people find nuclear energy unacceptable.

The ICQ research was executed by Jessanne Mastop, Marjolein De Best-Waldhober (ECN), Andrea Ramirez (UU) and Chris Hendriks (Ecofys).

HIGHLIGHT

Pitfalls in the communication about CCS

Researchers at Leiden University identified three important pitfalls in the use of persuasive techniques when communicating about CCS. First, irrelevant details in communications dilute the persuasiveness of a relevant message. Second, emphasis on either advantages or disadvantages of CCS is perceived as manipulative. Finally, CCS stakeholders should best cite a credible motive for their involvement to avoid being perceived as dishonest.

Public attitude is very relevant for the implementation of CCS. That is, implementation might be delayed or cancelled if the public does not accept the technology. For instance, in 2010, a CO_2 storage demonstration project in the Dutch town Barendrecht was cancelled; in part because the local residents did not support implementation.

Attitudes towards CCS are partially influenced by how organisations communicate about the technology. These communications are often persuasive, which means that they intend to influence the beliefs, attitudes or behaviours of the audience with regard to CCS.

Suspicions of strategic behaviour by companies could lead to perceptions of corporate 'greenwashing'. Cartoon Pavel Constantin/Cartoon Movement/Hollandse Hoogte.

From both sides

Proponents of CCS as well as opponents use persuasive communication techniques to convince the public of their views. Examples of such techniques are: conveying lots of information at one time (heaping), giving more weight to either advantages or disadvantages (emphasis framing), and citing pro-environmental motives for involvement with CCS (greening).

These techniques tend to be judged on their persuasiveness. However, up till now, less attention was paid to how unfavourable recipients might evaluate a communication in which persuasive techniques are applied as well as the source that produced it. Yet, such message and source evaluations can have long-term costs for the stakeholders' reputation and corporate performance. Detecting possible negative side-effects of persuasive techniques reveals the pitfalls in communication about CCS.

Three lines of research

Leiden University conducted three lines of research to examine potential pitfalls. A first line of research aimed at examining whether or not the pitfall of heaping information lies in the possibility that irrelevant details dilute the persuasiveness of a relevant message. A second line of research focused on potential pitfalls of applying emphasis framing. Could it be that people feel they are manipulated when CCS advantages are emphasized over disadvantages (or vice versa)? This pitfall might be especially severe if people receive persuasive communications when they expect to be informed in an objective manner. A third line of research examined public suspicion that a company's investment in CCS is actually guided by corporate motives such as image-building or satisfying customers, instead of public motives such as caring for the environment. These suspicions of strategic behaviour could lead to perceptions of corporate 'greenwashing', which implies that a company makes corporate activities look 'green', and makes itself look more environmentally friendly than it actually is.

Pitfalls confirmed

The results of the research confirm the occurrence of these pitfalls. First, details about CCS can dilute the persuasiveness of a relevant message about CCS because the perceived quality of a communication decreases when irrelevant information is added. Second, people perceive a biased news article about CCS as more manipulative than a balanced article. They even judge a message that emphasizes advantages of CCS over disadvantages as illegitimate when they expect an objective message. Finally, oil and gas companies that cite pro-environmental motives for involvement with CCS can be perceived as greenwashing activities. Moreover, even without communicating any motive, oil and gas companies that invest in CCS are by default perceived as 'greenwashers'.

Perceptions of greenwashing can be reduced when companies are transparent about their economic considerations to invest in CCS, because people generally perceive this as a credible motive. The research further reveals that expectations about the communication source play an important role in how the use of persuasive techniques is perceived.

In sum, to avoid negative evaluations of the message and the communicating source, stakeholders with an interest in CCS can best take people's expectations into account and provide a relevant, balanced, and credible message about CCS.

This work has been executed by PhD student Gerdien de Vries (Leiden University) as part of her dissertation, in collaboration with Bart Terwel, Naomi Ellemers and Dancker Daamen.

HIGHLIGHT

Community compensation for hosting a CCS site

Public acceptance is a major challenge for the siting of CCS facilities. The offering of compensation to communities potentially helps to create a fairer distribution of local risks and benefits, which may increase public acceptance. Such 'host community compensation' had not been empirically examined in a CCS context before. An extensive research programme provides insights into why and when host community compensation has the potential to solve (CCS) facility siting controversies.

Preventing or overcoming opposition

In the past years, several CCS projects have suffered from public opposition. A clear example in the Netherlands was the Barendrecht CO_2 storage project, where local opposition played an important role in the National Government's decision to cancel the project in 2010. Clearly, preventing or overcoming public opposition is a major challenge for the siting of (onshore) CCS projects.

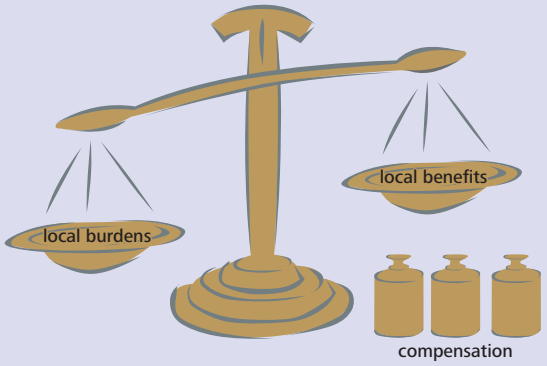
As with the siting of other (energy-related) facilities, a problem with CCS is that in people's perception there is an unfair distribution of risks and benefits. That is, the risks and impacts of CCS developments are perceived to be local (e.g., risks to human health and safety, declines in property value), while the main benefits are at the national or global level (i.e., reductions in CO_2 emissions to meet national standards and to address global climate change).

Host community compensation may help to restore this imbalance and therefore could help increasing local public acceptance of CCS. Host community compensation can be seen as a form of equity adjustment aimed at correcting imbalances between regional benefits and local burdens associated with the siting of new or expanded facilities. These burdens are not limited to economic losses, but can take various other forms, such as impacts to human health and degradation of the physical environment.

Further, different types of host community compensation exist, for instance monetary incentives or the provision of public goods. Some compensation measures are designed to 'reward' local host communities for accepting local risk or inconveniences, for example in the form of community development initiatives, such as the improvement of local roads. Others are designed to mitigate and compensate for costs resulting from the construction or operation of a facility, such as property value guarantees or contingency funds.

Compensation has actually been considered and applied in specific projects. For example, in the FutureGen project in Illinois, USA, among the compensation measures considered were improvements to local roads, landowner compensation, the build of a visitor/education centre, and the installation of a trust fund.

Until 2011, however, there was no empirical research that addressed the question of whether (and under which conditions) host community compensation can actually



| **Host community compensation may help to restore a perceived unfair distribution of risks and benefits. Picture C&M Geosciences UU.**

help prevent or solve CCS siting controversies. CATO2 research by Leiden University aimed to fill this void.

The central research question was: "Can the offering of host community compensation help to prevent or solve (CCS) siting controversies and if so, why, and under which conditions?" The research project was designed to develop fundamental insights on factors that influence public responses to compensation – insights that are relevant to the realm of CCS as well as beyond – so that project developers and government can use the acquired knowledge to develop effective compensation regimes.

Solution

As a first step towards understanding why and when host community compensation may or may not work, CATO researchers reviewed the broader empirical literature on the potential of host community compensation in facility siting. They identified several factors that may co-determine how local communities respond to compensation offers. Such factors are for instance the type of compensation offered, the perceived risk of a proposed facility, and the initial local opinion.

Importantly, also large knowledge gaps existed on *why* compensation works (or does not work). A number of factors might affect the local public's response to compensation offers, but these factors had not been investigated yet. As a next step, Leiden University conducted several extensive experimental studies to systematically examine these factors.

As an example, CATO-2 compensation research shows that the effectiveness of host community compensation depends on how compensation is framed and justified. Also the type of compensation matters, and its perceived 'match' with risks associated with the facility. Importantly, the studies also reveal that people consider social aspects in their evaluations of and responses to host community compensation. For example, people appreciate having a fair say in the process of deciding about compensation.

Further, preferences for compensation measures between the public and local politicians were found to coincide, with a preference for a compensation fund and measures to improve the local economy over monetary compensation for individual households. The public also did not really appreciate compensation in the form of a sum of money allocated to local government.

However, experimental CATO2 research also shows that members of the public respond relatively positively if compensation in the form of a sum of money allocated to local government is 'rhetorically redefined' as having sacred (moral) value, rather than merely secular (non-moral) value. This can be done, for instance, by suggesting using the money for the implementation of measures to increase public safety in another domain (e.g., placing a traffic light at a dangerous crossroad in town). This way, the perceived commensurability of the compensation offer and the (safety) risk posed by the facility increases, and people experience less negative emotion.

The way to effective strategies

The knowledge acquired in CATO2 contributes to the existing facility siting literature in several ways, and provides project developers and governments with relevant building blocks towards effective (evidence-based) compensation strategies. A number of interesting research questions remain. For instance, it is interesting to systematically examine public responses and preferences regarding compensation at various stages of the planning process. What difference would it make to make an offer prior to versus after siting decisions are made? Such research will also shed some light on the related issue of what the best time is to start discussing compensation with local communities and political authorities.

This research has been conducted by Leiden University, with Emma ter Mors, Bart Terwel, and Dancker Daamen as principal researchers.

For further reading

This chapter lists a selection of the main public literature on the specific issues per chapter and per highlight. This is only a limited selection, aiming at servicing readers that want to dive deeper into the specific subjects. More literature (sometimes restricted access) is available at the CATO2 website, where the book will also be available in pdf: www.co2-cato.org/LinkingtheChain.

Part I: CATO2 in the context of global CCS

Climate Change 2013: The Physical Science Basis, IPCC Working Group I Contribution to the IPCC Fifth Assessment Report (AR5).

Climate Change 2014: Impacts, Adaptation, and Vulnerability, IPCC Working Group II Contribution to the IPCC Fifth Assessment Report (AR5).

Climate Change 2014: Mitigation of Climate Change, IPCC Working Group III Contribution to the IPCC Fifth Assessment Report (AR5).

GEA, 2012: Global Energy Assessment – Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

IEA World Energy Outlook 2013, International Energy Agency.

IEA Technology Roadmap: Carbon Capture and Storage 2013, International Energy Agency.

The Global Status of CCS: February 2014, Global CCS Institute.

Part II: The Science of CATO2

Capture: reduce costs, improve and demonstrate performance

Boon, J., J.A.Z. Pieterse, J.W. Dijkstra, Y.C. van Delft, P. Veenstra, Nijmeijer and D. Jansen (2013), *Benchmarking of Hydrogen Selective Membranes: Experimental and Modelling Approach to Compare Membrane Performance*, Energy Procedia 37, p 1020-1029.

De Miguel Mercader, F., G. Magneschi, E. Sanchez Fernandez, G.J. Stienstra and E. Goetheer (2012), *Integration between a demo size post-combustion CO_2 capture and full size power plant. An integral approach on energy penalty for different process options*, Int. J. of Greenhouse Gas Control 11 (supplement), p 102-113.

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Van Eckeveld, A.C., L.V. van der Ham, L.F.G. Geers, L.J.P. van den Broeke, B. J. Boersma, E.L.V. Goetheer (2014), *Online Monitoring of the Solvent and Absorbed Acid Gas Concentration in a CO_2 Capture Process Using Monoethanolamine*, Ind. Eng. Chem. Res. 53 (13), p 5515-5523.

Highlight: Developing a new low-cost capture technology

Veneman, R., Z.S. Li, J.A. Hogendoorn, S.R.A. Kersten and D.W.F. Brilman (2012), *Continuous CO_2 capture in a circulating fluidized bed using supported amine sorbents*, Chem Eng J 207, p 18.

Veneman, R., H. Kamphuis, D.W.F. Brilman (2013), *Post-Combustion CO_2 capture using supported amine sorbents: A process integration study*, Energy Procedia 37, p 2100.

Highlight: Chemical looping combustion: efficient power production with integrated CO_2

Hamers, H.P., F. Gallucci, P.D. Cobden, E. Kimball and M. van Sint Annaland (2013), *A novel reactor configuration for packed bed chemical looping combustion of syngas*, Int. J. Greenhouse Gas Control, 16, p 1-12.

Hamers, H.P., F. Gallucci, P.D. Cobden, E. Kimball and M. van Sint Annaland (2014), *CLC in packed beds using syngas and CuO/Al2O3: model description and experimental validation*, Applied Energy, 119, p 163-172

Highlight: Post-combustion capture: from lab towards implementation

Khakharia, P., L. Brachert, J. Mertens, A. Huizinga, B. Schallert, K. Schaber, T.J.H. Vlugt and E. Goetheer (2013), *Investigation of aerosol based emission of MEA due to sulphuric acid aerosol and soot in a Post Combustion CO_2 Capture process*, Int. J. of Greenhouse Gas Control 19, p 138-144

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Current CATO2 Parties

DAP (www.delftaardwarmteproject.nl)
DCMR-RCI (www.rotterdamclimateinitiative.nl)
Delft University of Technology (www.tud.nl)
DLO (www.wageningenur.nl)
Eindhoven University of Technology (www.tue.nl)
E.ON (www.eon-benelux.com)
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Gasunie (www.gasunie.nl)
GDF-Suez (www.electrabel.nl)
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ROAD (road.2020.nl)
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SHELL (www.shell.nl)
TAQA (www.taqaglobal.com)
TATA steel (www.tatasteel.nl)
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Utrecht University (www.uu.nl)
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Wageningen University (www.wageningenur.nl)
Wintershall (www.wintershall.com)

In 2014, the Dutch CATO2 programme comes to an end. CATO2 represents a broad collaboration of industry and science in research and development on the subject of CO_2 capture and storage (CCS). This chain of technologies is regarded by many as important for future climate change mitigation.

The knowledge achieved by CATO2 and its predecessor CATO has now resulted in a realistic view on the opportunities for establishing a large-scale demonstration of CCS in industrial processes and energy generation. This book reflects on ten years of consistent and coherent CCS research programmes in the Netherlands, with an emphasis on the last five years.