Executive Summary of CATO-2a, including the Executive Summaries of deliverables

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1 Executive Summary of CATO-2a (restricted)

This section gives the Executive Summary of CATO-2a, which is subdivided per SP (Sub Program).
The remainder of this document gives the Executive Summaries of the CATO-2a deliverables. The full versions of the documents are available on the website (www.co2-cato.nl).

1.1 SP0: Coordination & Communication

Coordination:

- The Program Office has been installed and has set up all necessary administration for CATO-2a and CATO-2b.
- A Consortium Agreement has been drafted and has been signed by all Consortium Parties.
- The different Consortium Bodies (Executive Board, General Assembly, International Advisory Board and Program Council) have been installed and have had their meetings.
- The CATO-2a Program Plan has been detailed and updated.
- The CATO-2b program has been prepared and approved by the Netherlands Ministry of Economic Affairs.

Communication & dissemination:

- A start has been made with building an energetic CATO-2 community of almost 400 experts.
- The international position of CATO (and Dutch CCs in general) has strongly improved by the organisation of the GHGT-10 conference in September 2010, with 1500 participants.
- The media attention for CCS has grown strongly the last year, often aiming to polarize CCS debate. CATO-2 responded by o.a. providing objective information, organizing a workshop with concerned inhabitants of Barendrecht and experts, and finally by the Argumentmap, that contained all pro en cons on CCS.

1.2 SP1: CO_2 Capture

Post-combustion capture:

- A set of user requirements for the 250 MW E.ON post-combustion capture demo case has been established. These user requirements (e.g. composition of the flue gas, type of coal used, cool water volumes) will be input for the modeling work on the demo plant.
- To be able to design the most cost efficient capture plant and integrate it with the power plant (i.e. MPP3) a modeling infrastructure has been established. The model links the capture plant with the power plant and is used to evaluate different operating cases. Preliminary results of the first cases are available and reported in CATO2A. The results provide important input to industry partners E.ON Benelux and GDF/Electrabel in the procurement process of equipment for the 250 MW capture plant.
- In CATO2A the search for new solvents for capture of carbon dioxide continues. Most efforts have been put into developing models and tools that can predict and measure the performance of solvents. Before solvents are tested in the CATO CO_2 Catcher (pilot plant) they need to be screened and tested on lab scale first. Until today no new pilot-ready solvents have been identified, because more measurements are required. However, in

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CATO2A the most promising solvent of the first CATO program has successfully been tested in the pilot and results have been reported
- In general, the focus of solvent testing has moved from energy consumption to control over environmental aspects such as emissions and waste. CATO2 has noticed this trend and will include this subject into the research programme.
- In the work package on the optimization of the desorber equipment fundamental assumptions on mass transfer processes and kinetics of desorption have been successfully verified.

Pre-combustion capture:
- Development of the SEWGS process at ECN started in the CATO-1 programme. The SEWGS process is now moving towards the pilot phase. Preparations for scaling up to pilot scale take place within the CATO-2 programme and also the pilot plant (if decided) will become part of the CATO-2 programme. Plans are there to scale up the technology with a factor 100 to a size of 25 MW_e equivalent.
- Modelling tools are developed to make it possible to optimize the SEWGS process. Furthermore, the models are also used to investigate applications of this process outside the power sector (e.g. steel and refineries).
- The process development unit (PDU) that has been built in CATO-1 for testing of hydrogen membrane reactors on basis of Pd–alloy has been used for several membrane reactor tests. The installation is unique in the world in the sense that multi-membrane reactors can be tested for membrane-water gas shift and for membrane reforming. Several experiments have been carried out illustrating the potential of the membranes reactors for CO_2 capture. The test results also provide model-input and design data and will form the basis for the future design of the pilot- and full-scale membrane models.
- Next step is a first benchmark of ECN membranes and membranes from a Chinese manufacturer. This benchmark did already start. In the CATO-2B programme the benchmark will be extended with at least 5 more manufactures of Pd membranes. The output of the benchmark will give better understanding of the performance of membranes and might support membrane manufacturers in defining their relative market position.
- Modelling work has been carried out to be able to interpret the results of the benchmark.

Oxyfuel:
- It has been identified that in order to use chemical looping technology with high efficiency it is needed to perform the process at high temperatures (1100 ℃) and pressures (20 bar). The difficulty is to design reactors, which can cope with these aspects. At this moment the state of the art is based on fluidized bed. However, it is expected that this is difficult to scale up. The research within CATO2B will focus on the development of fixed bed reactor technology that has the advantage of getting high pressure and temperatures more easily.

1.3 SP2: CO_2 Transport and Chain Integration

- For safe and efficient operation of CO_2 pipelines, accurate knowledge of the gas composition from each source is required. The effects of impurities concentration on the properties of the gas and supercritical fluid were observed to be very small. But when in its liquid state, large variations in density and speed of sound of the CO_2 stream appear with only small impurities concentrations.

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- A preliminary assessment of the potential of CCS in the Dutch industrial sector (compared with other measures such as efficiency) and of its potential impacts in terms of operation and logistics. From a top-down perspective the results indicate that efficiency measures in the industrial sector could decrease CO_2 emissions by 30% in 2040 (about 9% lower than 2008 levels) and that CCS could further reduce the emissions to about 4 Mt CO_2/yr, (91% reductions compared to the 2008 level; 38 Mt CO_2 would be avoided). However, if costs of avoidance and the geographic potentials are considered these potentials are lower. More than a quarter of these emissions could be captured using CCS at a cost lower than the carbon allowance price foreseen by IEA for years 2025 and 2040 (52 €/tCO_2 and 84 €/tCO_2). A large share of the remainder could be captured at costs up to €150/tCO_2 and more.
- A first assessment of competition between CCS and other low carbon technologies shows that competition between public financial means for CCS and other low carbon options will most likely be limited. However, competition between CCS and renewable energy cannot always be avoided when policies with budgetary constraints are concerned.
- An assessment of the impact of CCS in CDM concludes that, though controversial, the impact of CCS on the carbon market is unlikely to be significant. The impact of inclusion of CCS in the CDM is estimated between $ 0 and $ 4 per tonne of CO2-eq, with higher probability for the lower end of this range. The potential for CCS projects is estimated at 4 – 19% of the CDM supply in 2020. This large range represents the uncertainty with regard to the carbon market after 2012.
- Large investments are required in capture installations, transport infrastructure and storage facilities. The challenge is to get private markets mobilized to commit their resources to the deployment of CCS. CATO-2 research found that private investors are typically not opposed to CCS as such, but the projects should projects satisfy a set of qualification criteria. Investors can deal with risks, but not with uncertainties. For any project, uncertainty about permits, legal procedures and liability claims will result in very high rates of return.

1.4 SP3: CO_2 Storage and Monitoring

In SP3, the storage of CO_2 in depleted gas fields, aquifers and other options is investigated. Emphasis is put on storage capacity, injectivity, cap-rock and well integrity, alternative CO_2-applications and monitoring.

- The main results up to now are obtained with the feasibility study on the TAQA depleted gas field P18, the preferred storage location of the EEPR selected E.ON Rotterdam project (ROAD). No show stoppers could be identified from a technical point of view and P18 gas field remains as one of the main candidates for storage in the ROAD project.
- In SP3 two 3D models of the subsurface around the P18 storage sites have been made available: a regional-scale geological model for geomechanical modeling studies and a reservoir-scale geological model for reservoir engineering studies. Both studies are currently ongoing.
- Two workshops have been organized to exchange data with TAQA Energy and to facilitate rock sampling of cores of the P18 wells and analogue outcrops in Germany for laboratory work. Also, a first 3D static reservoir model was made of the subsurface at the Chemelot potential storage site owned by DSM.

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- Static and dynamic reservoir models have been constructed to estimate the injectivity of the reservoir, associated potential (including thermal) injection problems, chemical rock-fluid-CO_2 interactions, well integrity and cap-rock integrity.
- With respect to monitoring, both shallow and deeper (geophysical) monitoring techniques are evaluated. For example, seismic sensors have been placed in Ketzin (a running CO_2-storage pilot project in Germany) to evaluate the benefit of permanent monitoring of CO_2-storage behaviour in the sub-surface. First results show improved resolution a superior quality of the down-hole array as compared to the surface seismic sampling traditionally applied.
- In order to allow all partners within CATO2 to work on and share essential, subsurface related data an online working space was created. The online working space is accessible to partners via the Internet and will also function as a database from WP3.01. It is based on Microsoft SharePoint and implemented by TNO.

1.5 SP4: Regulation and Safety

In general, the work in SP4 Regulation and Safety is closely related to the ongoing first stages of the CCS projects in the Netherlands. In the first phase of CATO-2 close interaction with the location managers identified a number of issues. These managers have been consulted by questionnaires, interviews and workshops, covering permit issues, environmental impact assessments, ETS monitoring, the risk management of geological storage, and their expectations vis-à-vis the CATO-2 project.The following topics show a snapshot of the most relevant results.

- Recommendations to meet the monitoring and reporting guidelines for capture and transport of CO_2 are of great importance to permit holders. It is concluded that four measurement analyses per year for the CO_2 concentration is sufficient. There is very few CO_2 leak detection equipment on the market, which is readily suited for fugitive CO_2 emission measurement. Further development and standardization of measurement methodologies, further research, practical experiences and standardization of methods are needed to establish proven and accepted methodologies for quantifying CO_2 leakages. Some concern exists about the effect of too a comprehensive monitoring programme. Measurements should take place only when it makes sense.
- Environmental performance of CCS chains. A literature study (31 studies) on the potential environmental effects of deploying CCS technologies resulted in average values and uncertainty ranges for these effects, often based on partial life-cycle assessments (LCA's). Most studies are based on post-combustion capture with MEA, less on oxyfuel and IGCC (pre-combustion). The most studied effects include: energy demand, global warming potential, eutrophication and acidification. No agreement was found on the level and direction of impacts of CCS on environmental categories such as (human) toxicity. CCS provides a trade-off between greenhouse gas mitigation in the order of 80% for coal (complete chain with an average capture rate of 95%) and a (moderate) increase of most other environmental impacts due to additional energy consumption for capture, transport of fuels and solvents and emissions from some of the solvents. The sometimes large ranges often indicate that specific regional or technical issues influence the overall environmental performance of a CCS chain. This requires further research.
- In the next phase, the focus will be on developing a strategic environmental performance assessment tool. Besides that a selected number of environmental issues as part of in-depth cases studies will be addressed. Furthermore, work on screening of second generation CO_2

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capture technologies and life cycle assessments of solvents used will be conducted. Concrete results aimed at are to make: (1) an analysis tool (2) a (restricted) web-based information exchange platform (3) an environmental database.

- Risk management of CO_2 transport and storage. This resulted in literature studies on: (1) modelling the physical effects and subsequent risk of the accidental release of CO_2 and (2) Impacts of accidental CO_2 release on humans and environment. A conclusion is that probabilistic ecological risk assessments of CO_2 exposure can only be used as an indicative tool. It should not be used to estimate field effects.
- Some of the preliminary SP4 results were presented at the large international GHGT-10 conference (September 2010, Amsterdam).

1.6 SP5: Public Perception

SP5 ("Public perception") aims to improve CCS communication to the general and local public. SP5 also aims to identify and rectify shared misconceptions among the general public and to predict public support (or lack of support) for CCS.

- In WP5.1 ("Local communication near CCS") the intervention program in the Northern Netherlands (NN) was prepared and three awareness and opinion questionnaires were administered to representative samples of inhabitants in three Dutch regions. The results of the survey show that public knowledge and awareness of CCS is quite low: 50% of the respondents indicated to have never heard of CCS and only 2.6% of the full representative sample is able to correctly indicate which environmental problem CCS aims to address and which environmental problems CCS does not address.
  The results also show that on average, both people living in the Northern Netherlands and people living in other Dutch provinces trust knowledge institutes most, followed by environmental NGOs.
  Finally, the results indicate that initial public attitudes toward CCS are, on average, neither extremely negative, nor extremely positive.
  This study is a relevant first step for future research and interventions within WP5.1 and provides support for the proposed procedure how to introduce a CCS project in a local community and how to communicate on such a project. Once a specific storage location is known in Northern Netherlands subsequent surveys will be repeatedly conducted.
- Results from the first survey in WP5.3 ("Trends in public opinions on CCS") indicate that among the general public several misperceptions can be identified about CCS, but also about CO_2 and electricity production, that strongly relate to people's overall attitude towards CCS. The first results show that a substantial percentage of people have a lack of knowledge and quite a few misconceptions on CO_2, climate change, energy technology and the relation between the three.

The remainder of this document gives the Executive Summaries of the CATO-2a deliverables. The full versions of the documents are available on the website (www.co2-cato.nl).

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Document Change Record

(this section shows the historical versions, with a short description of the updates)

Version	Nr of pages	Short description of change	Pages
Draft 2010.11.00	1-97	Draft version for Program Council	
See header	See header		

Table of Content

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2 Applicable/Reference documents and Abbreviations

2.1 Applicable Documents

(Applicable Documents, including their version, are documents that are the "legal" basis to the work performed)

	Title	Doc nr	Version date
AD-01	Beschikking (Subsidieverlening CATO-2 programma verplichtingnummer 1-6843	ET/ED/9078040	2009.07.09
AD-02	Consortium Agreement	CATO-2-CA	2009.09.07
AD-03	Program Plan	CATO2-WP0.A-D.03	2009.09.29

2.2 Reference Documents

(Reference Documents are referred to in the document)

	Title	Doc nr	Issue/version	date

2.3 Abbreviations

(this refers to abbreviations used in this document)

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3 Overview Deliverables CATO-2a

WP0A.1	Program Coordination	D01a	Program Plan year 1	31-aug-10
WP0A.1	Program Coordination	D02	Organisation and preparation of meetings (EB, Program Council, Advisory Committee) and meeting minutes	31-aug-10
WP0A.1	Program Coordination	D03a	Program reporting to EZ (2009.04.15-2009.10.15)	15-dec-09
WP0A.1	Program Coordination	D03b	Program reporting to EZ (2009,10.15-2010.04.15)	15-jun-10
WP0A.1	Program Coordination	D03c	Program reporting to EZ (2010.04.15-end)	15-dec-10
WP0A.1	Program Coordination	D04	Financial Program administration	31-aug-10
WP0B.1	Programme Dissemination	D05	Organizing the (semi) annual Dutch CCS Conference. (Q0)	31-aug-10
WP0B.1	Programme Dissemination	D06	CATO-2 brochure and poster (ongoing)	31-aug-10
WP0B.1	Programme Dissemination	D07	CATO templates with PowerPoint sheets for individual participants of CATO-2 (Q2)	31-aug-10
WP0B.1	Programme Dissemination	D04	Digital CATO-2 newsletters (ongoing, first Q1)	31-aug-10
WP0B.1	Programme Dissemination	D05	Public website (Q0 definition, Q1 first phase online)	31-aug-10
WP0B.1	Programme Dissemination	D06	Rapid response team on incorrect information on CCS in media (ongoing, first meeting Q1	31-aug-10
WP0B.2	Internal communication and integration	D08a	Annual Cato day	31-aug-10
WP0B.2	Internal communication and integration	D09	Terms of reference for the CATO-2 extranet (Q1) followed by implementation (ongoing	31-aug-10
WP0B.3	Sharing external information & dialog	D10	Plan for Staccato newsletter on developments in CCS outside CATO for the CATO partners (Q2)	31-aug-10
WP0B.3	Sharing external information & dialog	D11	First Staccato newsletter (Q2)	31-aug-10
WP0B.3	Sharing external information & dialog	D12	Dialog with stakeholders (ongoing)	31-aug-10
WP0B.4	International cooperation	D13	Plan for capacity building and international knowledge exchange (Q4)	31-aug-10
WP0B.5	Education	D14	Inventory on available education and needs for CCS education (Q4)	31-aug-10
WP1.1.A1	User Requirement Specification	D01	User Requirements Specification for E.ON case	31-aug-10
WP1.1.A1	User Requirement Specification	D02	User Requirements Specification for other cases	31-aug-10
WP1.1.A2	DEMO Preliminary Design	D01	Preliminary Design Report	31-aug-10
WP1.1.A3	Solvents	D01	Report in inventarisations of leads	31-aug-10

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WP1.1.A3	Solvents	D02	Report on Simplified Model	31-aug-10
WP1.1.A3	Solvents	D03	Report on Optimization (in concept)	31-aug-10
WP1.1.A3	Solvents	D04	Database solvent system description	31-aug-10
WP1.1.A3	Solvents	D05	Expert system description	31-aug-10
WP1.1.A4	Absorber	D01	Investigation report on 'state of the art' for large scale absorbers	31-aug-10
WP1.1.A5	Stripper	D01	investigation report on 'state of the art' for large scale strippers	31-aug-10
WP1.1.F1	Phase Change Solvents	D01	Progress report on DECAB	31-aug-10
WP1.1.F1	Phase Change Solvents	D02	Progress report on MCCS	31-aug-10
WP1.1.F2	CO2 - SO2 removal	D01	Progress report on DECASOX	31-aug-10
WP1.1.F3	Thermodynamic Models	D01	Progress report on molecular modelling	31-aug-10
WP1.1.F3	Thermodynamic Models	D02	Progress report on molecular simulation	31-aug-10
WP1.1.F3	Thermodynamic Models	D03	Progress report on Raman infrared spectroscopy	31-aug-10
WP1.1.F6	Hybrid system for gas fired power plants	D01	Report on basic design and process descriptions	30-jun-10
WP1.1.F6	Hybrid system for gas fired power plants	D02	Report on first set of selected solvents	31-aug-10
WP1.2.A2	Water gas shift catalysis	D01	Progress report on development of new catalyst type	31-aug-10
WP1.2.A4	Sorption-Enhanced Water Gas Shift (SEWGS)	D01	Progress report and selected location for pilot plant SEWGS	31-aug-10
WP1.2.F1	Hydrogen Membrane Technologies	D01	Progress report on PDU membrane reactor tests	31-aug-10
WP1.2.F2	Nano-structured sorbents for CO2 capture	D01	Postdoc proposal (Nano-structured sorbents for CO2 capture)	31-aug-10
WP1.2.F3	Novel materials for H2 - CO2 separation	D01	Report on viability of reactor/process and boundary conditions i.e. PhD proposals	31-aug-10
WP1.2.F6	High pressure and temperature selective solvents	D01	Progress report on high pressure and temperature solvents	31-aug-10
WP1.3.F2	Chemical Looping Combustion	D01	Progress report on chemical looping combustion	31-aug-10
WP1.3.F3	Oxy combustion of solid fuels	D01	Progress report on oxy-combustion of solid fuels	31-aug-10
WP1.4	Techno-economic evaluation & Benchmarking	D01	Documented agreement on selected integrated capture technologies, evaluation criteria and evaluation method	30-jun-10
WP1.4	Techno-economic evaluation & Benchmarking	D02	Report describing identified and selected integrated capture technologies, system boundaries, interfaces, evaluation criteria and evaluation method	31-aug-10

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WP2.1	Technical Aspects of CO2 transport infrastructure	D01	Report: Inventory of key aspects for (technical) transport design	31-aug-10
WP2.1	Technical Aspects of CO2 transport infrastructure	D02	Report: Identification and priorisation of technical design conditions and parameters of C02 pipelines that should be addressed within CATO-2	31-aug-10
WP2.1	Technical Aspects of CO2 transport infrastructure	D03	Report: Inventory and quantitative characterisation of technologies available for each part of the CO2 infrastructure system	31-aug-10
WP2.1	Technical Aspects of CO2 transport infrastructure	D04	Report: First Assessment of the technical possibilities and constraints for use of existing pipelines and production facilities	31-aug-10
WP2.1	Technical Aspects of CO2 transport infrastructure	D05	Progress report: evaluation of technical and costs implications of several CO2 qualities for the transport infrastructure	31-aug-10
WP2.1	Technical Aspects of CO2 transport infrastructure	D06	Progress report: guidelines on the quality of CO2 in a common transport infrastructure	31-aug-10
WP2.1	Technical Aspects of CO2 transport infrastructure	D07	Progress report: evaluation of the technical possibilities of ship transport into the CO2 transport infrastructure	31-aug-10
WP2.1	Technical Aspects of CO2 transport infrastructure	D08	Detailed and up-to-date view on the (inter)national development in CO2 transport	31-aug-10
WP2.2	Techno economic chain analysis	D01	Report; Screening of the impacts of large scale development of CCS on the reliability of the electricity market	31-aug-10
WP2.2	Techno economic chain analysis	D02	Report: Screening of the technological and economic implications of retrofitting CO2 capture for the industrial sector	31-aug-10
WP2.2	Techno economic chain analysis	D03	Report: First evaluation of competition between different CCS chains and other carbon low supply and energy efficiency options in the medium and long term	31-aug-10
WP2.2	Techno economic chain analysis	D04	Report: Inventory and first assessment of different funding sources and incentive structures	31-aug-10
WP2.2	Techno economic chain analysis	D05	Report: First assessment of the costs and logistic of re-using existing infrastructure (pipelines and production facilities) in the short term.	31-aug-10
WP2.2	Techno economic chain analysis	D06	Progress report: (detailed description of the work and methodologies to be used for the) assessment of investment models for the deployment of a large scale CO2 transport infrastructure	31-aug-10
WP2.2	Techno economic chain analysis	D07	Documentation of: Regular stakeholder consultations, through workshops, enquiries, discussion form and individual interview (throughout the project)	31-aug-10

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WP2.3	International CCS policy	D01	Report/paper on CCS in the CDM, including quantitative insight into the market impacts of including CCS in the CDM (Month 12). The paper will a) describe the current CCS market and prevailing market conditions; b) attach CDM potentials and abatement cost numbers to CCS options; c) evaluate the impact of CCS in the CDM market	31-aug-10
WP2.3	International CCS policy	D02	Publicly available Marginal Abatement Cost curve for CDM with CCS options (Month 12) The MAC, updated with the CCS data, will be made available on the internet.	31-aug-10
WP2.3	International CCS policy	D03	Background paper on “Role of CCS in the international climate regime” (Month 12). Depending on the timing of the project and the outcomes of COP15 in Copenhagen in December 2009, this paper will assess the consequences for CCS, and the possibilities for a greater role for CCS as a consequence of what was decided in Copenhagen (or a greater role UNFCCC mechanisms in CCS demonstration and diffusion).	31-aug-10
WP2.4	Chain integration and CCS Implementation plan	D01	Progress report: Frameworks for reporting pilot plants results	31-aug-10
WP2.4	Chain integration and CCS Implementation plan	D02	Report: Specifications for an improved version evaluation tool	31-aug-10
WP3.01	Geological modelling	D01	Progress report on the combined adaption and use of existing/novel models/simulators: 1)Static high-resolution geological Petrel models of all storage sites. 2) Database comprising all data relevant to the various tasks of SP3	31-aug-10
WP3.02	Reservoir Behaviour	D01	Progress report on Calibration and testing of models to experimental data (such as core flooding experiments, study of phase behaviour, swelling in coals, residual saturation, use of surfactants)	31-aug-10
WP3.02	Reservoir Behaviour	D02	Progress report on Development of both flow models and flow simulators (such as coupled thermo-physical-thermal simulations, reactive transport modelling, modelling phase behaviour)	31-aug-10
WP3.03	Caprock and Fault Integrity	D01	Progress report on: Computational facilities for advanced geomechanical modelling.	31-aug-10
WP3.03	Caprock and Fault Integrity	D02	Progress report on: Results of preliminary simulations of the impact of CO_2 injection on generic models.	31-aug-10

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WP3.03	Caprock and Fault Integrity	D03	Progress report on: Inventory of sealing, transport and mechanical properties needed	31-aug-10
WP3.03	Caprock and Fault Integrity	D04	Progress report on: Laboratory facilities for transport and mechanical properties determination	31-aug-10
WP3.03	Caprock and Fault Integrity	D05	Progress report on: Agreement on representative sites	31-aug-10
WP3.03	Caprock and Fault Integrity	D06	Progress report on: Site-representative caprock and fault rock samples acquired and characterised	31-aug-10
WP3.03	Caprock and Fault Integrity	D07	Progress report on: Preliminary data on gas/CO_2 transport through intact caprocks, plus parameter computation and interpretation based on numerical simulations	31-aug-10
WP3.03	Caprock and Fault Integrity	D08	Progress report on: First data on the permeability and mechanical properties of faulted caprocks and of simulated clay-sealed fault rock; effects of CO_2-water-rock interaction	31-aug-10
WP3.03	Caprock and Fault Integrity	D09	Progress report on: Preliminary data on entry pressure, wetting behaviour and transport properties of coal/caprocks from the DSM site	31-aug-10
WP3.04	Well Integrity	D01	Progress report on: Qualitative well assessment of field cases, including recommended well-specific work over and abandonment strategies and remediation/mitigation techniques	31-aug-10
WP3.04	Well Integrity	D02	Progress report on: Application of advanced materials/treatments for abandonment and mitigation	31-aug-10
WP3.04	Well Integrity	D03	Progress report on: Development of chemical and mechanical experimental laboratory measurements	31-aug-10
WP3.04	Well Integrity	D04	Progress report on: Development of numerical models of (coupled) processes	31-aug-10
WP3.04	Well Integrity	D05	Progress report on: Specifications and design criteria for innovative corrosion monitoring and (downhole) sensor systems, including sensitivity analysis	31-aug-10
WP3.04	Well Integrity	D06	Progress report on: Monitoring strategies for inaccessible/abandoned wells	31-aug-10
WP3.05	Additional benefits of CO2 injection	D01	Progress report on: Numerical model data and reports on the effect of seasonal CO2 delivery on storage efficiency and capacity	31-aug-10

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WP3.05	Additional benefits of CO2 injection	D02	Progress report on: Preliminary of experiments and appraisal to investigate the effect of CO_2/water volume combined with gravity flow characteristics in the Delft sand reservoir	31-aug-10
WP3.05	Additional benefits of CO2 injection	D03	Progress report on: Strategies to use buffering capacity to mitigate the effects of temporal variation of CO_2 delivery volumes, to be investigated in detail in the next phase	31-aug-10
WP3.06	Shallow (sub) surface monitoring	D01	Progress report on: Development and preparation of test sites (time-series of CO_2 concentrations)	31-aug-10
WP3.06	Shallow (sub) surface monitoring	D02	Progress report on: Maps of CO_2 concentrations varying in time. Interpretation per region of the data	31-aug-10
WP3.06	Shallow (sub) surface monitoring	D03	Progress report on: Preparation of site specific geodetic remote sensing techniques for ground movement	31-aug-10
WP3.06	Shallow (sub) surface monitoring	D04	Progress report on: Development of an atmospheric pipeline monitoring strategy	31-aug-10
WP3.07	Permanent Geophysical Monitoring	D01	Progress report on: Feasibility studies for permanent seismic/EM monitoring	31-aug-10
WP3.07	Permanent Geophysical Monitoring	D02	Progress report on : Development of processing, analysis and interpretation techniques of the data	31-aug-10
WP3.07	Permanent Geophysical Monitoring	D03	Progress report on: Start of a PhD or PD on the improved interpretation of combined EM and seismic data	31-aug-10
WP3.08	Laboratory experiments geophysical	D01	Progress report on: The set-up and calibration of specific laboratory measurements regarding complex impedance in the frequency range from 1 kHz to 1 MHz.	31-aug-10
WP3.08	Laboratory experiments geophysical	D02	Progress report on: Preparations for a PhD thesis on electric properties, as a function of pressure, temperature and water saturation, of porous reservoir- and cap-rocks saturated with gas-water mixtures.	31-aug-10
WP3.09	Site specific monitoring	D01	Progress report on: Preliminary advisory reports on monitoring plans for assigned and potential sites	31-aug-10
WP3.09	Site specific monitoring	D02	Progress report on: Preparation and installation of a sounding board committee for the interpretation of Barendrecht data: Meeting reports	31-aug-10

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WP3.09	Site specific monitoring	D03	Progress report on: Monitoring activities at K12-B. If available: • Preliminary (raw) results of the monitoring and the downhole measurements • Preliminary results of chemical and tracer analysis • Progress report on the interpretation of the measurements	31-aug-10
WP3.09	Site specific monitoring	D04	Progress report on: Planning/development of site specific monitoring and control programs	31-aug-10
WP3.09	Site specific monitoring	D05	Progress report on: 5. Developing a "Vault" for data storage and a website for: • Raw data storage from field locations and experimental work • Data collection and (applied) data storage • Storage of reports, find	31-aug-10
WP4.1	Legal framework and guidance	D01	Support to the implementation of the proposed Storage	31-aug-10
WP4.1	Legal framework and guidance	D02	Practical guidance for monitoring plans for CCS	31-aug-10
WP4.1	Legal framework and guidance	D03	Assessment of accuracy required by the MRGs for CCS under the EU	31-aug-10
WP4.2	Permitting and best practice	D01	Progress report on: Best practices in CCS demonstrations	31-aug-10
WP4.2	Permitting and best practice	D02	Proceeding Workshop on licensing activities	31-aug-10
WP4.2	Permitting and best practice	D03	Briefing on identified best practices in relevant networks	31-aug-10
WP4.4	Risk management of CO2 transport	D01	Literature study on release and dispersion models for accidental releases from CO_2 pipelines	31-aug-10
WP4.4	Risk management of CO2 transport	D02	Literature review of CO_2 impacts on humans and the environment	31-aug-10
WP4.4	Risk management of CO2 transport	D03	Detailed proposal for the release and dispersion	31-aug-10
WP4.4	Risk management of CO2 transport	D04	Theoretical model for outflow of CO_2 and dispersion	31-aug-10
WP4.5	Risk management of CO2 storage	D01	Technical report describing the draft workflow and tools for qualitative and quantitative risk management including uncertainty analysis	31-aug-10
WP5.1	Local communication near CCS	D01	Progress report on the procedure and the resulting information on attributes of the CCS demonstration project which is according to the SSC (Stakeholders and Scientists Committee) balanced, relevant and comprehensible information (actual report to be delivered in Month 15 after start, that is, after decision on onshore CO2 storage location/transport route)	31-aug-10
WP5.1	Local communication near CCS	D02	Report on survey among residents: results and implications for decision procedure and communication campaign (Month 6)	31-jan-10

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WP5.1	Local communication near CCS	D03	Only in case of a strong public controversy, a progress report on the convening assessment as a start for an integrated approach (planning procedures and research) for public mediation regarding decision making on CCS (actual report will be delivered in Month 18)	31-aug-10
WP5.2	Framing effects in communication about CCS	D01	Progress report on first (half) year of this PhD project (including detailed research plan written by senior researchers)	31-aug-10
WP5.3	Trends in public opinions on CCS	D01	Progress report on the public's awareness and knowledge regarding CCS and on shared misconceptions with implications for targeted communication to refute false beliefs	30-jun-10
WP5.4	Resistance of valid beliefs about CCS against low quality information	D01	Progress report on first (quarter) of this PhD project (including detailed description of planned research written by senior researchers)	31-aug-10

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4 Executive Summaries Deliverables

5 SP 0 Coordination & Communication

5.1 0.A coordination

WP0.A-D01a, Program Plan year 1

The Program Plan for CATO2a Year 1 was submitted and approved by the EB in the meeting of 25 September 2010. Minutes are available on the restricted CATO-2 website http://www.co2-cato.nl/my-cato2/online-workspace/category/20

WP0A-D02, organisation and preparation of meetings and drawing up minutes

Ongoing task for the program director and program officer
All minutes of the meetings below are available on the restricted CATO-2 website http://www.co2-cato.nl/my-cato2/online-workspace/category/20

Executive Board

10 February 2010
16 March 2010 (extra meeting)
16 June 2010
22 September 2010
1 December 2010

Program Council
17 March
4 June
3 November

General Assembly
27 January 2010

Advisory Board
28 January 2011

WP0.A-D03, Program reporting to EZ (2009.04.15-2009.10.15)

- WP0.A-D03a Program Reporting to EZ (2009.04.15-2009.10.15) was send to EZ on 2009.12.15.
- WP0.A-D03b Program Reporting to EZ (2009.10.15-2010.04.15) was send to EZ on 2010.06.15.
- WP0.A-D03c Program Reporting to EZ (2010.04.15-end) Will follow at the end of the program e.g. 15 December 2010.

All Program Reporting to EZ consist of a technical and financial progress.

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WP0.A-D04, Financial Program Administration

Ongoing process, monitored by the program director and the financial officer.

5.2 O.B Communication and Dissemination

WP0B.1-D01, Organizing the (semi) annual Dutch CCS Conference

On June 25, CATO organised the Fifth Dutch CCS Symposium

Over 200 participants learned about the latest development on CCS in the Netherlands and the world. In the afternoon the 'Impact of CCS on the public, climate change, energy markets and local authorities' was discussed in parallel sessions.

Stan Dessens (chairman of the Dutch Taskforce CCS and the CATO Executive Board) chaired the symposium.

Former assistant deputy secretary of the Bush US government, Justin Swift, was one of the key note speakers. Graeme Sweeney (Shell, Chairman Zero Emission Platform) and Bob Pegler (Global CCS Institute) gave their views on EU and global developments

Experts and stakeholders presented their views on the impact of CCS in four parallel sessions. They assessed the impact on the public, on climate change, on energy markets and on local authorities.

Just day before the CCS Symposium, the Dutch Government presented candidate locations for CO_2 storage in the North of the Netherlands, making some headlines in Dutch newspapers. Key note speaker Max van den Berg (the Queen's Commissioner in the Province of Groningen) reacted on this actual development during the symposium. The symposium was concluded by a debate based on the newly presented "Argumentenkaart" (Issue Map). The map of arguments in favour of and against CCS was presented by Frank Kalshoven (manager of the "Argumentenfabriek").

All presentations are available on the CATO-2 website http://www.co2-cato.nl/cato-2/publications?showAll=0&keyword=&version=&type=&theme=&workpackage=&location=&event=900&person=0

WP0B.1-D02, CATO-2 Brochure and poster

The latest version of the CATO-2 brochure can be found on the website:
http://www.co2-cato.nl/cato-2/publications/publications/the-dutch-national-research-programme-on-co2-capture-transport-and-storage

WP0B.1-D03, CATO templates with PowerPoint sheets for individual participants of CATO-2

Three PowerPoint templates were made available on the CATO-2 restricted website on 29 April 2010.http://www.co2-cato.nl/my-cato2/online-workspace/category/8

The short version is presented below.

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The Dutch CCS program
in a glance

www.co2-cato.nl

CATO-2 in a glance

CATO-2 in a glance

- Applied and scientific research
- Complete CCS Chain
- Demand driven & flexible program
- 60 M€ (50% government)
- Coordination: TNO
- 2009-2014
- Partners from industry, SME, university, NGO

www.co2-cato.nl

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WP0B.1-D04, Digital CATO-2 newsletter

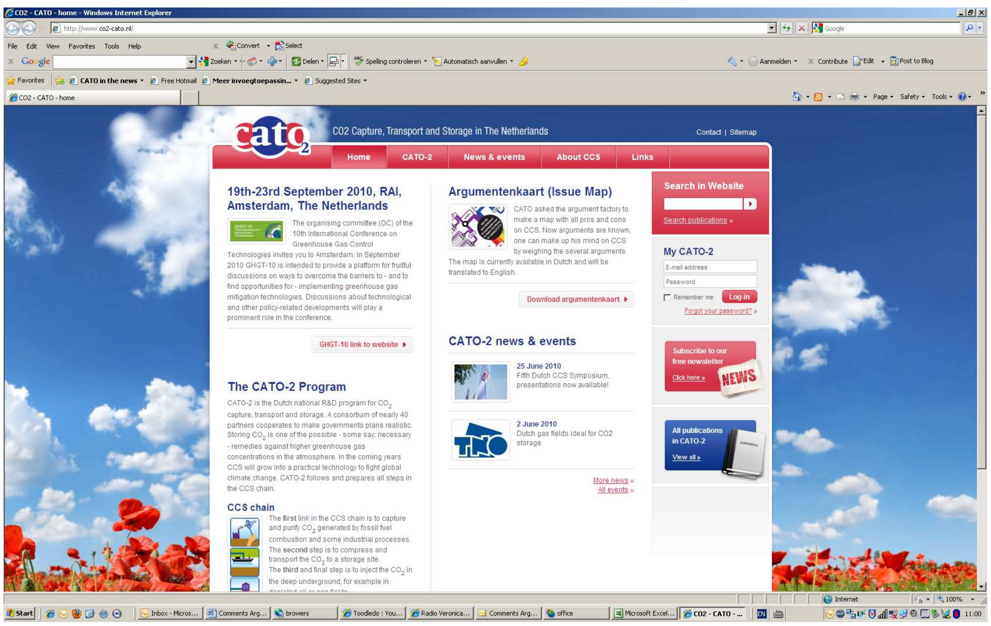
Up to now 4 newsletters were published on the website and sent to all persons who expressed their interest in CATO-2.

The newsletters were published on:
3 November 2009
9 February 2010
26 April 2010
21 June 2010

They are available at http://www.co2-cato.nl/news-events/newsletter-archive

WP0B.1-D05, Public Website

The website can be found at http://www.co2-cato.nl



WP0B.1-D07, Rapid response team on incorrect information on CCS in the media

Goals:

- To inform the (Dutch) public with objective/positive CCS information
- To brand the CATO2 trademark.

Strategy:

- React on “un nuanced” CCS information in the media, when needed.
- Bring CATO2 regularly (4/year?) in the media.

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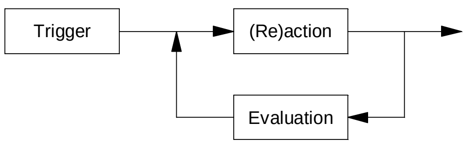
- Good/reliable/respectful relation with media.



The Rapid response team meets when needed; during CTAO-2a meetings were held 8 times

WP0B.2-D08, Annual CATO day

Several gatherings for the CATO-participants were organised in 2010.

On 27 January a New Years drink was held, the Advisory Board of CATO joined as special guests. The New Years drink was after the General Assembly meeting, which consisted of a meeting and presentations by CATO-participants.

On the 4 June the CATO day was held at Utrecht University, on this day the CATO2-program presented and discussed its first results. Participants highlighted their work and discussed the results with fellow-CATO-2 participants.

Plenary Sessions
- Jan Brouwer (CATO) - welcome and status CATO-2
- Stichting Borg - CCS in the Northern Netherlands
- Henk Bak (EON-Benelux) - Development of the project ROAD
- Markus Hagemann (Ecofys) - A foggy matter - CCS in the International Climate Regime

Workshops
In the afternoon presentations and workshops are planned on different subjects. A full programme will be available on the CATO website.

The day ended with a BBQ, which was joined by a Chinese delegation visiting TNO, to exchange information on CCS

WP0B.2-D09, Terms of reference for the CATO-2 extranet, followed by implementation

This deliverable gives the Terms and Reference for the external website.

WP0B.3-D10, Plan for the Staccato newsletter on developments in CCS outside CATO for the CATO partners

Summary to be translated !!!
De STACCATO nieuwsbrief is een voortzetting vanuit CATO-1. Toen verzorgde de KEMA (Bennie Stortelder) voor de energiebedrijven een update over CCS. De energiebedrijven waren toen geen onderdeel van CATO, KEMA was een intermediair tussen CATO en de Energiebedrijven.

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Doel:
Het doel van de STACCATO nieuwsbrief is het informeren van de CATO gemeenschap over de ontwikkelingen op het gebied van CCS die plaatsvinden buiten de CATO. (van buiten naar binnen). Het betreft hier meer achtergrond informatie, trends en ontwikkelingen binnen en buitenland. Voor het dagelijkse nieuws is er een digitale knipselkrant van de Nederlandse media. De artikelen zijn vooral gericht op de implementatie van CCS, dus bijvoorbeeld over een nieuw roadmap, beleid in Brussel, klimaatverdragen, etc. Voor de meer wetenschappelijke achtergronden hebben de partners binnen CATO kunnen eigen kanalen, zoals wetenschappelijk tijdschriften en internationale onderzoek programma's

WP0B.3-D11, First Staccato newsletter.

The Staccato newsletter contains "teasers" of articles, that are available on the intranet part (My CATO) of the CATO website (www.co2-cato.nl). The staccato newsletter can be printed as one document and contains 10 articles on average.

- Frequency: 4 times/year.
- Website: http://www.co2-cato.nl/my-cato-2/staccato

WP0B.3-D12, Dialog with stakeholders

For this purpose, a "CCS-Issue-Map" was developed and presented at the National CCS-day. The "CCS-Issue-Map" can be found on the website: http://www.co2-cato.nl/cato-2/publications/publications/de-argumentenkaart

WP0B.4-D13, plan for capacity building and international knowledge exchange

CATO is the Dutch national research program on CCS. Although the programme has a *Dutch* focus, the programme is well imbedded in the international community.

First of all, about a dozen CATO participants, like Shell, E.ON, Corus, Schlumberger have a strong international focus and are engaged in CCS related activities outside the Netherlands.

Secondly, CATO partners participate in an enormous amount of EU-projects that (partly) work on CCS issues. From the almost 50 R&D cross-country projects in EU, in only 7cases no CATO participant was represented. Although not all information of those projects is public, the general knowhow and network is imported in the CATO programme (see section XX.)

CATO is also represented in the important international CCS bodies like the IEA Greenhouse Gas programme.

The Netherlands lies in the forefront of CCS knowledge. The 10th international CCS conference was organised last September in Amsterdam (GHGT-10) and was attended by over 1500 experts from all over the world. Together with the US, UK, Australia and Norway and followed by Japan, Germany, France, Canada and South Africa (and emerging economies like China and Brazil) the Netherlands are in the lead with respect to the development of CCS technology. CATO encourages cooperation with these countries. Last year, special attention was paid to the cooperation with Canada. A mission to Canada was organised as well as a return visit to the Netherlands during the GHGT-10 conference. CATO has a small travel fund and sponsored two Dutch geology students to do part of their thesis research in Canada.

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WP0B.5-D14, Inventory on available education and needs for CCS education.

Within CATO-2 frame a survey of CCS education was performed, both the available current offer as the desired CCS education were examined. Universities and colleges are the places where education on CCS will be provided to students. Universities will not present CCS as the single solution to climate change but they will place CCS as one of the elements in a balanced energy policy in an era of climate change. This position will discriminate education from communication, and makes the target audience for CCS-education the active professionals and students, the future CCS-professionals.

The survey of the current CCS-education was performed by sending out a personalized mailing to people active within CATO-2 and connected to an education institute. This mailing was complemented with an internet search and a series of phone calls.

<u>Results:</u>
Within the Netherlands CCS-education is currently not offered as an entirely new discipline or master course. Instead, CCS appeared in many places as part of a course in existing disciplines. Courses were given in specific parts of the CCS-chain, certainly not covering the whole field. In general students come in contact with CCS-related subjects during the later stages of their studies when they choose their own projects. In some cases interdisciplinary CCS-related projects are offered to the students, recent CCS-summer schools being a fine example.

In the United States the long experience in EOR results in considerable knowledge on and education in CCS related subjects. Universities actively participate in applied projects together with industry. The recently initiated nation-wide education program the "Grand Challenges for Engineering" promotes (among others) the interdisciplinary and focused cooperation on CCS of some 40 universities. In the UK world's first master course on CCS is offered covering the entire CCS-chain.

The survey of desired CCS-education was performed with a limited-scope poll. In spite of the rather low response some conclusions were obtained. The majority of the respondents was unfamiliar with CCS education. Most demands were noticed for courses in risk analysis and CCS-communication, with legal issues at a good third place. The requested high level education should indeed be targeted at professionals.

In <u>conclusion</u> it's important to put CCS in a broad perspective with global energy policies, climate change, changing economies, politics and sustainable development. CCS-education is often offered in a T-shape model: after a broad general introduction only a specific subject is deepened. The availability of good and 'CATO-approved' material for education is widely welcomed. Good starting material is provided by the CO2NET series of lectures. Possible additions are practical exercises and links to expert information and availability. The actual subject of legal issues/permitting within the EU-CCS-directives also deserves attention.

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6 SP 1 Capture

6.1 WP.1.1 Post combustion capture

WP1.1A1-D01, User requirements specification for E.On case & WP1.1A1-D02, User requirement specification for other cases

In CATO-2 Work Package WP1.1A1 the user requirements have been established for the post combustion capture cases to be considered in other applied research Work Packages, in particular WP1.1A2 DEMO Preliminary Design. In several working sessions a table of requirements and other parameters have been agreed upon by the CATO-2 parties E.ON, GDF, KEMA and TNO.

These values are used for the modelling of the power plant and capture plant. The table is listed in

Chapter 4, below. The table is a living document; it has been and will be updated when new information becomes available.

The table contains parameters for both the 250MW E.ON post-combustion capture demo case and the full scale case. Therefore, the deliverables D01 and D02 have been combined in the table. Because the table contains commercially sensitive data, the actual values are confidential and may not be distributed outside the parties who signed the NDA, i.e. E.ON, GDF, KEMA and TNO.

WP1.1A2-D01, Preliminary design report

In the first year of CATO2 the focus of the Work Package pre-design is on the design of the 250 MW capture unit to be located at the E.ON coal fired power plant at the Maasvlakte. The starting points of the design followed from the user requirements drafted in the Work Package WP1.1A1. The following tasks are part of this Work Package

- Design capture plant
- Design compressor train
- Integration with power plant
- Equipment selection
- Economic evaluation
- Dynamics
- Retrofit possibilities of the capture plant for novel solvents (will start in the second phase of the project.

To be able to the design the capture plant and to integrate with the power plant (ie MPP3) a modelling infrastructure has been established. This modelling infrastructure consists out of SPENCE® models (activities KEMA) for the power plant and the compressor train and ASPEN® models (activities TNO) for the capture plant. Using a structured interface iterative communication is possible between the two models. In the picture below the structure is schematically given. The modelling structure will be used for the evaluation of different operating cases (eg. load variation, summer and winter conditions). Reporting of the different cases will be done in the second phase of the project.

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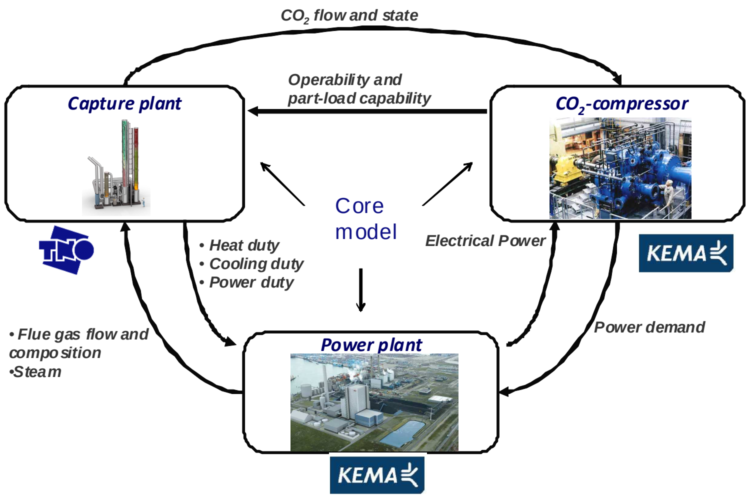

Based on the outcome of the models, the needed equipment was sized and via vendors price estimation were obtained. Based on these data an economic evaluation has been made.

Within ASPEN® dynamics, models have been made to evaluate the dynamics of the 250 MW capture plant. The study to the dynamics of the capture plant will be continued in the second phase of this project.

WP1.1A3-D01, Report in inventarisation of leads

In this period tools for the generation of leads have been designed, constructed and validated. These tools consist of NMR, FT-IR and medium/high throughput equipment for the measurements of vapour liquid equilibria. In this report the medium/high throughput equipment is mainly discussed.

This set-up was build with 6 small autoclaves, called the mini-autoclave (MAC). Three autoclaves are used for vapour-liquid equilibrium (VLE) measurements at 40°C and three for VLE measurements at higher temperatures (typically 120°C). The MAC was tested thoroughly. It was found that different pulse criteria, in the control software, should be applied for fast and slow reacting systems.

Other possible error sources were investigated. It was found that the volume of the solvent should be accurately measured. Leaking of the autoclaves should be minimized.
It was shown that reproducible VLE curves could be obtained that are comparable with literature.

WP1.1A3-D02, Report on Simplified Model

In Work Package WP 1.1A3, a solvent is to be developed for the (post-combustion) capture of carbon dioxide from flue gas. Two basic (modelling) routes are being followed to arrive at new and improved solvents: the QSAR model approach (led by TNO) and the flow sheet model approach (led by PROCEDE). In this deliverable this rate based model is described shortly and the most important features of this flow sheet program are shown.

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Because in this report commercially confidential information is reported on the modelling method, the remainder of this report is confidential

WP1.1A3-D03, Report on Optimization (in concept)

This report summarizes the work and results of the second testing campaign done at TNO's pilot plant in the Maasvlakte power plant of E.on. This work was done within the Sub Program 1 of CATO-2. CATO-2 is the Dutch national R&D program for CO_2 capture, transport and storage, which aims to aid the fast implementation of CCS in The Netherlands. Sub Program 1 aims to and develop knowledge on the technical performance of solvents in absorption and desorption columns.

Several piloting activities are described, which include testing and modelling. Activities took place in the period from October 2009 to February 2010. The solvent tested is the potassium salt of taurine. This amino acid serves as a model solvent and is an example of the applicability of amino acids to CO_2 scrubbing.

After solvent selection, tests were conducted in the TNO's laboratory to determine the physical properties of the solution and the CO2 solubility. The data were used to make a simple model that could initially predict solvent performance. For this purpose an in-house tool (VLEMS) was used. In parallel, an experimental plan was implemented and conducted in the period between October 2009 and November 2009. The pilot data were compared to the model data and used for model validation.

During operation the pilot plant run stable from October to November 2009 (about 500 h of operation). The tests conducted aimed at model validation and not at optimisation of process conditions. For 90% capture the lowest energy consumption was found to be 4.3GJ/tonCO_2 at 120ºC and 0.77 barg in the reboiler. However, this figure has two sources of errors: 8% heat losses and high temperature approach in the Lean Rich Heat exchanger (LRHEX).
After fitting the pilot data with the VLEMS model, the influence of the high temperature approach in the LRHEX can be corrected giving a result of 3.77GJ/tonCO_2.

Because commercially confidential information on solvent systems is reported the remainder of this report is confidential.

WP1.1A4-D01, Investigation report on 'state of the art' for large scale absorbers

This document describes the research plan for the upcoming years on the further development of better understanding of absorbers and the improvement this equipment. In this plan the following items are considered:

- Definition of the state of the art
- Process intensification
- Modelling
- Control

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- Construction

WP1.1A5-D01, Investigation report on 'state of the art' for large scale strippers

Aqueous solutions of (alkanol)amines are frequently used for the removal of acid gases, such as CO_2 and H_2S, from a variety of gas streams. A conventional acid gas removal plant is operated with an acid gas absorption / desorption cycle of the acid gas. In the absorber, the acid gas is (chemically) absorbed by the basic absorbent. At an elevated temperature in the desorber and usually a reduced pressure, the acid gas is released. The transfer of the acid gas from the gas phase into the liquid phase during absorption, and in the opposite direction during desorption, is governed by two limiting factors; (1) mass transfer limitation, and (2) kinetic limitations. The former is dependent on the solution containing the (reactive) absorbent and the process equipment used, while the latter is dependent only on the solution containing the dissolved reactive absorbent. For a better performance of an acid gas removal process, both factors have to be taken into account, i.e. fast mass transfer and fast kinetics. The mass transfer characteristics are usually dependent on the diffusivities and fluid mixing / geometries, etc. of the equipment used. The kinetic characteristics are dependent on the type(s) of reactive chemical(s) being used and the solvent in which they are dissolved, e.g. aqueous amines, alkanolamines, etc. In a conventional absorber / desorber configuration, the bottom of the absorber and the full length of the desorber are generally limited by the mass transfer characteristics, whereas the top of the absorber is generally limited by the kinetics.

Gas absorption is undoubtedly one of the most important industrial operations of gas purification mass transfer processes and is used in an extensive amount. This process is frequently coupled with a desorber to permit regeneration and recycling of the absorbent. Traditionally, focus and attention have been given to the improvement of the gas absorber section through better (reactive) absorbent(s), gas-liquid mass transfer characteristics, heat integration, etc. This has been carried out mainly for the improvements of high pressure gas treating processes, such as natural gas. The gas desorber section has lately gained increased focus and attention, in the interest of reducing the energy consumption of gas desorption from a (reactive) absorbent. This is of particular financial interests in the case of the removal of low to medium partial pressure carbon dioxide from gas streams, e.g. flue gases. Still, fundamental aspects of gas desorption characteristics are lacking in the open literature. When a gas is desorbed from a reactive absorbent, the equilibrium of the dissolved gas in the bulk of the liquid and that at the interface is altered. If the total pressure at the interface is sufficiently less than that in the liquid bulk, bubbles may spontaneously begin to form in the bulk and much of the gas will be transferred by diffusion to the interface of the bubble. This is a process very different from the absorption process, in which the interfacial area is determined by external factors and not the process itself. When the partial pressure of the gas in the liquid bulk has fallen to a value equal to the total pressure at the interface, bubbling formation will cease. The desorption process will further continue through the normal interfacial area and be limited by diffusion or the kinetics of the reactive absorbent until equilibrium between the partial pressures in the bulk and the interface is achieved It is often assumed that the theory and basic phenomena for absorption processes are also valid for this diffusion or kinetic limited desorption process, and that these are symmetrical of each other; however, experimental validation in the open literature is extremely limited.

This deliverable is divided into 3 sections; (1) established that the liquid phase mass transfer coefficients for non-reactive systems are identical for absorption and desorption mass transfer processes given identical operating conditions for the two processes; (2) establishment of similar characteristics for absorption and desorption mass transfer processes in reactive systems. The

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absorption performance of an absorbent is often given in terms of an enhancement factor. The enhancement factor concept is introduced to describe the influence of a reaction on the total mass transfer rate, and is defined as the ratio of the rate of absorption of a gas into a reactive liquid to the rate of the physical process at identical process conditions; and (3) the establishment of kinetic rate constants for absorption and desorption mass transfer processes. The backward reaction rate constant for absorption and desorption mass transfer processes has never been studied, and the present work aim for a better insight into these kinetic rate constants.

WP1.1F1-D01, Progress report on DECAB

These reports would have described in more detail the DECAB process. However, it was decided not to continue MCS project due to budget cuts.

WP1.1F1-D02, Progress report on DECAB

This work describes the conceptual design of a novel separation process for CO_2 removal from flue gas based on precipitating solvents. The process here described (DECAB) is an enhanced CO_2 absorption based on the Le Chatelier's principle, which states that reaction equilibrium can be shifted by removing one of the constituents in the reaction. A conceptual design of this process has been developed based on literature data, thermodynamic principles and a limited number of experiments. As solvent example, the potassium salt of taurine was selected. The strategy followed is based on the compilation and determination of the key properties and parameters that govern the absorption and regeneration of the solvent. Then, the performance of the process is evaluated with the aid of short cut design methods. Results show that the key advantages of this process are environmental friendliness (no emissions to the air) and low energy consumption related to a lower vapor pressure of the solvent and higher net loading than conventional processes. The design developed allows for future economic evaluation and assessment of options that will further lead to benefits over conventional processes.

WP1.1F2-D01, Progress report DECASOX

The intent of the DECASOX project was to develop combined absorption of CO_2 and SO_2. The absorption liquid is then step wise regenerated leading to purified stream of CO_2 and a stream containing sulphur It was envisaged that in year 1 a project plan will be made as a basis for the further investigation of the DECASOX concept. However, this work will be further continued in the European project iCAP. Therefore, it has been decided not to pursue this work any further in CATO-2. Due to the presence of TNO in iCAP, it will still be possible to incorporate knowledge on this topic within CATO-2. Nevertheless, some high level insights in the possibilities for the combined removal of CO_2 and SO_2 are given in this report.

WP1.1F3-D01, Progress report on molecular modelling & WP1.1F3-D02, Progress report on molecular simulation & WP1.1F3-D03, Progress report on Raman infrared spectroscopy

This report the high level plans for the work envisaged in the Work Package dealing with thermo dynamical models. The work can be divided into four parts, namely:

- Quantum chemical calculation (WUR)
- Molecular simulations (TUD)
- Raman Spectroscopy (RTWH/TUD)
- Technical and economic feasibility analysis (TNO)

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The first three tasks will be done by PhD students at three different universities. The idea is to create an infrastructure to establish the synergistic effects of the different tasks. The last task is to evaluate the outcome by doing technical and economic feasibility studies

WP1.1F6-D01, Report on basic design and process descriptions

The report describes the basic design and the processes of a post-combustion carbon capture concept for gas-fired power plants. The concept consists of three subsystems: flue gas looping, membrane and solvent technology. The following topics are treated:

- A conceptual process description of the proposed integrated capture system with its benefits;
- An initial overview of absorber solvents potentially of advantage in the system;
- An overview of commercial available membranes that would fit the system;
- An analysis of the state of the art of flue gas recycling technology related to gas turbines;
- The interfacial parameters of the three subsystems once integrated into one capture system and their accompanying challenges;
- An analysis of the energy and water usage of the complete capture system.

The findings form the basic understanding and include the starting points and system boundaries for further research on the concept currently being executed

WP1.1F6-D02, Report on first set of selected solvents

A solvent screening has been performed for the most promising physical and mixed physical/chemical solvents in the hybrid CO_2 capture process for gas fired power plants. Five promising physical solvents and one mixed (physical/chemical) solvent were found, from which three physical solvents were pre-selected. Two physical solvents were excluded because of doubts or lack of data on full process suitability in combination with expected low commercial availability. The mixed solvent candidate was excluded because of the expected higher energy penalty.

It has been concluded that detailed open literature data is missing required to make a comprehensive evaluation on the feasibility of the hybrid system incorporating these solvents. Especially, the solubilities of oxygen and sometimes nitrogen are often not very well known as these solvents typically are not operated under oxidizing conditions. Additionally, the degradation effect under oxidizing conditions is not fully known. To establish these data, a significant experimental effort is needed, which will not fit within the current WP budget.

It is expected that for glycol based solvents currently enough model info is available to perform a first global process evaluation. It is therefore proposed to wait for the conclusions of this global process evaluation before commencing experimental work. The experimental work to be executed will then be aiming at filling in the most demanding knowledge gaps to improve the process evaluation

6.2 WP 1.2 Pre combustion capture

WP1.2A2-D01, Progress report on development of new catalyst type

Ontbreekt nog

WP1.2A4-D01, Progress report on selected location for pilot plant SEWGS

Sorption Enhanced Water Gas Shift (SEWGS) is a pressure swing adsorption process based on reversible CO_2 adsorption on solid materials at elevated temperatures between 350 and 550 °C.

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Accordingly, cooling and partially condensing the fuel gas and subsequent reheating upstream of the gas turbine are avoided. The reactor vessels are loaded with sorbent pellets. As CO_2 is removed from the synthesis gas by adsorption, CO is simultaneously converted to CO_2 by the water-gas shift reaction, which ultimately ensures low CO_2 emissions and high carbon capture ratios. The sorbent is periodically regenerated by purging with steam at low pressure.

In order to develop novel cycles and design the reactors, a dynamic model of a SEWGS reactor, including the chemical reactions and adsorption and desorption processes, has been developed. The model contained mass and energy balances, kinetics of commercial shift catalysts, and a CO_2 adsorption isotherm for a reference promoted hydrotalcite. The model has been validated with experimental results from a test rig consisting of 6 adsorption columns each 6 m tall. CO_2 breakthrough curves as well as desorption curves could be predicted. The model allows to simulate the performance of a SEWGS unit by simulating the dynamic composition of the feed and product streams during cyclic operation. Using the model, simulations of SEWGS pressure-swing cycles can reveal design knowledge for power generation (NGCC and IGCC) and for non-power applications.

Promising non-power applications include carbon abatement from blast furnace top gas in the steel sector and gasifiers in refineries. Conceptual designs for these applications are planned for next year.

The current Technology Readiness Level (TRL) of SEWGS is assessed as Level 5. This implies that in a couple of years the technology could be scaled up to a pilot unit and be demonstrated on this scale with a real feed gas. The demonstration of the technology in this pilot unit is a key step towards successful commercialisation. A first step in the pilot plant planning process is the selection of the best application for SEWGS, such as NGCC, IGCC, or blast furnace application. The best application will benefit most from the characteristics of SEWGS in comparison to competing technologies, such as chemical or physical absorption. Also, the best application will have a large market potential. The choice of the best application will be an important criterion for the following step: the selection of the location of a host site. Important considerations for the choice of a location include: commitment and value for the owner of the host site, availability of sufficient land area and utilities such as steam, safety, operational and legal issues. A list of potential host sites in the Netherlands include hydrogen production plants, a coal-gasifier, an oil-residue gasifier, and a blast furnace. A decision for a specific location will be made in the second year of the CATO-2 project.

WP1.2F1-D01, Progress report on PDU membrane reactor tests

A process development unit (PDU) has been built for the testing of hydrogen membrane reactors. The PDU consists of a test rig section for gas supply, product processing and gas analysis, and a membrane reactor section for carrying out reaction and membrane separation. The membrane reactor in place is an 8-tube reactor applicable for both membrane assisted water-gas-shift and membrane reformer applications. The application aimed at is primarily hydrogen production with CO_2 capture.

The test rig is designed to supply gas mixtures with a variable composition up to 40 bar(a) and 600 ºC. Gas preheating, active cooling, water removal, condensate treatment, pressure reduction, safe venting, data acquisition, automatic pressure control, gas detection and local ventilation are in place. In addition, gas samples from the 8 membrane tubes can be analyzed individually or together by a gas chromatograph. The unit is computer controlled and is designed for unattended

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automatic experiments. If required, other types of membrane reactors than the one now in place can be connected.

The box type membrane reactor that is tested is derived from an envisaged full scale methane steam reformer type reactor with membranes inserted into the reactor tubes. The reactor is also suitable for conducting membrane water-gas shift experiments. Mani folding is done by using headers and flanges. For the connection to the retentate header a gland packing is utilized, in such a way that membrane tubes are individually removable without disassembling other membranes. The membrane reactor can operate at conditions up to 40 bar(a) and 600 °C. The membrane reactor can hold up to 8 membranes with a maximum length of 50 cm heating is done by radiating electrical elements.

The PDU is used to demonstrate the feasibility of the reactor concept allowing experimental data to be taken for both design purposes and to improve process modelling. Experiments are dedicated to determine the effect of critical process variables (pressure, temperature, feed composition) on the reactor/membrane performance (conversion, permeability, H_2 recovery, heat transfer).

In year 1 of the CATO-2 project the commissioning of the PDU was finished and two experiments were carried out at 400 ℃ with three Pd membrane t ubes of 50 cm long (44 cm effective length): WGS-mixture separation and integrated WGS-reaction tests. The overall performance of the membranes and the PDU was evaluated with series of experiments including pure nitrogen and hydrogen permeance measurements, hydrogen/nitrogen mixture and WGS-mixture separation test. The gas separation experiments were succeeded by the water gas shift (MWGS) reaction test using the same membranes combined with precious metal shift catalyst.
During this first test period the PDU worked very well without any major problems. A homogeneous gas distribution and temperature distribution were derived among the three membranes. The pure H_2 permeance remained stable during the time span of the testing in the separation-only test and WGS-reaction test, for 23 days and 27 days respectively. Also the pure N_2 permeance remained unchanged during the loading of catalyst indicating that no membrane surface layer damage was induced by the loading of the catalyst. CO and CO_2 have a negative effect on the H_2 permeation. During MWGS, a CO conversion and hydrogen recovery factor was obtained exceeding 90%. Good gas and temperature distribution was also found with the full 8 membrane modules during the high temperature permeation experiments at 550 ℃.

The results provide already good model-input and design data and will form the basis for the future design in pilot-scale or full-scale with, parallel to the experimental work, in-house developed membrane (and module) models.

WP1.2F2-D01, Postdoc proposal (Nano-structured sorbents for CO_2 capture

This deliverable is the following Postdoc Proposal.

WPnr + Deliverable nr + thesis title	WP1.2-F2 Nano-structured sorbents for CO_2 capture D08 - Two peer-reviewed publications on the structure-activity relationships of nano-sized oxide particles in relation to CO_2 capture properties
Version date	2010.03.19
Promotor + University	Promotor n.a. the project will be executed with a postdoctoral fellow at University Utrecht,Department of science, Inorganic Chemistry and Catalysis
Objective	Develop fundamental understanding of particle size effects and doping on basic-metal-oxidebased sorbents for CO_2 at intermediate temperature (400-

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	600 ^oC)
Description of Work	The currently existing CO_2 sorbents for application in the temperature range of 400-600 ^oC have drawbacks related to their relatively low capacity (e.g. hydrotalcites), or can become mechanically unstable under hydrothermal conditions present during pre-combustion decarbonisation (e.g. hydrotalcites and CaO), or due to the high stability of the formed carbonates and kinetic limitations in their formation (e.g. CaO). The former would gain from higher stability, the latter from reduced stability and thus improvements to regeneration. It is proposed to modify basic-metal-oxide-based materials in such a way that the stability of the carbonate is decreased in the case of Ca, Ba, K, Cs and Na sorbent and increased in the case of Mg-based sorbents. Leads from other areas such as hydrogen storage indicate that the particle size of the active phase might have an influence on their stability e.g. by decreasing the size of Mg to about 2 nm the stability of the hydride decreases compared to the metal thus allowing easier desorption of hydrogen. A similar hypothesis holds for K_2CO_3, a post combustion CO_2 capture material. The UU group showed that the capture properties of that material, at 100 ^oC, were significantly enhanced by supported it on carbon nanofibers which is claimed to be the result of smaller K_2CO_3 entities as compared the bulk K_2CO_3. The latter did not show any capture activity under identical condition. Here we propose to follow, as a first attempt, a similar strategy i.e., we propose to investigate whether the size of metal-oxide particles (chosen from Ca, Ba, K, Na, Cs and Mg) is related to their properties for CO_2 capture in the range of 400-600 ^oC. Our approach would be to develop and understand nano-sized metal oxides for CO_2 capture i.e., develop a structure-performance relation for these materials. To achieve these goals synthesis routes to prepare monodisperse stable particles need to be developed (UU). We opt for a bottom-up approach to prepare the sorbents. CaO based materials are our initial candidates. To stabilize these particles an relatively inert support is needed. After synthesizing the sorbents a thorough characterization is needed. Our (UU and ECN) extensive experience with *in-situ* characterization techniques such as IR, Raman, Exafs (UU), and gas sorption and breakthrough measurements will be performed (ECN) in the current project to establish in a quantitative way the structure performance relations for these systems..

WP1.2F3-D01, Report on viability of reactor process and boundary conditions i.e PhD proposals

In order to meet the future requirements of energy supply, fossil fuels will continue to be used in the following decades even though the awareness of the environmental impact of these sources. Besides this, introduction of renewables in the energy system has aggravated the dynamics of the supply side. Hence, in order to continue fossil fuel utilization and ensure future energy supply, development and introduction of low-carbon, more efficient and flexible technologies have to be applied.

The current project aims to provide guidance for future research in order to reach a future coal-based Integrated Gasification Combined Cycle (IGCC) plant with demands of low GHG emission, flexibility of energy supply and high efficiency.

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The process selected that accomplishes these objectives consists on a IGCC plant with carbon capture that incorporates of Sorption Enhance and Water Gas-Shift (SEGWS) technology and polygeneration of Synthetic Natural Gas (SNG). The proposed concept makes use of a novel adsorbent with partial CO_2-adsorption and enhanced adsorption/regeneration characteristics. Thus, further research on this concept in the areas of development of novel materials and optimization of the system is proposed

WP1.2F6-D01, Progress report on high pressure and temperature solvents

This document describes the updated high level plans for the CATO-2 Work Package WP1.2F6 dealing with high pressure and high temperature solvents. These solvents will be evaluated and tested for pre-combustion capture application. The work envisaged will be executed by TNO and ECN

6.3 WP 1.3 Oxyfuel

WP1.3F2-D01, Progress report on chemical looping combustion

This report describes the state of the art of chemical looping. Based on the state of the art, a PhD research program have been developed. Chemical looping is basically a from of oxyfiring. However, in stead of using a cryogenic technique for the separation of oxygen from air, the oxygen separation step is directly combined with the combustion process. This is achieved by using a solid, oxygen carrier, such as an easily oxidized/reduced metal/metal-oxide combination to provide the oxygen source for combustion. This greatly improves the efficiency of power generation systems where CO_2 separation is required, for example when CO_2 sequestration is needed. On complete combustion in a N_2-free environment, a hydrocarbon fuel will produce only CO_2 and H_2O. The H_2O can easily be separated by condensation.

It have been identified that to use the technique of chemical looping with high efficiency that it is needed to perform this process at high temperatures (1100 ℃) and pressures (20 bar). The difficulty is to design reactors, which can cope with these aspects. At this moment the state of the art is based on fluidized bed. However, it is expected that this is difficult to scale up. For the coming research, the focus will be on the development of fixed bed reactor technology. Fixed bed reactors has the advantage that it is more easier to have high pressure and temperatures. Nevertheless, research is needed to design and model the reactor and operating conditions. Special attention will need to be paid to hot spot formation, i.e. temperature control and CO_2 capture ratio will decrease as the necessary reactor purges will lead to some loss of gas.

Aspen simulation model have been developed to describe the low pressure situation. Results show (the models can be further optimised) that chemical looping combustion can be done with high efficiency. This model can be extended and improved in the coming years towards the desired operating window.

WP1.3F3-D01, Progress report on oxy-combustion of solid fuels

This report on task 1.3 is an overview on the current state of the art in research and demonstration activities of oxyfuel combustion of coal and biomass, including references to studies and techno economic evaluations. Reviews on oxy-fuel state of the art may be present to a certain extent but this report summarises all the available the available literature and experimental activities of the last decade and focuses on the main findings which can be of importance for the CATO project.

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Implementation of the oxy-fuel combustion technology in existing pulverized-coal-fired power plants induces some changes of the plant configuration when comparing to the post-combustion absorption processes. Apart from several demonstration activities, presently , there are no full-scale plants using oxy-fuel combustion in operation at this moment. Studies combined with lab- and pilot-scale work have provided understanding of the design parameters and main operational issues, such as O_2 production and heat transfer optimisation. The heat transfer patterns inside the boiler and the convection banks can be completely different compared to an air fired boiler. Also there is a difference for the retrofit situations and new to be build installations.

A potential disadvantage of the oxy-fuel combustion technology is the requirement for almost pure oxygen. This creates the need for an expensive preparation factory. The available large-scale technology for air separation is based on cryogenic distillation which imposes an efficiency drop of about 15–30% of the generated electricity (net power output), depending on the initial plant efficiency. Laboratory-scale studies are valuable to study the combustion characteristics; however these are not able to adequately simulate aspects such as heat transfer characteristics and to some extent, pollutant formation. Pilot-scale studies are far more effective for this purpose.

Table: Summary of Large Scale Pilot and Demonstration Oxyfuel Projects

Project	Location	MWth	Start Up	Boiler Type	Main Fuel	CO_2 Train
B&W	USA	30	2007	Pilot PC	Bituminous, Sub-Bituminous, Lignite	No
Jupiter	USA	20	2007	Industrial No FGR	NG, Illinois No. 6 Coal	No
Vattenfall (Schwatze Pumpe)	Germany	30	2008	Pilot PC	Lignite (Bituminous)	With CCS
Alstom (Windsor Facility)	USA	15	2009	Pilot PC (Tangential)	Bituminous, Sub-Bituminous, PRB	No
Oxy-coal UK	UK	40	2009	Pilot PC	Bituminous	No
Total/Lacq	France	30	2009	Industrial	NG	With CCS
Pearl Plant	USA	66	2009	22 MWe PC	Bituminous	With CCS (Side Stream)
Callide	Australia	90	2010	30 MWe PC	Bituminous	With CCS
Ciuden -PC	Spain	20	2010	Pilot PC	Anthracite, Bituminous, Lignite, Petroleum Coke	Not known
Ciuden – CFB	Spain	30	2010	Pilot CFB	Anthracite, Bituminous, Lignite, Petroleum Coke	Not known
Praxair (Jamestown)	USA	150	2013	50 MWe CFB	Bituminous	With CCS

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Endessa/Ciuden	Spain	~1500	2015	300 MWe CFB (?)	Not known	With CCS
Vattenfall (Janschwalde)	Germany	~1000	2015	~250 MWe PC	Lignite (Bituminous)	With CCS
Black Hills Power/B&W	USA	~ 400	2015	~ 100 MWe PC	Bituminous, PRB	Not known
KOSEP/KERPRI ((Youngdong)	Korea	~400	2018	~100 MWe PC	Not known	Not known

6.4 WP 1.4 Techno-economic evaluation and benchmarking

WP1.4-D01, Documented agreement on selected integrated capture technologies, evaluation criteria and evaluation method

This report describes the cases that are chosen to be evaluated in WP1.4. The cases have been discussed with participating companies, that have each indicated their willingness to participate. A final decision is dependant on the specific data requirements for the performance of benchmarking and on how confidentiality can be maintained during data sharing for the purpose thereof. Further detailing will take place on a case-by-case basis.

WP1.4-D02, Report describing indentified and selected integrated capture technologies, system boundaries, interfaces, evaluation criteria and evaluation method

This report contains a description of the methodology to be used in WP1.4. This methodology has previously been applied in other research programs, is well suited for use in CATO-2 and amongst others addresses choice of the reference and how to compare inherently different technologies

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7 SP 2 Transport & Chain Integration

7.1 WP 2.1 Technical Aspects of CO_2 transport infrastructure

WP2.1-D01, Report: Inventory of key aspects for (technical) transport design

For the proper realization of a CO_2 transport network, a number of technical issues need to be addressed. Of these issues an inventory is given in this report.

The design of a CO_2 pipeline involves a proper assessment of issues like the boundary conditions, the routing of the pipeline, the phase choice and the effects of impurities, the pipeline material and the safety requirements. Modelling the thermodynamics of CO_2 transport is vital to a good pipeline design. However, the existing models have to be validated.
The operational aspects of CO_2 transport need to be addressed as well. Therefore, procedures for building, maintaining, commissioning, decommissioning and operating a pipeline are necessary.
Furthermore, the availability of compressors, heaters, coolers and other unit operations needs to be investigated, as well as their ability to meet the specific CO_2 transport requirements.

A schematic summary of the topics that need to be addressed is given in the figure below.

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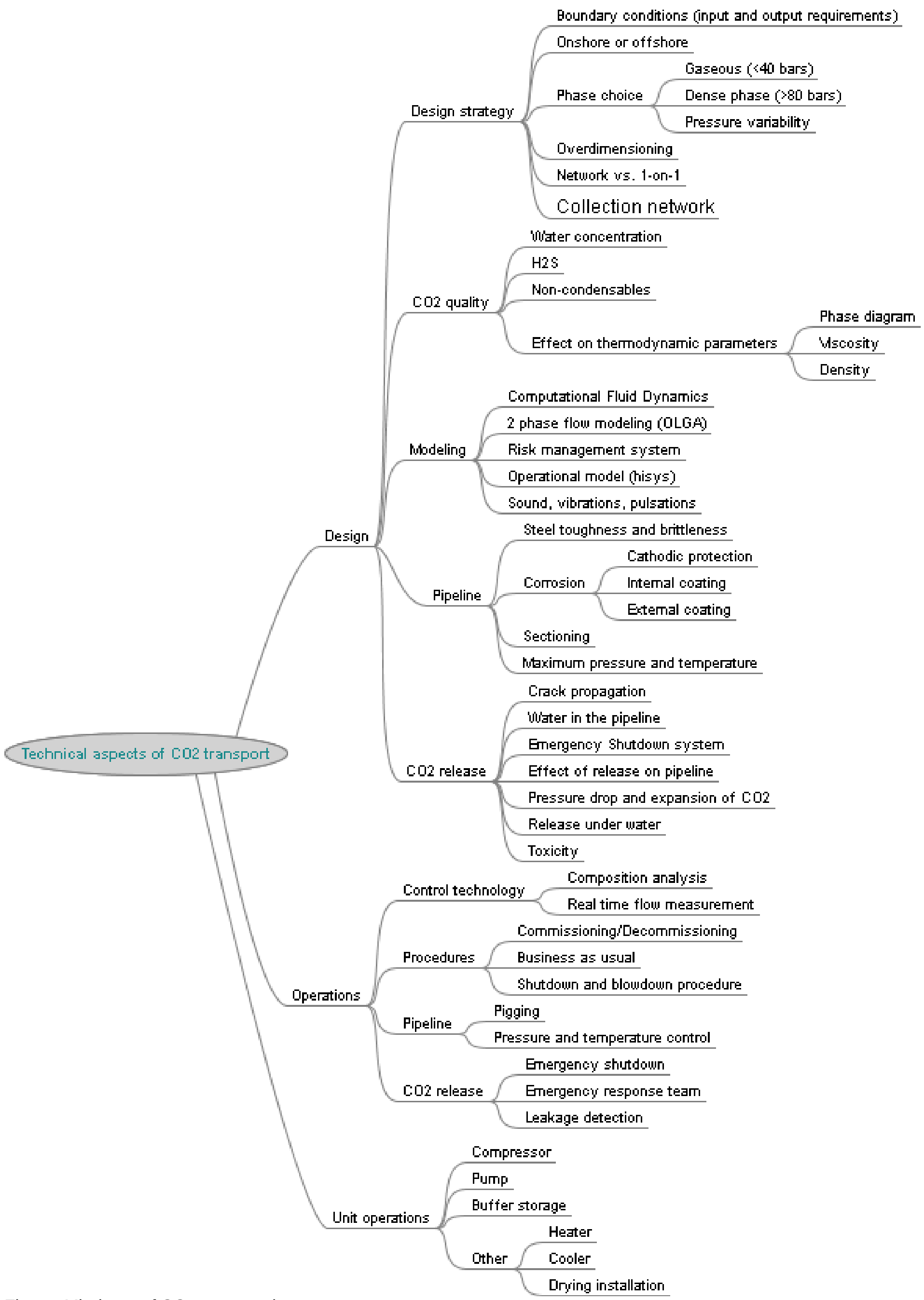

Figure: Mindmap of CO_2 transport issues

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WP2.1-D02, Report: Identification and priorisation of technical design conditions and parameters of CO2 pipelines that should me addressed within CATO-2

In Work Package 2.1 of the CATO-2 program the technical aspects of CO_2 transport in the CCS chain are addressed. Work Package 2.1 is split in 2 parts: year 1 in which an inventory and prioritization of key aspects are made and year 2 to 5 in which further research on specific topics is carried out. The main objective of Work Package 2.1 is to compose a set of guidelines for the design and operation of a safe, efficient and controllable CO_2 transport system.

This document describes the analysis of gaps in knowledge for the transport of CO_2 in the CCS chain. It summarizes the conclusions of the first year of Work Package 2.1 in the CATO-2 program. Based on the results of the other year one deliverables, a prioritization is made on subjects that need further research before a CO_2 transport system can be designed and operated. From the analysis it was learned that models to describe the physical properties of CO_2 with various concentrations of impurities that can be expected from capture processes are available but not validated.

These models are essential for the design of transport systems as they determine the pressure drop in the pipe line and therefore energy consumption, compressor power etc. Furthermore the effect of leakages and other extra-ordinary performances on the pipeline are unknown and also dependent on the physical properties. These effects must be known before designs of a safe system can be made.

The plan of action describes the topics on which further research is proposed. The plan describes per topic issues to be investigated and methods to be use.

The main topics are:

1. Guidelines for CO_2 transport systems
2. Model description and simulation of CO_2 transport systems
3. Leakage and other extra-ordinary performance of CO_2 transport systems

WP2.1-D03, Report: Inventory and quantitative characterisation of technologies available for each part of the CO_2 infrastructure system.

The goal of this report is to give an overview of the available technology status with respect to the pipeline transport. In the first section the pipeline itself is considered. Typical operational areas and geometrical layouts are considered, as well as the integrity issues that are encountered in the piping system

This report gives an overview of the available technologies which are important for the large scale transport of CO_2. The main conclusions are:

- A large operational experience exists in small and large scale CO_2 transport.
- All classic heat transfer and pressure drop models are valid including in the supercritical phase.
- Due to the low viscosity and low surface tension caution must be used in using classic flow regime maps. Additional research is required.
- Good experience is available in using models based on for instance the Friedl model or the commercial model OLGA to predict the flows in leaks in pipes. The main uncertainties in the dispersion models are present downstream of the leak.

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- Attention should be given in the material selection for seals. Fluorite elastomeric materials, FKM, are regarded as promising materials to be used in seals
- Due to the low viscosity, CO_2 has poor lubrication properties.
- The current corrosion model over predict the corrosion rate up to two orders of magnitude.
- CO_2 compressor technology is available.
- A typical polytropic efficiency for the classic systems is 86%.
- A new concept RAMJET by Dresser-RAND may be promising if heat integration in the total power plant - capture process – compression is possible.
- Due to the high Joule Thompson coefficient attention should be given to seals in the compressor system and recycle and anti-surge systems.
- Heat integration of the compressor system in the power plant and capture process may increase the overall efficiency.
- CO_2 pump technology is readily available.

The main attention points for increasing the confidence in the viability of large scale CO_2 transport are:
- CO_2 multiphase flow
- CO_2 behaviour in the outflow of leaks with special attention to the dispersion models.
- Material selection
- Corrosion models
- Heat integration compressor system with the power plant and/or the capture process.

The main conclusion is that the basic technology is present and that the operations of a large scale CO_2 network including capture units, storage sites, compressor, booster and mixing stations must be analysed. This includes start-up, shutdown, normal and non-normal operations. This also includes the influence of source compositions and the requirements for intermediate storage sites and/or mixing stations.

WP2.1-D04, Report: First assessment of the technical possibilities and constraints for use of existing pipelines and production facilities.

Deliverable 4 describes the current experience on transporting CO_2 with pipelines. In the Netherlands there are three projects running in practice:

- OCAP pipeline: pure CO_2 for greenhouses in the Westland from the Shell refinery, operates at low pressures (20-30 bar) in the gas phase
- WarmCO2: transport of heat and CO_2 from the YARA fertilizer plant to greenhouses in Zeeland.
- Barendrecht: transport of CO_2 from Pernis to the empty gas fields of Barendrecht.

Where Barendrecht is a test case, OCAP and WarmCO_2 transports limited volumes of CO_2 already. Valuable information is gathered on technical aspects related to CO_2 transport. Furthermore the document describes the transport of CO_2 in the USA, like the Kinder Morgan project, where large scale transport is realized.

The reuse of pipelines for CO_2 transport, as occurred in the OCAP project, is investigated. For large scale transport of CO_2 for CCS the availability of and requirements on the pipeline are investigated. Main conclusion of this case is that for large scale transport, reuse of pipelines will not be a feasible option.

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WP2.1-D05, Progress report: Evaluation of technical and cost implications of several CO_2 qualities of the transport infrastructure

The purpose of this document is to provide, through a literature survey, a basic knowledge of the level of impurities expected for a typical CO_2 transportation network. Furthermore, an assessment is then provided of the validity of different equations of states (EOS) to properly predict the properties of CO_2, pure and with impurities. The effect of the presence of each impurity on the thermodynamic properties of the stream is then assessed, through numerical simulation, and conclusions are drawn on the preferable gas thermodynamic conditions for transportation.

No economical analysis were done at this stage as no requirements could be established with respect to separation and injection gas quality, the scope of the required cleaning step is yet unknown.

The validity of various Equation of State to properly model the thermodynamic properties of CO_2 was assessed. The Wagner EOS showed the best correlation with the NIST database, while the PR and SRK models showed significant discrepancies in the prediction of the speed of sound and density of liquid CO_2. Due to the lack of availability of the Wagner EOS for other species than CO_2, the relative effect of impurities on the thermodynamic properties of the mixture was evaluated using the PR model. The effects of impurities concentration on the properties of the gas and supercritical fluid were observed to be very small. The effects appear much larger on the density and speed of sound of the liquid phase, as well as on the pressure at which the phase change occurs. Realistic concentrations were used, based on literature survey, showing that density and speed of sound variations of the order of 15% can be expected compared with a pure CO_2 stream.

WP2.1-D06, Progress report: Guidelines on quality of CO_2 in common transport infrastructure

The implementation of Carbon dioxide Capture and Storage (CCS) will require very large quantities of high concentration CO_2 to be transported from point of capture to point of injection into geological repository. Pipelines are seen as the primary transportation means of CO_2 in the context of CCS.
There is limited experience worldwide in pipeline transportation of CO_2 in its liquid and/or supercritical phase (i.e. collectively termed "dense phase") in the scale that will be required for CCS.

This report presents the setup for the guideline in order to address the need for guidance on developing of a CO_2 transport network. Also the design, realization and operation requirement of a CO_2 pipeline are addressed as well.

WP2.1-D07, Progress report: Evaluation of the technical possibilities of ship transport into the CO_2 transport infrastructure

This report presents a study on CO_2 shipping transport. Goal is to answer the following main question: which aspects are important for successful transport of CO_2 by ship?

A general comparison of pipeline vs. marine transportation is described. Also a summary of liquefied gas carrier types is given. Demands for CO_2 carrying ships are given. The different process steps are described including developments nowadays:
- Liquefaction

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- Storage
- Loading facilities
- Shipping transport
- Unloading facilities

An integrated liquefaction process (Liquefied Energy Chain) is described. Recent initiatives are described.

Conclusions, drawn from this study, are:
- CO_2 shipping transportation can be seen as an enabler for CCS projects because it is more flexible with respect to pipelines and can be built as required.
- Physical conditions for CO_2 shipping transportation are:
  temperature approx. -50 ℃ and a pressure approx. 7 bara
- Small scale CO_2 shipping transport (till 1,500 m^3) already takes place with a very small fleet of ships (< 10).
- Large scale shipping transportation is economically more feasible with respect to pipeline transport if distances are greater than:
    - approx. 1,000 km for onshore transportation
    - approx. 1,700 km for offshore transportation
- LPG and ethylene gas carriers can be modified relatively simple to CO_2 transportation by changing physical conditions in the storage tanks onboard.
- Experience on liquefaction has been gathered by LNG and LPG production. CO_2 liquefaction already takes place. Large CO_2 liquefaction facilities can be designed and built by gathering the experience of LNG/LPG and existing CO_2 liquefaction facilities.
  Studies are carried out to integrate other processes with the CO_2 liquefaction process to reduce Opex.
- Loading facilities of liquefied gases exist nowadays. CO_2 loading facilities can be derived from these.
  CO_2 floating liquefaction storage and offloading (CO_2 FLSO) facilities for are subject for study nowadays.
- Large CO_2 carriers are in development nowadays. Combined ships (e.g. LGP/CO_2 or LPG/CO_2/ammonia of LPG/CO_2/ethylene) with reconditioning equipment onboard are recommended to be highly economical feasible and having low risks for early movers.
  Studies are carried out for design of these ships with cargo volumes of 20,000 – 40,000 m^3.
- Studies are carried out to use liquid CO_2 and liquid nitrogen to produce LNG offshore (Liquefied Energy Chain) with a special type of ships (combined carrier ship).
- Offshore unloading facilities have to be designed and built. Existing platforms have to be modified for CO_2 storage. CO_2 floating storage and injection units (CO_2 FSIU) are subject for study nowadays.
  Onshore unloading facilities of liquefied gases exist nowadays. Onshore CO_2 unloading facilities can be derived from these.
- Activities for setting up inland water way transportation of CO_2 are taking place in the neighbourhood of Rotterdam. Chemgas Shipping, Vopak, Shell and Port of Rotterdam are looking for opportunities.
- The effect of impurities in CO_2 has to be taken into account in designing various equipment with respect to material choice and energy balances.

Important aspects for successful transport of CO_2 by ship are:

1. Technically:
    - LNG/LPG experience can be used in designing CO_2 liquefaction facilities and carriers.

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- An integrated process design is recommended for the liquefaction step and the offshore unloading step, resulting in minimal energy demand.
- Combined ships with reconditioning equipment onboard are recommended to be highly economical feasible and have low risks for early movers.
- Intermediate storage facilities are necessary because of the fact that shipping transport is batch wise.
- It is recommended to design and develop offshore CO_2 floating storage and injection units (CO_2 FSIU) because transportation to another geographical location after completely filling a depleted gas/oil field with CO_2 and re-usage are relative easy, especially in case of EGR/EOR.

2. Regulatory:
   Preferable international (safety) regulations shall be taken into account during design and operation of process steps and gas carriers because of the international scale of operation.
3. Strategically:
   It is recommended to make a good choice in geographical locations for unloading facilities in the neighbourhood of available depleted gas/oil fields because of the logistics behind shipping transport. A combination of offshore pipeline transport and unloading facilities probably can help.

WP2.1-D08, Detailed and up-to-date view on the (inter)national development in CO_2 transport

Deliverable D08 provides an inventory of CCS projects all over the world with a particular focus on transport in CO_2 in pipelines. To this end both formal CCS research programs, as well as CCS-related programs are incorporated. It is observed that many projects do not specifically address CO2 transport, although there are many partners involved in CO_2 transport

7.2 WP 2.2 Techno economic chain analysis

WP2.2-D01, Report: Screening of the impacts of large scale development of CCS on the reliability of the electricity market.

The Netherlands is heavily dependent on the success of both carbon capture and storage (CCS) and renewable electricity for its decarbonisation policy. The same holds for the EU and some of its Northwest European Member States like Germany and the United Kingdom. This report discusses several scenarios for the Netherlands within the context of a liberalised and a more and more connected energy market in Northwest-Europe. These scenarios are based on the recent ECN/PBL reference projections ‘Energy and Emissions 2010-2020’ published in April 2010. These scenarios have been expanded up to the time horizon of 2030 and have been subject to additional sensitivity analyses on the role of CCS, other fossil fuel price and CO_2 price paths.
The research reported here shows that CCS on the new coal fired power plants currently under construction does not pose a threat to the increase in the electricity production by large quantities of wind energy in the electricity system, and vice versa. For renewable energy, several additional policies are currently still in place mainly in the form of financial support as long as these renewable options are not yet profitable (SDE, Stimulering Duurzame Energie). For CCS, financial support is only granted now for a selection of the first demonstration projects planned in the EU. At the start of this research, it was not yet clear if large scale CCS and high shares of wind energy can be incorporated in a balanced way in the electricity system. This report shows that from a technical and economic point of view, there is room for deployment and growth of both technology options. In addition, it shows under conditions such a two fold growth will be feasible.

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These conditions are mainly of a policy and economic nature. As future is inherently uncertain, the most important uncertain driving forces are highlighted and discussed. Recent changes in the political arena may also induce changes in policies. Further analysis of these recent developments will be part of phase B of the CATO-2 WP 2.2 research.

This report highlighted the joint role of CCS and wind energy in reducing CO_2 emissions. In addition it has looked into the issues of flexibility and reliability of the energy system. These issues have been analysed in the context of scenarios with both large-scale penetrations of CCS and high shares of electricity production by wind energy. The analyses and electricity market model runs for the Dutch electricity system have been embedded in an increasingly coupled and interconnected Northwest European market and policy context. Therefore, also the electricity scenarios for these neighbouring countries have been taken into account in the analysis.

From the analyses and within the context of the scenario assumptions, it follows that:

- Flexibility or reliability considerations seem to impose no technical constraints on CCS in Dutch power generation.

- Operational behaviour and merit order remain main drivers for power generation. The most important explanation for the quantitative analysis results is that electricity generating units are dispatched according to the merit order, i.e. the supply/demand curve with increasing marginal cost of production. Marginal costs comprise the cost of fuel, the CO_2 price and other O&M costs (such as start-up). Moreover, the actual construction of new coal-fired power plants should be considered as a fact from the market investor’s perspective. Once fully licensed and built, these plants will produce electricity as long as their marginal cost of production is below the wholesale market electricity prices. In addition, older and less efficient coal or more costly natural gas power plants will produce less or, eventually, be decommissioned.

- The expected construction of new coal-fired capacity, either with or without CCS, does not hamper high penetration of wind energy and vice versa in the Netherlands up to 2030. At very high shares of wind energy the operating hours of new coal-fired power plants without CCS will remain high enough for a sound business case as long as the CO_2 price is not too high. At CO_2 prices of 50 €/ton or higher, the variable cost of production for new coal-fired power plants will become too high compared to the wholesale market price: variable cost exceeds the returns. Gas fired production would then be more attractive, but would result in a higher electricity price due to the higher natural gas prices. In that case, deployment of CCS can reduce the variable cost of production and improve the position of these coal power plants in the merit order, compared to gas fired power. However, the higher investments needs of CCS may constitute a barrier. The high investment would need a higher wholesale electricity price or a higher CO_2 price that can deliver such a higher electricity price. Additional and dedicated CCS policies are needed as long as CCS is not cost-effective on its own.

- For new coal-fired plants now being constructed in the Netherlands in the period 2009-2013, either without CCS, or eventually with CCS, the business cases remain sound in the context of the (macro-economic) scenarios outlined, even with high shares of renewable electricity production from wind energy. For CCS, this will only be the case when the CO_2 emission price is high enough. Based on the cost assumptions and scenario calculations, this would require more than 60 €/ton CO_2.

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- Therefore, a successful demonstration programme in the next 10 years and further scaling up of CCS in the period 2020 to 2030 are essential for further penetration of CCS in power generation in Northwest Europe in the period 2030 tot 2050.

- Dedicated specific CCS policies are needed in the period after the first demonstrations, assuming that the CO_2 price will be too low.

WP2.2-D02a, Report: Screening of the technological and economical implications of retrofitting CO2 capture of the industrial sector.

Industrial energy accounts for roughly 36% of the total CO_2 emissions emitted worldwide (about 12 $GtCO_2$ in 2007). Most of the energy consumption and CO_2 emissions occurs in industries that produce raw materials: chemicals and petrochemicals, iron and steel, cement, pulp and paper, and aluminium. To reach stabilization targets around 450 ppm or lower, combined portfolio of mitigation options including energy and material efficiency, feedstock substitution, and carbon capture and storage, are necessary. In this portfolio CO_2 capture and storage (CCS) is also an important CO_2 mitigation option for the industrial sector. However, most studies addressing CCS focussed so far mostly on the power sector. Assessment of the techno-economic potential of CCS in the industrial sector have been assessed mostly at the aggregate or sector level. The first type of studies are mainly exploratory in nature and tend to take average industrial conditions. Some of the studies at the sector level, do take (some) specific conditions into account but fail to assess the potential of CCS in comparison to other potential CO_2 mitigation options.

This study aims to make a first inventory of the most important implications of implementing CO_2 capture in the industry. These implications concern CO_2 emission reduction potential, costs, and technical and practical issues. The ultimate goal is twofold. On the one hand to get more insights into the overall potential of applying CCS in the industry over time taking into account its relation to other CO_2 mitigation options. On the other hand to assess the technical, economic feasibility, and pre-conditions of applying CCS at industrial plants.

The focus of this study is on seven sectors in the manufacturing sector, namely the chemical, fertilizer, iron and steel, non-ferrous metals, paper, food, and building materials industry. In addition, petroleum refineries, which are part of the energy transformation sector, are also included in the analysis. The textile, metal products, plastics and rubber products industries, and the manufacturing industries that are not categorized, are excluded. The sectors included in the analysis are hereafter referred to as "industry" in the whole study. The industry was responsible in total 41 Mt of CO_2 in 2008, whereas the manufacturing subsectors that were not included, were only responsible for 4.5 % of these industrial CO_2 emissions. The results will be subdivided into results for the short term (2020-2025) and longer term (2040-2050). Thus, also possible fundamental changes in industry could be addressed.

In order to be able to assess implications at the national as well as the industrial site level, we adopt a two-perspective approach, a top-down and bottom-up perspective. The top-down perspective is characterised by an analysis of the possible role of CCS in the whole Dutch industrial sector. This analysis takes into account possible developments of the activity level in the different sectors and of other CO_2 mitigation measures such as energy efficiency measures. The starting point of this analysis is the Dutch energy statistics which includes data of the energy use for each sector, and subsector.

The bottom-up perspective is an analysis from a technical point of view. In this analysis, disaggregated data with respect to performance and costs of technologies, and characteristics of

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specific industrial sites are used to evaluate the implications of the deployment of CCS in the industry. The bottom-up analysis is based on case studies, literature review, and expert consultations.

In this progress report (part A), a detailed description of the top-down and bottom-up methodology is given and a number of preliminary results. The top-down preliminary results concern an overview of the CO_2 emissions in the industrial subsectors, the scale of the point sources, and how the CO_2 emissions may develop in a frozen efficiency, a baseline efficiency, and an advanced efficiency scenario. This gives a first indication of the total CCS potential in the industry. In the final report (part B) an overview of the CO_2 capture potential will be given per subsector over time, and the associated costs. Furthermore, the CO_2 capture options are ranked according to a technical, geographical, and economic indicators. The bottom-up preliminary results deal with CO_2 capture potential associated additional energy use and costs for 3 case studies including a refinery, and two chemical facilities. In the final report the case studies will be worked out further and a number of case studies will be extended. Furthermore, a detailed overview will be given of practical implications of CO_2 capture in the industry.

WP2.2-D03, Report: First evaluation of competition between different CCS chains and other carbon low supply and energy efficiency option in the medium and long term.

This review report addresses the competition between CCS technologies on the one hand, and other low carbon energy options on the other. It summarises the main policy instruments that are currently in place to promote renewable electricity (RES-E) and industrial energy efficiency, and discusses possible interactions with policies for carbon capture and storage from power plants (CCS). It also lines out where the deployment of RES-E, notably from wind, might impact the implementation of CCS technologies.

Competition from incentivizing policies for CCS with other low carbon options will most likely be limited, since many policies are conceivable that are not characterized by budgetary constraints. These policies include fiscal measures, soft loans, emissions trading or an emissions performance standard. The Dutch feed-in tariff scheme for renewable energy, the SDE, in its present form has a limited budget for stimulating renewable energy. Inclusion of CCS in the scheme would thus imply a competition with renewable energy. The transformation of the scheme into a feed-in premium regulation (SDE+) would require a fee from consumers and would be an improvement in this respect.

The introduction of large scale wind power might result in the need to reduce output of base load coal-fired power plants at times of peak production of wind power. As a result, CCS capacity may not be used optimally. This can be mitigated by applying demand side management and increasing the (international) transmission and storage capacity of power. These fundamental changes in the current energy system are required when the share of renewables becomes significant, but is even more required while applying CCS.

A special position in the discussion about stimulating both RES-E and CCS is the combination of biomass and CCS. Biomass is a renewable energy source and the combination with CCS can result in ‘negative emissions’, i.e. carbon dioxide is extracted from the atmosphere. CO_2 emissions from biomass are not recognised within the framework of the EU-ETS, which implies that there is no incentive to store this CO_2.

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WP2.2-D04, Report: Inventory and first assessment of different funding sources and incentive structures

This part of (a two part) report addresses the question under what conditions which private funding options are available for investments in Carbon Dioxide Capture and Storage (CCS). R&D has slowly moved from proof of concept to pilot and demonstration plans. The question however remains on "who will fund these investments".[1] Large investments need to be made in the capture installations, in transport infrastructures and the storage facilities. Given the limited and uncertain public commitment to CCS, the challenge is on getting private markets to commit its vast resources to the deployment of the option. However, the private market has its own logic and dynamics. CCS projects will have to compete with the many alternatives that private investors have and it will have to do so on different fronts. Answering the above question thus requires us to present a taxonomy of available funds and an analysis of the criteria that private investors apply in making the decision to commit these funds to one project or the other. The findings of this report can be summarized as follows.

Investment decisions are theoretically simple
A review of standard textbook investment theory shows that investment decision rules are relatively straightforward (chapter 5). Designing a CCS project to satisfy these criteria is not a big challenge.

Investments are not restricted on the supply side
In mature financial markets such as the Netherlands, the availability of funding is never a serious constraint (chapter 6). Provided the projects satisfy a given set of investment criteria, private investors are typically not opposed to investing in CCS.

CCS projects can attract private funding
That is the good news. If CCS projects have a positive NPV and there is not too much uncertainty to cause strategic waiting (real option value), then private investors should be willing and able to fund the large-scale implementation of CCS in the Netherlands.

But investors do more than follow simple theoretical decision rules
In order to mobilize and attract private funding, evidence from interviewing investors (chapters 6 and 7) suggests that CCS projects will have to be structured in such a way that different investors can be attracted to different projects. Projects that involve proven technology and that require large investments should be structured using little equity and a lot of debt. When the expensive equity involved is adequately leveraged using cheap bank credit or corporate debt, low returns in the project may still provide sufficient returns to satisfy the investors. For smaller, high-risk early stage projects only potentially high returns may convince venture capital and private equity funds to engage, as equity cannot be leveraged with debt in such projects.

CCS projects should be structured to be low risk/large scale or high risk/ small scale
In general one can conclude that private funding is available for large riskless and small risky investments. Structuring the projects would thus involve shifting risk out of the large investments (e.g. to governments and large corporations' balance sheets) and cutting up projects in which the risks cannot be shifted.

And market, technology and managerial risk have to be controlled

[1] IEA (2009a) estimates that a total of 2.5 to 3 trillion dollars in investments from 2010 to 2050 (about 6% of total needed to achieve 50% GHG-emissions reduction) is required. In the next decade alone some 42 billion additional dollars in 100 demonstration projects would be required to keep on track. Ernst and Young (2009) put the estimate at a much higher 100 billion dollars annually. CCS is considered a low cost mitigation option, but requiring vast sums nonetheless.

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In addition, the interviews with decision makers have shown that financially restructuring the projects cannot amend all concerns. There are three key questions any investor wants to see answered: “who is willing to pay how much for the products/services the project produces?”, “ how much will it cost me to produce these products/services?” and “who is managing the project?”. I refer to these as the market, the technology and the management risks, respectively. Some investors desire/require less precision and certainty than others in these categories and they have different instruments to control such risks.

Verifiable information helps

One strategy to increase the availability of private funds for CCS would therefore be to reduce the perceived risks and uncertainty on these three key aspects. The need for reliable and verifiable information on the business case, the technology and the managing team and sponsors has little to do with how the project is structured financially. It does suggest that for example ensuring free flows of information on pilot and demonstration projects may be as important in mobilizing funds than subsidies and guarantees on loans.

And regulatory uncertainty hurts

It was also concluded from the interviews that investors can deal with risk but hate true uncertainty. Regulation, permits and legal liability issues should be settled and preferably set in stone. Uncertainty over permits, legal procedures and liability claims imply that required rates of return have to be very high indeed before any private investor is tempted. By definition the project managers and/or investors have little or no control over these regulatory risks and this puts CCS-projects at a huge disadvantage in the competition over private investment funds. The business case of a project should not depend on discretionary government commitment and support alone.

An “optimal project” can mean something different to engineers, politicians and investors

Finally, we have concluded that what engineers or politicians consider the optimal project structure and lay out, may in fact not be feasible financially. The least cost pipeline infrastructure, the energetically most efficient capture unit or the politically least controversial storage facility is not necessarily the one that fits the desires and requirements of a private investor best. In fact, as different types of investors apply different criteria and decision rules in their activities, to optimize a project for a specific type of financier involves understanding very well what matters most from their perspective.

A lot was learned but more can be done

The current interviews have helped me to gain more insights into the key criteria and considerations that mobilize or prevent private investors from moving into CCS-projects in the Netherlands, but more can be done. First of all the sample surveyed here is too small to be anywhere close to representative. Joining forces with international research and extending the sample in the Netherlands can remedy this. To survey a significant number of decision makers, however, the questions need to be much more focused. In the next stage of the project 3 representative hypothetical case studies will be develop and 30-40 decision makers will be asked to evaluate these cases. This will help to extend, qualify and corroborate the findings reported here.

WP2.2-D05, Report: First assessment of the costs and logistic of re-using exiting infrastructure (pipelines and production facilities) in the short term.

Costs may be a potential barrier for large-scale deployment of CCS. Capture costs are typically a dominant factor in the costs of the full CCS chain. Costs for transport and storage –forming typically a share of less than 25% of the costs - may become more relevant in case storage

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capacity is not available in the vicinity of the capture installation and/or are on offshore locations. It has therefore been recommended to seek ways to reduce the costs for transport and storage.

Reusing infrastructure is one of these options. This study aims to give an in-depth overview of the possibilities and limitations of reusing existing offshore infrastructure. The focus is on platforms and subsea completion systems, which are mature technologies that are currently applied in the gas and oil exploration industry. The comparison is made based on three key parameters: technology, economics and legal aspects. The information provided in this study is based on a literature review and interviews with experts.

The findings of this research indicate that reusing both platforms and subsea infrastructures is technically feasible under the condition that maintenance has been carried out regularly and that the constructions are in a proper state. When reusing platforms, timing will be an additional factor. If reuse of a platform is demanded but not instantly possible, it can be “mothballed”, meaning that the platform will be disconnected from its wells and that most equipment will be removed. This is followed by a period of hibernation, during which operational costs are kept low by reducing the intensity of maintenance. During the hibernation period the structure will remain at sea under salty conditions which can lead to degradation of the structure. It is therefore important to keep this period as short as possible, at least shorter then 10 years. Even then, it is possible that parts of the structure or even the entire platform needs to be replaced.

There are two key considerations that need further examining. The first one is whether CO_2 needs to be heated before injection. The required additional equipment to heat the CO_2 would place restrictions on the size of the platforms that could be reused and increase the requirements for subsea completion. In that case a platform may be needed to place heating equipment, the costs will increase considerably. Currently there is no agreement on whether heating is required and under what circumstances. Further research is needed before definitive conclusions can be drawn. The second issue is the number of wells per structure needed for injection. Most literature sources report costs for platforms and sub-sea completion with an average of 4 to 8 wells. Though these are common configuration for the oil and gas industry, several experts indicate that 1 or 2 wells will typically be sufficient for CO_2 injection operations. Both issues will influence the technological possibilities and the costs of the storage activity.

A comparison of the costs between platforms and subsea completions reported in the literature indicates that subsea completions are considerably less expensive than platforms (see Figures A and B). However, the costs on subsea completions - presented in figure B - exclude the costs of a platform which may be required for heating equipment. If this is the case, costs for platforms and subsea completions appear in the same order of magnitude. Furthermore, if heating is not needed, the costs for platforms will decrease and new opportunities will appear for the use of smaller platforms. This option will become even more attractive, if only one or two wells per field are going to be used to fill the fields with CO_2.

From a regulatory point of view, there is no legislation on CO_2 injection, on mothballing and hibernation of structures, and on liability for injected CO_2 in the Netherlands. Current Dutch legislation states that structures should be dismantled immediately after production activities have been stopped. In practice the Ministry of Economic Affairs will grant a 2 years period to remove the structures. The periods of hibernation could however be longer, with some experts indicating periods of 8 to 10 years maximum. The Ministry of Economic Affairs is currently working on new legislation that includes regulation on injection and on mothballing and addresses responsibility issues on injected CO_2. A draft version is expected beginning of 2011.

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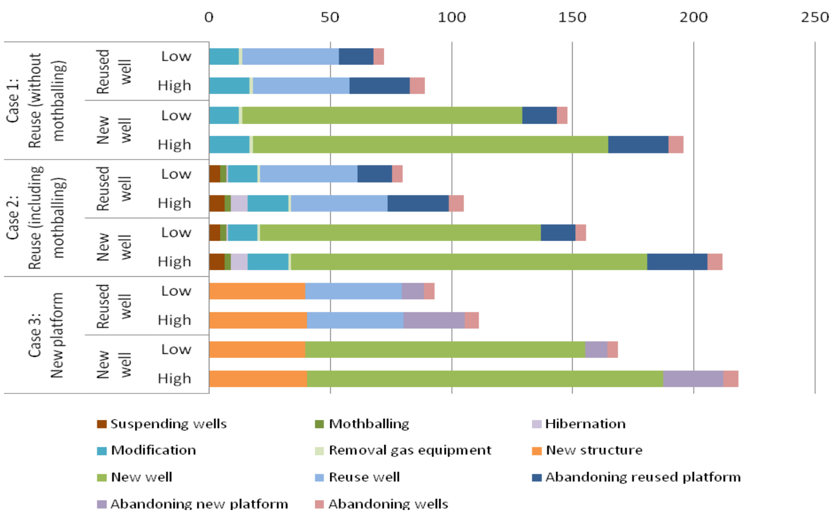

Figure A: Cost for platforms with four wells (in million euro 2010)

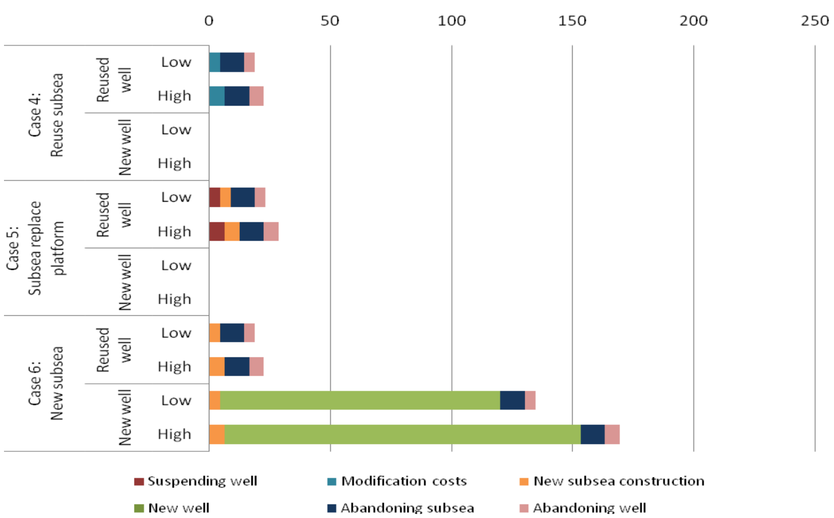

Figure B: Costs for sub-sea completion infrastructure with four wells (in million euro 2010)

WP2.2-D06, Progress report: (detailed description of the work and methodologies to be used for the) assessment of investment models for the deployment of a large scale CO2 transport structure.

This report provides an update on the key issues regarding economics of Carbon Dioxide Capture and Storage (CCS). It reviews the literature on potential barriers to its implementation, costs and marketability. It also discusses (potential) incentive schemes to make CCS viable. It

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furthermore provides a framework to summarize cost types and forecast uncertainties. Finally, it addresses knowledge gaps. The review deals with the studies published after the United Nations Intergovernmental Panel on Climate Change (IPCC) 2005 Special report on CCS which is considered as the natural benchmark in terms of expertise in this field. Comparison of these recent papers with those discussed in the IPCC report provide insights into the development of the economic, political and social environment of CCS

WP2.2-D07, Documentation of; regular stakeholder consultations, through workshops, enquiries, discussion form and individual interview (throughout the project)

The CATO-2 program brings together a strong coalition of knowledge institutes and public and private parties. Exchange of information, in the form of input data, feedback on research goals, methodologies, and results as well as a common understanding on how the research can support the development of CCS in the Netherlands is an important feature of the program. In this context the term ‘stakeholder consultation’ is used to describe the overall process and approach to communicating with stakeholders. This reports provides an overview of the process consultation that has taken place in Work Package 2 (Techno-economic chain analysis) during the first phase of CATO-2 and which will be continued during phase two.

7.3 WP 2.3 International CCS policy

WP2.3-D01, Report/paper on CCS in the CDM, including quantitative insight into the market impacts of including CCS in CDM. WP2.3-D02, Publicly available marginal abatement Cost curve for CDM with CCS option.

In order to avoid dangerous climate change, CO2 capture and storage deployment is required on a significant scale globally by 2020. Currently the CDM is the only international instrument that could provide a financial incentive for CCS in developing countries. However as of October 2010 CCS is not eligible as a project activity under the CDM, and a decision at the UN level is required to ensure CCS is allowed under the CDM, which may never come.

The objections against this are partly political and partly technical. One of the concerns is that CCS project could flood the CDM market, thereby crowding out other – more sustainable – technologies. This report therefore aims to quantify the possible impact of CCS on the CDM market. It also takes a broader look at the potential for CCS in other types instruments.

The first result of this study is a marginal abatement cost curve (MAC) for CCS in developing countries for 2020. Based on existing MAC studies, the IEA CCS Roadmap and an overview of ongoing and planned CCS activities, we compiled three scenarios for CCS in the power, industry and upstream sector, as shown below. The major part of the potential below \$30/tCO_2-eq (70 – 80 MtCO_2/yr) is in the natural gas processing sector. The most important region is the Middle East and North Africa, followed by Asia-Pacific.

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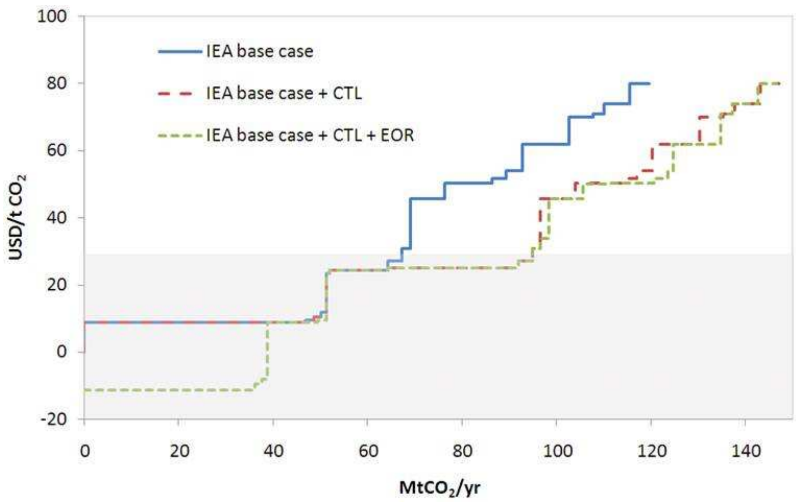

Figure ES.1. CCS MAC for developing countries in 2020.

Using MACs for the CDM market, we estimate the potential for CCS projects to be 4-19% of the CDM supply in 2020. The uncertainty in these figure is predominantly a result of the uncertainty with regard to the carbon market after 2012. The lower figure corresponds to the scenario where the CDM covers all the demand for international carbon offsets, and the higher figure refers to the possibility that only the European Union continues to the use the CDM after 2012.

The potential impact inclusion of CCS in the CDM may have is estimated to be between $ 0 and $ 4 per tonne of CO_2-eq, with higher probability for the lower part of this range.

WP2.3-D03, Background paper on "Role of CCS in the international climate regime".

In its recent roadmap the IEA argued that CCS, in order to be effective, needs to be implemented on an international level. International cooperation is necessary to reduce costs, exchange ideas with implementation issues learned from experience and increase CCS implementation in developing countries. The aim of this study is to analyse ways to increase international cooperation in order to roll out CCS globally in developed but also developing countries.

In a first step we analysed the interests and involvements of countries with respect to CCS. We found that developed countries can be split into supporting (e.g. Norway, Australia and the US) and neutral countries (e.g. Germany). A major driver for support is the availability of fossil fuel resources when there is no implemented alternative. For example because wind energy is implemented in Germany, there is less support for CCS. Involvement of developing countries is also driven by the availability of resources but is restricted by the role the countries see for themselves in combating climate change. China is therefore very engaged, yet India and South Africa are engaged only to a very limited extent at this point in time.

In a second step we reviewed current international support mechanisms for CCS. Under the international climate agreement, the UNFCCC and the Kyoto Protocol, CCS does not play a major role. The clean development mechanism (CDM) is an instrument that could potentially

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support CCS in developing countries, but currently does not allow CCS and has no approved methodology for this technology. There are some promising developments in other areas of the international negotiations under the UNFCCC, but it is open as to what role CCS will play in them. Possible instruments include nationally appropriate mitigation actions, technology innovation centers and the Technology Mechanism.

We conclude that it is promising to consider bilateral and multilateral country partnerships outside the UNFCCC process. A review of existing CCS-related partnerships, undertaken within this study, showed that there are already a number of processes in existence and that the number is growing. These processes tend to focus on a limited number of issues, such as R&D, and regions such as China. They do not sufficiently cover other important issues, such as financing and the implementation of regulatory frameworks. Partnerships with countries other than China, such as South Africa and India, are only small in size to this date.

Considering the background information as analysed in this paper, we suggest three possible combinable pathways for CCS for the future. The first is to develop a sophisticated technology mechanism for CCS. The goal of such a mechanism would be to coordinate international efforts better and to create a common voice for CCS. A second option is to use current or create new bilateral partnerships that can be accounted as fast track financing under the UNFCCC, which amounts to $30 billion USD until 2012. The third option is to create bilateral initiatives between developed and developing countries that lead to a new type of carbon credits.

7.4 WP 2.4 Chain integration and CCS implementation plan

WP2.4-D01, Progress report: Frameworks for reporting pilot plant results.

Several methods approached for information sharing have been investigated, and one method for gathering information needs was attempted within this WP.

In the course of 2010 a framework was setup to that helps in identifying information needs for CATO-2 WP's, and that can facilitate in matching those needs, with information available elsewhere in the CATO-2 program.

In the summer of 2010 meetings were scheduled to make an inventory of the information need of the different WP-leaders. These meetings were cancelled due to limited attendees. The CATO-2 wide inventory resulted in only several specifications of the need information for a WP. Ad hoc information sharing within CATO-2 has proven up to now most effective.

WP2.4.1 is discontinued in CATO-2b for the years 2-5.

WP2.4-D02, Report: Specifications for an improved version evaluation tool.

The development of CCS in NNL depends on the availability of both captured CO_2 and storage capacity. The growth curve of the captured CO_2 determines the speed at which consecutive storage locations need to be developed, while the location of storage capacity determines where transport routes are constructed. Where multiple storage locations are available, site choice becomes an economic decision. To ensure cost-effective development of CCS, a good understanding of options, cost and timing is required, to enable guidance and support from the government, as well as to provide all relevant information to industrial parties. Results such as

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those provided in the EBN/Gasunie report and in more detailed and longer-term studies as those to be delivered in CATO2 will help realise CCS.

This report is a first step to modelling of CCS development in North Netherlands. The aim is to extract the information required for modelling of the development on a longer timescale and in more detail than that provided in the EBN-Gasunie report; this modelling is foreseen for the remainder of the CATO2 program.

Information on storage capacity, injection rates and cost of storage and transport is derived from the EBN-Gasunie report, for both onshore and offshore CCS. As the EBN-Gasunie report was partly based on confidential data, and the work in the CATO2 program is done with publicly available data, a comparison is made between the data from the EBN-Gasunie report and the data available for the CATO2 work.

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8 SP 3 Storage & Monitoring

8.1 WP 3.1 Geological modelling

WP3.1-D01, Progress report on the combined adaption and use of existing/novel models/simulators

WP3.01 contributes to the CATO-2 program by coordinating data exchange with the site owners, and by making available 3D static reservoir-geological models of the storage sites to other work packages for further study. Progress in WP3.01 is according to plan and objectives.
Focus of our efforts this year has been on the P18 field of TAQA Energy, a potential storage site 20km offshore of the "2e Maasvlakte" near Rotterdam. TAQA Energy plans to apply for a storage license at the end of this year, and technical feasibility and potential risks must be assessed before then. WP3.01 has contributed to this by making available two 3D models of the subsurface around the P18 storage sites: a regional-scale geological model for geomechanical modelling studies, and a reservoir-scale geological model for reservoir engineering studies. Both studies are currently ongoing. Furthermore, WP3.01 has coordinated the data exchange with TAQA Energy, and organized two core workshops to facilitate rock sampling of cores of the P18 wells and analogue outcrops in Germany for laboratory work in work packages *reservoir behaviour* and *Cap rock and fault integrity*. Also, a first 3D static reservoir model was made of the subsurface at the Chemelot potential storage site owned by DSM.

8.2 WP 3.2 Reservoir Behaviour

WP3.2-D01, Progress report on Calibration and testing of models to experimental data (such as core flooding experiments, study of phase behaviour, swelling in coals, residual saturation, use of surfactants) & WP3.2-D02, Progress report on Development of both flow models and flow simulators (such as coupled thermo-physical-thermal simulations, reactive transport modelling, modelling phase behaviour

Successful implementation of CO_2 storage in depleted gas field and saline aquifers requires a detailed design, planning and execution of the storage operations. The knowledge of the physical and chemical processes involved at various time scales is critical for optimizing the storage process and for ensuring long-term safety of the storage sites. The report presents a critical analysis of flow and transport coupled with thermodynamic behaviour and rock fluid interactions for CO_2 storage in depleted gas fields and aquifers. Both CO_2 injectivity and the long term CO_2 migration have been analyzed in detail. The existing models, numerical simulations and experiments have been critically reviewed. The UNIQAC approach has been selected for further development and implementation in the numerical simulation tools. Core-scale modelling and numerical simulations were performed and a workflow for processing CT scan aided CO_2 injection simulations was developed. A detailed design of the CO_2 injection experiments was also done. Samples have been collected for the Bunter sandstone from the TNO core facility and from the Northern Eiffel of Western Germany. The composition of the Bunter sandstone samples has been determined on 4 of the 12 samples. The gas permeability of the Bunter sandstone samples has been determined for most samples. The rest of the analyses are underway.

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8.3 WP 3.3 Caprock and Fault Integrity

WP3.3-D01, Progress report on: Computational facilities for advanced geomechanical modelling

Subsurface storage of CO_2 poses new challenges to the geomechanical analysis of caprock and fault integrity. Compared to conventional geomechanical analysis of hydrocarbon depletion, advanced analysis techniques need to be developed accounting for changes in stress state due to injection and changes in the mechanical and transport properties of faults and caprock due to reactions with CO_2-rich fluids.

This report describes the status of computational facilities (both hardware and software) for advanced geomechanical modelling at TNO available to the CATO-2 project (deliverable WP3.3-D01).

Most of the hardware and software facilities were already available at the start of the project. During the first project year the existing software was updated where applicable, initial simulations were run to test computation requirements and boundary conditions, and the feasibility and value of coupling of different modelling techniques was investigated.

Hardware and various commercially available numerical codes, including (i) the finite element code DIANA, (ii) the finite difference codes FLAC and FLAC3D and (iii) the discrete element codes PFC2D and PFC3D, are now available for geomechanical simulations and tested. TNO has vast experience in using these software packages as well as in exchanging the models and data between geological modelling packages, reservoir simulators and geomechanical simulators. The computational facilities can now routinely be applied in research on caprock and fault integrity analysis performed in the Work Package.

WP3.3-D02, Progress report on: Results of preliminary simulations of the impact of CO2 injection on generic models.

Geomechanical analysis of the impact of C_{O2} injection is a crucial part in validating suitability of subsurface reservoirs for long-term CO_2 storage and optimizing injection scenarios. Leakage of CO_2 to the surface may occur if breach of fault and top seals occurs as a result of changing stress conditions associated with CO_2 injection.

This report (deliverable WP3.3-D02) describes results of preliminary geomechanical simulations of the impact of CO_2 injection on generic models. Numerical models are commonly used to model thermo-hydro-mechanical effects of CO_2 injection because they can account better than analytical models for structural complexity of the reservoirs, non-linear behaviour and spatial variability of different geomaterials present in the subsurface.

We choose to use different numerical techniques in geomechanical simulations: finite element (FEM), finite difference (FDM) and discrete element method (DEM). The different numerical techniques are incorporated into two separate workflows for geomechanical modelling currently under development. The workflows are based on (i) a continuous (macro-scale) approach (FEM/FDM) and (ii) a discontinuous (micro-scale) approach (DEM).
The continuous approach to geomechanical modelling is based on uncoupled flow-stress simulations. This is a frequently used way of combining fluid flow modelling and stress modelling in oil and gas industry applications. In continuous approach we use the finite element code

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DIANA coupled to an industry-standard reservoir simulator. FE analysis results allow evaluating the dynamic effects of CO_2 injection which determine how the sealing integrity of top seals and faults will evolve during the period of CO_2 injection into the target reservoir.
The discontinuous approach uses local stress conditions from the FE analysis to investigate fracture initiation and propagation in generic reservoir-seal models. It specifically aims to investigate the long-term effects of CO_2 injection on fault and top seal integrity. Effects of reactive flow on the mechanical evolution of reservoir-seal systems are also investigated by explicitly modelling volume changes, alteration of rock mechanical properties and fracture propagation associated with reactions between CO_2-rich fluids and reservoir-, fault- and caprock

WP3.3-D03, Progress report on: Inventory of sealing, transport and mechanical properties needed

The reliability of geomechanical analysis of caprock and fault integrity is depended on the availability and quality of data on rock physical properties, such as strength, elasticity and permeability as well as on knowledge of the in situ stress.

This report (deliverable WP3.3-D03) provides an inventory of sealing, transport and mechanical properties needed for geomechanical evaluation of specific sites. These properties will be largely determined by experimental testing program (WP3.3-D04, D08) aimed at determining baseline properties as well as changes in the properties as a function of mineral reactions with CO_2.

The physical and mechanical properties, which determine strength and deformability of the reservoir rock and caprock, commonly required in geomechanical analyses, are as follows: density, porosity, elasticity modulus, Poisson's ratio, bulk modulus, shear modulus, compressional and shear wave velocities, Biot's coefficient, tensile strength, unconfined compressive strength, friction angle, cohesion as well as other constitutive material parameters needed to define failure and dilatancy envelopes for the caprock. Sealing and transport properties of the caprock here of interest are: effective permeability, and capillary entry and breakthrough pressure to supercritical and gaseous CO_2.
The properties of faults and fault zones needed are: friction angle and cohesion as well as other constitutive material parameters needed to define the mechanical/frictional behaviour of faults, its evolution during slip, and the stability of slip. Sealing and transport properties of fault zones of interest are effective permeability and capillary entry and breakthrough pressure to supercritical and gaseous CO_2.
Another parameter of utmost importance for geomechanical modelling is the in situ stress. This parameter will be estimated from available regional stress data and site-specific field data.

This inventory helps with planning the experimental program carried out in this work package and with prioritizing requests for data from operators of potential CO_2 storage sites that are candidates for site-specific geomechanical analysis

WP3.3-D04, Progress report on: Laboratory facilities for transport and mechanical properties determination

In WP 3.03, a wide array of experimental facilities will be brought to bear on the task of investigating the transport and mechanical properties of the caprock in CO_2 sequestration reservoirs. The present work is divided into separate sections describing apparatus and methodological developments from three different laboratories.

1) Utrecht University – HPT Laboratory
    a. Triaxial Deformation Apparatus (Heard)
        i. Triaxial Compressive Failure

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1. To develop a failure envelope for CO_2 reservoir caprock and determine how mechanical strength is affected by supercritical CO_2 which could lead to failure of the caprock and loss of reservoir integrity

ii. Direct Shear Friction
1. To measure the coefficient of friction of caprock derived fault gouge and determine how supercritical CO_2 pore fluid can alter frictional strength. Significant changes could result in fault reactivation
2. To measure the frictional stability of caprock derived fault gouge and determine how supercritical CO_2 pore fluid can alter frictional stability. Significant changes could result in increased seismicity.

iii. Fault Zone Permeability
1. Measurement of the permeability of simulated fault zones to determine the degree to which ongoing reaction with supercritical CO_2 may alter the sealing ability of laterally bounding fault zones

b. Argon Permeameter (APE)

i. Low Confining Pressure (≤ 2 MPa)
1. Argon Transient Step (ATS) permeability measurements on Röt and Solling caprock to investigate variations in permeability based on mineralogy, orientation to bedding, formation of origin, etc.
2. Argon Flow Through permeability tests will be used to validate the findings of the more precise ATS method

ii. High confining pressure (≤ 100 MPa) measurements of permeability will be conducted to determine if there is a significant systematic variation in permeability based on confining pressure.

c. Autoclave and cold-seal reaction vessels will be used to analyze the long term mineralogical changes likely in caprock and caprock derived fault gouge under CO_2 reservoir conditions, and also to provide large volumes of reacted caprock gouge for use in frictional experiments.

2) TNO-Rijswijk – Prins Maurits Laboratory

a. Static batch reaction vessel which will allow for long term reaction experiments on cylindrical caprock samples under CO_2 reservoir conditions with very limited ability for extensive fluid flow and also under more dynamic conditions to analyze the effects of pore fluid mobility on the degradation of caprock.

3) Technical University Delft – Laboratory of Geotechnology

a. Large sample triaxial trtesting machines - use of ductile metal sample jackets capable of withstanding the aggressive conditions associated with investigating chemical interactions in the caprock-fracture-CO_2-H_20 system, such as fracture compaction, dissolution, (re-)mineralization, and permittivity.

WP3.3-D05, Progress report on: Agreement on representative sites

During Year 1 of CATO-2, the following reservoir-caprock systems were jointly agreed upon, by researchers and site-owners, as having the highest priority for studies of caprock and fault integrity, at least in Years 1 and 2 of the programme:

1. The Bunter sandstone plus overlying Solling & Röt claystone/marl caprocks (cf. P18);
2. The Rotliegend sandstone plus overlying Zechstein anhydrite caprock;
3. Carboniferous sandstones, shales and coals (cf. DSM Chemelot site).

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For laboratory experiments under WP3.03 (and for WP3.02 and 3.04), samples have been obtained that are considered reasonably representative for all three of these choices. Bunter/Solling/Röt samples and statigraphic equivalents have been obtained from:

- TAQA P18/P15 and from the Q16 field;
- Field excursions by Utrecht University (UU) and TU Delft to Germany;
- The TU Delft sample collection/repository.

Pore fluid compositions relevant to the Bunter reservoirs at P18/15, Q16 and Q08 have been obtained from Wintershall. Rotliegend & Zechstein samples, and closely similar equivalents, are available from:

- The UU sample collection/repository (including Zechstein anhydrite cores provided by Shell);
- TU Delft sample collection/repository.

A sample inventory at TU Delft has provided Carboniferous coal, sandstones and shales of Westphalian origin that can be used to represent the Chemelot site if needed, though older material would be preferred.

Characterisation work on the various samples is reported in Deliverable WP3.03-D06. First results from experiments are reported in Deliverable WP3.03-D08 and WP3.02-D01.

Geomechanical modelling in WP3.03 has concentrated to date on generic reservoir-caprock systems (see Deliverable WP3.03-D02), in line with later application to the Bunter and Rotliegend reservoirs-caprock sequences chosen for obtaining samples for experiments

WP3.3-D06, Progress report on: Site-representative caprock and fault rock samples acquired and characterised

WP 3.03 of CATO-2 focuses on caprock and fault integrity, namely on the response of the reservoir-caprock-fault system to injection and storage of CO_2. Experimental studies under WP 3.03 (as well as WP 3.02 on Reservoir Behaviour and WP 3.04 on Wellbore Integrity) accordingly require representative samples of cap rocks, reservoir rocks and fault rocks, the last of which often contain components of the other two. In particular, site-specific experimental studies require cm- to dm-sized samples of the underground reservoir rocks and their sealing cap rocks. These studies must address the complex interactions of thermo-mechanical and chemical effects on the reservoir-seal system that may result from injecting CO_2 rich fluids.

Obtaining the necessary information and material from specific sites presents a problem of its own, in that very little actual rock material is available from the earlier drilling operations. However, detailed information on the rock formations is often present in proprietary reports by the well operators. The lack of material to make test samples requires alternative sources of equivalent rocks to be obtained from accessible geological sites such as outcrops on land, or from drilling operation in similar formations where more samples were taken. Once such material is located it must be examined and characterized to assess its suitability and equivalence to the actual in situ material of the target reservoir-seal system. Similarity in mineralogy, grain structure, porosity and permeability are just a few factors which, ideally, need to match the site specific material properties.

Unfortunately the natural environment is heterogeneous and lateral variation in geology is the rule rather than the exception. At UU we have called upon archived material held at NAM (Assen) and TNO (Zeist) to provide site-specific caprock and reservoir samples, as well as similar materials from nearby boreholes for comparative study. Attention to date has focused on reservoir and caprock material from the Bunter sandstone reservoirs and overlying Solling/Röt caprock formations found in the TAQA P18 field and in the nearby Q16 field. The available samples of these units have been characterised by means of microstructual, petrographic and X-ray

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diffraction analysis and their permeabilities have been measured. Approximately equivalent material from the Triassic Buntersandstein of Germany has been collected and characterised, for comparison with P18 and Q16 material, and as a potential source of larger volumes of sample material. TUD has performed a similar characterisation study of cap rocks from the Carboniferous and Cretaceous for comparison with onshore underground sites, notably the DSM site in Carboniferous strata.

The reports of UU and TUD are combined via Parts I and II of this report to create this deliverable D06 to WorkPackage 3.03 of CATO-2. Characterisation work on Zechstein anhydrite caprock used by the UU team in the experimental programme on Rotliegend reservoir topseal integrity (WP3.03-D-08) has been reported in earlier publications and in D-08.

WP3.3-D07, Progress report on: Preliminary data on gas/CO_2 transport through intact caprocks, plus parameter computation and interpretation based on numerical simulations

Subsurface storage of CO_2 is beneficial only if long-term containment in storage sites can be ensured. Therefore, scenarios for the development of potential leakage pathways for CO_2 through the caprock need to be analysed.

This report (deliverable WP3.3-D07) describes the preliminary data and simulations for CO_2 transport through caprocks. In this task, experimental data on reactions between CO_2-rich fluids and caprock is combined with numerical modelling of mineral reactions, reactive flow and coupled chemical-mechanical deformation of the caprock.

In the first year of the CATO-2 program, the following activities have been performed relevant to CO_2 transport through caprocks have been performed: (1) Experimental facilities for reactions between caprock and CO_2-rich fluids have been set up (c.f. WP3.3-D04, D08, D09), (2) data for the P18 reservoir caprock was collected and a model (TOUGHREACT) for reactive flow through the caprock was set up, (3) a discrete element model (PFC2D) of an anhydrite caprock sample was developed and initial simulations of the effect of chemical reactions with CO_2 on the caprock mechanical properties were performed.

Initial data and models show that fluid penetration in the caprock and reaction rates between caprock and CO_2-rich fluids are generally very slow. However, some long-term weakening of caprock by reactions with CO_2 occurs. More data and simulations are needed to evaluate the effect of such weakening on top seal integrity and determine the feasibility of CO_2 leakage through the caprock.

WP3.3-D08, Progress report on: First data on the permeability and mechanical properties of faulted caprocks and of simulated clay-sealed fault rock; effects of CO2-water-rock interaction

One of the main concerns regarding geological storage of CO_2 is the potential for leaks via caprock fracturing or damage, or via reactivation of sealed, laterally bounding faults. Fault reactivation also presents potential for seismicity.
At Utrecht University (UU, HPT Laboratory), the focus of experimental activity in WP3.3 lies on measuring the mechanical strength of caprock and the frictional strength of caprock-cutting faults, as well as changes in these properties (and in sealing capacity) as a function of mineralogical and microstructural evolution due to chemical interaction with CO_2 under reservoir conditions.

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In Year 1, we have set up apparatus to conduct:

- Triaxial failure experiments to construct failure/dilatancy envelopes of Röt and Solling caprocks (Bunter/P18 topseals). Most experiments will be conducted dry in the absence of CO_2 due to limited sample availability, but we will conduct additional tests on samples saturated with formation water and supercritical CO_2 to determine if CO_2 reservoir conditions will significantly alter strength and sealing capacity.
- Direct shear frictional experiments to determine the coefficient of friction of caprock- derived fault rocks. Experiments will be conducted dry and saturated with formation water and supercritical CO_2 to determine if CO_2 storage results in significant changes in fault strength, which could result in fault reactivation and increased seismicity.
- Batch reaction experiments on powdered caprock to determine the likely long term reaction products of sequestration. These experiments will be conducted in a large volume autoclave from which material will periodically be harvested over the course of up to 1 year under reservoir conditions. Additional material will be harvested for use in friction experiments to determine how long term mineralogical changes affect fault friction and sealing capacity.
- Argon gas and steady state permeability measurements on caprock cylinders to determine the initial state of the top seal of reservoirs, such as P18. Measurements will be made of the permeability of caprock derived fault gouge also in both a pre- and post-sheared state to determine the influence of fault reactivation on permeability. Permeabilities will be measured at effective confining pressures up to in-situ values, to determine if there are significant systematic variations due to confining pressure.

The first results using the Argon transient step method show that the permeability of the caprock of the P18 reservoir can vary from as high as 10-17 m2 to far less than 10-19 m2. There is currently no indication that permeability is strongly dependent on the formation of origin (Röt or Solling) of the caprock nor on the orientation of the sample to bedding.
During Year 1, before the Röt and Solling claystone caprocks to the P18 field became available, we have conducted an experimental analysis of the compressive and tensile strength and mechanical damage (or dilatancy) behaviour of Zechstein anhydrite, the caprock to the Rotliegend reservoirs forming numerous gas fields. We found significant variation in mechanical strength and damage behaviour related to natural variations in composition and microstructure of the anhydrite. The results have enabled the stress conditions under which anhydrite caprock does and does not become mechanically damaged to be delineated, and shows that such caprocks will be mechanically stable under normal CO_2 storage conditions. Moreover, we find that on the timescale of the experiments performed, the presence of CO_2 in the pore fluid has little or no influence on strength or damage behaviour.

WP3.3-D09, Progress report on: Preliminary data on entry pressure, wetting behaviour and transport properties of coal/caprocks from the DSM site

The wetting behaviour of the (cap-)rock-water-CO_2 system plays an important role in long-term behaviour of sequestrated CO_2 and thus storage safety. For the accurate prediction of caprock sealing capacity, for example, the wetting behaviour needs to be determined by laboratory experiments. Previous results from the Delft University of Technology show that the capillary behaviour and contact angle of coal and sand can be measured at relevant pressure and temperature conditions using capillary pressure measurements and pendant drop cell measurements.

Sample material from specific sites, such as the DSM site, and detailed information on these materials is required, so that suitable replacement or analogue samples can be selected and

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acquired. The capillary pressure cell and the pendant drop cell have been refurbished and tested, using available coal samples, for application in the CATO-2 program and are now ready for use. Future experiments will investigate the wetting behaviour (capillary pressure curves and contact angle measurements) of site-specific seal materials, or a suitable replacement, at elevated pressure and temperature.

8.4 WP 3.4 Well integrity

WP3.4-D01, Progress report on: Qualitative well assessment of field cases, including recommended well-specific workover and abandonment strategies and remediation/mitigation techniques

CO_2 storage is being considered in TAQA's P18 gas field. In the context of the CATO-2 project the suitability of the existing wells in the field is being investigated for injection and long-term storage of CO_2. The well integrity assessment covers the operational phase of the injection project (decades) and the long-term post-abandonment phase. The study aims at the evaluation of the relevant well system barriers to identify potential showstoppers and recommendations on remedial actions and abandonment strategies. This report presents progress until September 2010, but does not describe the final conclusions of the well integrity assessment of the P18 field.

The P18 field comprises 3 reservoir blocks, penetrated by a total of 7 wells, some of which have been sidetracked. One of these sidetracks also penetrates the caprock and the reservoir.

One of the wells, P18-2, is plugged with several cement plugs. At this time the actual status of this well, i.e. abandoned or suspended, is not confirmed. The current layout of plugs in P18-2 is inadequate for long-term containment of CO_2, as it provides likely migration pathways from the reservoir to shallower levels, bypassing the caprock. In case the well proves to be permanently abandoned and remediation is not techno-economical feasible, this will be a showstopper for CO_2 storage in the largest P18-2 reservoir block.

There is uncertainty with respect to the sidetracked P18-2A6 well. From the limited available data on the sidetracking operation it is uncertain how the parent hole was abandoned and if this is satisfactory for CO_2 storage. This needs to be verified before final judgement can be passed on the suitability of the well for CO_2 storage.

All other wells are still accessible and therefore can be remediated. Most of these show questionable cement sheath quality at caprock level from CBL data (i.e. P18-2A1, P18-2A3, P18-2A6, P18-6A7) or lacked data to verify this (i.e. P18-2A6st, P18-4A2, P18-6A7). Inadequate primary cement imposes a risk to long-term integrity, but could also affect the operational phase. However, these wells can be accessed and, in order to prepare the accessible wells for CO_2 storage, it is recommended to re-evaluate and, if required, remediate the cement sheath quality at least over caprock level.

When considering wells that will be used for CO_2 injection it is recommended to check the packer operating envelope against CO_2 injection scenarios. Potential elastomers and wellhead configuration should also be verified and adapted where required. Moreover, it is suggested to adjust completion materials (tubing, tubing hanger and packer) to corrosive circumstances, where applicable. All operational wells will need abandonment in the future, either prior to or after the injection phase. For these wells abandonment can be designed specifically for CO_2 storage. At present, there are two general options to permanently seal a wellbore for CO_2 containment. If the

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quality of the primary cement sheath is ensured over critical intervals, traditional abandonment plugs can be positioned and tested at caprock level. Alternatively, and especially in the case of questionable cement sheaths, pancake plugs can be used at caprock level. This would involve milling out of the casing, annular cement and part of the formation, followed by placement of cement in the cavity. This operation may pose difficulty particularly in horizontal or strongly deviated wells. Both of these options should be accompanied by additional plugs higher up the well, according to common practice and as prescribed by governing abandonment regulations.

At present, the evaluation is ongoing and requires additional data on some of the wells to be able to draw final conclusions on the suitability of the P18 wells for CO_2 storage

WP3.4-D02, Progress report on: Application of advanced materials/treatments for abandonment and mitigation

Work on materials and treatments for improving well integrity, and for mitigating any leaks that might occur, is funded at Utrecht University (UU), IF Technology / Well Engineering Partners (IFWEP),and TU Delft (TUD).

During Year 1 of CATO-2, preparatory work has been conducted at UU with the aim of identifying mineral additives to wellbore cements (or injection fluids) that can act as clogging agents upon reaction with CO_2. Further preparatory work at UU has included assessing the geochemical and geomechanical effects of such reactions, and setting up equipment to study them. A variety of powdered minerals, such as olivine, serpentine and calcium hydroxide have been identified from the literature as potentially promising additives, alongside fly ash. Preliminary experiments performed on olivine and fly ash have also shown that reaction is rapid enough to be potentially useful and that significant reduction in permeability results. However, theoretical studies have indicated that the swelling that accompanies reaction can have both beneficial (clogging) and detrimental (fracturing) effects. Optimising clogging effects over fracturing will therefore be key to the work planned for Years 2-5.

IF-WEP will review current best practices from industry for plugging wells for standard and more advanced materials, applied in a CO_2 environment. This serves as a basis for identifying any shortcomings and possible new materials. Work will commence in year 2.
Work at TU Delft will begin in year 2, and will focus on assessing best practices and promising research ideas for remediation of casing leaks in the petroleum industry, and experimental study of flow of non-Newtonian (remediation) fluids through cracks and porous media.

WP3.4-D03, Progress report on: Development of chemical and mechanical experimental laboratory measurements

One of the main concerns with geological storage of CO_2 is maintaining reservoir integrity in the face of leakage pathways due to wellbore perforations of the topseal or caprock. Previous experimental analyses vary widely in their predictions of the long term integrity of wellbore cement as a sealing agent for sequestration reservoirs. The focus of the experimental activities in WP3.4, is to advance the science of understanding the evolution of a wellbore seal of a CO_2 reservoir.

At Utrecht University (UU, HPT Laboratory), the focus of experimental activity lies on attempting to mimic key components of the entire wellbore system and measure changes in mineralogy and permeability of the wellbore system as a function of continued reaction and mechanical deformation in a CO_2 reservoir environment. In year 1, UU has set up apparatus to conduct:

- Batch reaction experiments on powdered caprock mixed with powdered cement and ground casing steel to determine the long term, wellbore reaction products. These experiments will

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be conducted in a large volume autoclave over the course of up to 1 year under reservoir conditions.
- Permeability analyses on caprock cylinders to determine an initial state for the top seal of the P18 and other reservoirs. Experiments will predominantly be conducted using an Argon gas transient step technique at low confining pressures, with validation using an Argon flow through technique. Permeability will also be measured at in-situ confining pressure.
- Analyses on the evolution of the interfaces between caprock & cement and cement & casing steel. Experiments will be conducted on composite caprock-cement-steel samples. These will be subjected to CO_2 reservoir conditions for up to 1 year, and periodically analyzed for changes in bulk permeability, reaction progress and (interface) microstructure.
- Batch reaction experiments on varying mixtures of caprock, cement, and casing steel in a reaction vessel fitted inside of an Instron load frame under CO_2 reservoir conditions. This will be used to measure volume changes and swelling forces generated by reaction in the wellbore environment. Such effects may improve sealing but may also cause caprock fracture.

First results at UU using the Argon transient step method show that the permeability of the P18 caprock can vary from as high as 10^{-17} m^2 to far less than 10^{-19} m^2. There is currently no indication that permeability is strongly dependent neither on the formation of origin (Röt or Solling caprock) nor on the orientation.

At the TNO-Rijswijk Prins Maurits Laboratory, the focus will be on investigating the long term effect of CO_2 reaction with cement and caprock, and clarifying the findings of previous studies. A new reaction vessel is being developed for this purpose that will very closely simulate the natural conditions of a CO_2 reservoir. The new experimental design is a great step forward in apparatus design for this type of experiment in that it provides a much more realistic reservoir environment by jacketing the reacted sample and subjecting it to static interaction with CO_2 and brine, rather than placing the sample in a brine bath and pressurizing the bath with CO_2.

At TNO Science and Industry (Den Helder), the contribution to WP3.4 is directed at corrosion studies. Supercritical CO_2 plus moisture or formation water in the CO_2 storage well environment forms carbonic acid that causes corrosion of tubes and casing steels, which combined with rock-cement interactions, may result in CO_2 leakage. Understanding steel corrosion under CO_2 storage conditions is critical to modelling well integrity. A preliminary desk study on the electrochemical measurements for tubing and casing steels in CO_2 environment has been done in the CATO-2 year 1 program. In addition, the necessary experimental set-up for high pressure and high temperature (HPT) steel corrosion studies and the required electrochemical measurement protocol have been designed.

WP3.4-D04, Progress report on: Development of numerical models of (coupled) processes

Deliverable D04 describes progress on development of numerical models of (coupled) mechanical and chemical processes relevant for wellbore integrity. The activities related to the D04 are planned to be executed from year 2 to 5 of the CATO-2 project. In agreement with the project plan no activities were executed during the first year of the project. In this progress report we provide description of our plans with respect to the planned activities for years 2 to 5 of the project.

We will present an analysis of the processes that can affect well system. Processes that can lead to the mechanical damage of cement sheath in the axial direction are of particular importance as they can cause creation of communication pathways for migration of CO_2 upwards across the top seal. Axial deformation affects practically every well because each reservoir compacts and

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extends to some extent during production and injection. Axial well deformation and its effects on axial fluid migration were barely studied before. This is in contrary with radial and shear deformation, which were widely studied and reported in the literature.
The conceptual model of axial well deformation will be utilised to develop generic geomechanical numerical models of a reservoir with a production/injection well. The well system will be explicitly represented with the steel casing, cement sheath and the surrounding damaged rock. Geomechanical models will be used to investigate further the effects of reservoir compaction and decompaction on possible deformation along cement-casing and cement-rock interfaces and possible implications for fluid flow.

WP3.4-D05, Progress report on: Specifications and design criteria for innovative corrosion monitoring and (downhole) sensor systems, including sensitivity analysis

The objective of this Work Package is to establish specifications and design criteria for corrosion monitoring and corrosion sensor systems used in CO_2 storage wells; this includes sensitivity analysis and an evaluation of technological maturity.

In the Year 1 program, we review the tools deployed for downhole integrity monitoring principally in oil and gas wells. This is because there is an established body of literature and field experience in the oilfield. The tools reviewed in this document are based on mechanical, sonic, electromagnetic, optical and electrochemical principles.

The table below provides a summary.

Measurement principles, applications and limitations of the tools described in the report

Measurement principle	*Tool/measurement*	*Applications*	*Limitations*
Mechanical	Mechanical multi-finger caliper measurements	Used extensively to measure internal corrosion of tubulars	Cannot detect very small holes (pinholes) in pipe.
	Cased hole dynamic tester	Used to take formation pressure and fluid samples in cased wells	Can only be run in casings larger than 5½”
(Ultra)sonic	Sonic cement bond logging	Used to measure ‘average’ cement bond quality outside pipe	Cannot detect cement defects such as channels
	Ultrasonic cement bond logging	Provide information on both the cement sheath and casing	Can only be run in casings larger than 5½”
	Ultrasonic corrosion logs	Provides high resolution azimuthal coverage of the pipe	Cannot be run in gas
	Permanent ultrasonic corrosion monitoring	Permanent corrosion monitoring of the pipe	No evidence of actual deployment
Electromagnetic	Electromagnetic corrosion measurement	Corrosion in pipes	Responds to ‘metal’; therefore, cannot measure non-metallic accretions in pipe
Optical	Downhole cameras	Visual inspection of the wellbore	Can only be run in gas. Depends on downhole visibility
	Distributed temperature	Measure temperature	Measure subject to drift

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	sensor	profile along the well	over time
Electrochemical	Corrosion protection evaluation tool	Evaluation of effect of cathodic protection	

Many of the tools are used for integrity survey and a few for permanent monitoring. The sensitivity of the sensors needs to be investigated. In Year 2, we shall focus on investigating electrochemical sensors for monitoring the corrosion of the casing in CO_2 storage wells.

WP3.4-D06, Progress report on: Monitoring strategies for inaccessible/abandoned wells

The work on this deliverable will be executed by TNO B&O and IF-WEP. Due to the limited funding available for this task in year 1 of CATO-2 the work will start in year 2 of CATO-2. This report will therefore consist of a brief introduction into the subject and a plan for the coming years. When a potential site for CO_2 storage is evaluated in an area where drilling has taken place, one of the essential steps to ensure the integrity of the CO_2 storage site is to asses all current wells that might come into contact with the target storage interval. This is just as important for the active wells as for the abandoned/inaccessible wells.
In this study we shall differentiate for the various types of abandoned/inaccessible wells that can be encountered in practice. For instance between wells that are completely inaccessible from ground level to wells that are partially accessible by industry standard, low-cost well intervention methods. For the various types of abandonment stages different monitoring strategies shall be developed and evaluated on their ability to detect a CO_2 leak and their cost effectiveness.
Results from previous work carried out by IF-WEP show that current oil industry state-of-the-art wellbore logging tools - when applied to CO_2 injection wells - are still inconclusive or even lack the ability to detect CO_2 flow behind casing. Furthermore, storage of CO_2 introduces new conditions to long-term integrity of wells. Previously abandoned wells are of specific interest as these may be plugged decades ago – when regulations and technology were not at current high levels – and mostly are not easily accessible. IF-WEP and TNO B&O therefore strongly support to carry out work to improve the ability to detect CO_2 leaks in storage wells.

8.5 WP 3.5 Additional benefits of CO_2 injection

WP3.5-D01, Progress report on: Numerical model data and reports on the effect of seasonal CO2 delivery on storage efficiency and capacity

CO_2 buffering; seasonal storage and production
Seasonal storage: CO_2 from the Pernis refinery is currently supplied to farmers to increase the rate of grow of vegetables within greenhouses and to soft drink producers. This amount of required CO_2 depends on the weather and also on the season. For example: during the summer the farmers may need additional CO_2 than the refinery or electrify producer can provide, while during wintertime they may not need any CO_2. A possible solution may be the temporal storage the gas into a depleted gas field (during wintertime) or other underground structures, followed by reproduction during the pick demand periods. Several aspects need to be investigated:

- CO_2, tends to dissolve compositions such as water, hydrocarbons and maybe even radioactive elements. This could lead to well integrity issues (moist CO_2) Reproduced CO_2 may also not have enough purity for use in the various applications. Possibly the reservoir is cleaned after several cycles of injection and reproduction.
- The reservoir may dry out as a result of the repeated cycles of injection of dry and reproduction of wet CO_2.

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Activities year 1: Carry out geological, physical modelling and numerical simulation studies of the effects of seasonal variations of CO_2. Simulate CO_2 storage scenarios with quantitative predictions of responses.
This activity will be ceased after year one in according to the reduction of activities caused by budget cuts.

Summary of the activities:

- Started with a literature study on potential sites for seasonal storage:
  - Small gas fields
  - Salt caverns
- Discussion on effects on reservoirs by CO_2-injection and – production:
  The cleaning effect, i.e. removal of resins near the well was found to improve flow rates in the GdF-TNO field test in a previous storage program.
- Discussions together with members from SP1, SP2 and SP3 to make an inventory on supply, demand and transport capacities for CCS. (meeting SP1, SP2, SP3 on 26/02/10)
  A summary of this meeting, with consequences is provided here below. The minutes of the meeting are in the appendix.

Conclusions:

- A reservoir may dry out as a result of the repeated cycles of injection of dry and reproduction of wet CO_2.
- Reproduced CO_2 has a reduced purity for use in the various applications. Moreover, it may cause unwanted:
  - corrosion, and mineralization in the transport system.
  - and multi-phase flow.
- Advantage: possibly the reservoir is cleaned after several cycles of injection and reproduction.

Seasonal storage will cause significant technical problems during second stage transport.

WP3.5-D02, Progress report on: Preliminary of experiments and appraisal to investigate the effect of CO_2/water volume combined with gravity flow characteristics in the Delft sand reservoir

CO_2-injection in aquifers combined with geothermal energy
In the DAP project (Delft Aardwarmte Project) the aim is to combine CO_2 with the injected geothermal water to enhance CO_2 storage capacity and reduce costs. Since CO_2 will be dissolved in water early injectivity problems will be avoided. However long-term injectivity needs to be evaluated. The aim of this task is to understand which effects the variation in CO_2 injection volumes that will affect storage mechanism and the storage capacity of aquifers. It will also investigate how creation of buffering capacities can mitigate such effects.

In all WP's additional benefits of CO_2-storage are dealt with.

- In WP3.5.2 it is the objective to develop on-site small scale CO_2-capture and (low concentration) injection in order to go to a ZEP. Alternative small scale capture methods could come into view. The sub-WP runs parallel to the development of a geothermal plant.
- WP5.3.2. partly depends on WP5.3.3 in a common topic; CO_2-water sorption behaviour for CO_2-EOR water drive.

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Activities WP3.5.2.

1. Regular meetings with DAP about topic on education, research and innovation in CO_2-geothermals.
2. In cooperation with the Location Manager and DAP water and reservoir sand were sampled from the Bleiswijk geothermal site. A method of approach, specific for CO_2-geothermals has been developed to analyze the reservoir. This as an example for the DAP concession. . *In this approach, more emphasis is put on the use of image analysis and X-ray techniques.* Compositions of the fluid and particles provided compositions of the reservoir fluids, rock composition and a permeability profile of the pay zones. Report: Delft Thesis Report of N. Chun. Available from the Delft Thesis Repository.
3. An experimental set-up for water-CO_2-steel/composite/reservoir interaction is under construction. Delft Thesis Report of L. van Leeuwen. Available from the Delft Thesis Repository.
4. An exergy analysis has been developed for the entire system, during its lifetime. A temporary research assistant has been hired to finalize the first concept. All results will be available in a Delft Thesis Report of J. Mooij; not yet available.
5. A first static single layer homeogeneous reservoir model has been finished. Delft Thesis Report of D. Gilding. Available from the Delft Thesis Repository. It is the base for a dynamical model where production/injection interference and flow behaviour of CO_2-saturate water. Dr. H. Salimi continues the modelling work, using the input of previously mentioned activities.
6. Consultation between TU-Delft, the Pijnacker and EBN-Eneco well owners about data acquisition. Implementation of PVT-equipment for on-line acquisition, cuttings, coring and petrophysics. Status: Ongoing.

<u>Synopses of the activities in topic 2. and topic 4. are included below in chapter 3 and 4.</u>

1. Exergy analysis of geothermal energy combined with CCS in underground aquifers.
2. An Approach to Analyze CO_2-Geothermal Reservoir Properties Based on Minimum Information.

WP3.5-D03, Progress report on: Strategies to use buffering capacity to mitigate the effects of temporal variation of CO2 delivery volumes, to be investigated in detail in the next phase

CO_2-EOR/EGR

The storage of CO_2 in depleted gas and oil fields is very attractive because of the additional production of hydrocarbons. The injection of CO_2 helps pressure maintenance and increases the recovery factor of such gas (EGR) or oil reservoirs (EOR) and may help offset the storage costs. The proximity of aquifers to gas and oil fields offers a number of possibilities to combine CO_2 storage with enhanced gas recovery. Aquifers can be used as permanent storage sites or buffer capacity depending on the balance of incoming and utilized CO_2.

Activities:

1. Discussion with HC-field owners for data to investigate CO_2-EOR. Several meetings with TAQA and GdF. Various topics are discussed, such as; reservoir rock composition, Joule-Thompson effect and an EGS-experiment.

The results are summarized in the deliverables of WP3.1 and WP3.2, i.e. Joule-Thompson modelling work.

2. Slim tube experiments. Several WP's are interested. Hence, three meetings between the interested parties were organized that provided the information about the desired dimensions

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and PVT-conditions of such experiments. The equipment is under development. In addition CFW-experiments and heuristic modelling work already started.

The results are summarized in WP3.2 by P. Zitha and P. van Hemert.

8.6 WP 3.6 Shallow (sub) surface monitoring

WP3.6-D01, Progress report on: Development and preparation of test sites (time-series of CO2 concentrations)

This overall WP aims at establishing baselines in time and space for CO_2 concentrations in the groundwater, soil and atmosphere and for ground movement. Given these baselines, the aim is to establish whether events related to the CO_2 storage activities (either instantaneous or continuous) can cause detectable deviations from these baselines. Another goal is to develop a tool that is able to detect pipeline leakages.

Two gas fields in the Netherlands, Barendrecht and Barendrecht-Ziedewij, are selected as potential sites for geological CO_2 storage. A technical evaluation showed that migration of the stored CO_2 to overlying layers or the subsurface is very unlikely. However, this possibility cannot be completely excluded with 100% certainty. In this report, a monitoring strategy is designed to detect CO_2 in the unlikely case that leakage would occur from the reservoir to the surface. The focus is on the migration through the shallow subsurface and interaction with the groundwater. The goal of monitoring is to identify, if it would occur, migration of CO_2 from the reservoir to the surface. Secondly, the goal is to determine the lower detection limit of such migrated CO_2, given the natural variation of CO_2 concentrations and fluxes in the shallow subsurface.
The risk management evaluation of the Barendrecht and Barendrecht-Ziedewij fields (Van Eijs et al., 2008) indicated that leakage along boreholes is a low to medium risk, compared to a negligible risk of the other scenarios considered. After mitigation measures, leakage along boreholes is a negligible risk.
Because leakage along boreholes has a risk which is not negligible (before mitigation measures), this scenario is used to optimize the monitoring plan. In addition, spatiotemporal variations of CO_2 concentration in groundwater are determined using measurements. Changing CO_2 concentration in groundwater can have an effect on ecology, subsurface infrastructure and the use of groundwater for drinking water purposes.

WP3.6-D02, Progress report on: Maps of CO_2 concentrations varying in time. Interpretation per region of the data

The overall goal of this research is establishing baselines in time and space for CO_2 concentrations in the groundwater. Given these baselines, the aim is to establish whether events related to the CO_2 storage activities (either instantaneous or continuous) can cause detectable deviations from these baselines. The use of a groundwater monitoring network for CO_2 concentrations is proposed to meet this goal. Leakage from the storage reservoir is considered negligible, but can not be ruled out with 100% certainty.

To be able to detect a deviation in CO_2 concentration compared to the conditions before the start of the CO_2 injection, the baseline concentrations and natural variations of CO_2 in groundwater should be well known. In this study an inventory is made of available data of CO_2 concentrations in the groundwater in the Netherlands. Also, the hydrological and geochemical processes related to CO_2 concentrations in groundwater as well as the anthropogenic activities that might have an

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impact on CO_2 concentrations in groundwater are described. Using this knowledge the spatial and temporal variability of the available data of CO_2 in groundwater is explained and drawbacks of the currently available dataset were contained.

CO_2 concentrations of the groundwater vary between 0 mg/l and 5000 mg/l. High concentrations are found in the western and northern part of the country, except the dune area. Lowest CO_2 concentrations were found in groundwater below the Veluwe. The CO_2 concentrations in deep groundwater are lower than the concentrations in the shallower groundwater, but the spatial patterns are similar. High CO_2 concentrations in groundwater are the result of sulphate reduction and methanogenesis in aquifers rich in organic matter with brackish and salt formation water and seepaging formation water in the western and northern part of the Netherlands.

Although the inventory of the available data resulted in a good spatial overview of the range of CO_2 concentrations in the groundwater in the Netherlands, no small scale variations of CO_2 concentrations could be detected and the various sources could not be established with certainty. None the less, knowledge of such variations is important for being able to detect variations with the CO_2 storage and injection in geological formations. First concepts for more specific monitoring networks are described which will be designed in more detail during the next phase of this research project. Also, possible additional analyses based on the currently available dataset are described.

This report is complementary to the report of Sommer et al. (2010)) in which an inventory is made of strategies for monitoring CO_2 in (shallow) groundwater at sites of geological CO_2 storage.

WP3.6-D03, Progress report on: Preparation of site specific geodetic remote sensing techniques for ground movement

Case studies have been performed in the areas of Roswinkel and Barendrecht, which contain gas fields. The Roswinkel field had been selected to demonstrate the applicability of ground deformation monitoring to the characterization of the reservoir dynamics; the Barendrecht field is a potential CO_2 storage location. Ground deformation in these areas has been measured using Persistent Scatterer Interferometry (PSI). It is shown that these areas have insufficient persistent scatterer (PS) point density for accurate deformation monitoring if PSI is used as a standalone technology. The need for integration with complementary technology to improve monitoring accuracy is demonstrated. GPS receivers can be installed to improve the monitoring itself, or advanced inversion technology can be applied to extract a maximum of information by combining geodetic monitoring with subsurface modelling.

WP3.6-D04, Progress report on: Development of an atmospheric pipeline monitoring strategy

In the safety study included in the Environmental Effects Report (MER) of the Barendrecht CO_2 storage site it is concluded that monitoring of a stretch of the transport pipeline located in the vicinity of vulnerable objects is desirable from the perspective of safety management. This would also show that public concerns regarding safety issues are taken into consideration seriously. Therefore, a simulation study is performed that examines the feasibility of the detection of small leaks by means of the simultaneous monitoring of:

- atmospheric CO_2 concentrations at a distance of some tens of meters from the pipeline,
- local wind direction and

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- wind-force.

Points of leakage would be detected by correlating the CO_2 concentrations that would be caused by a leak with the actually observed concentrations. If a correlation exists, a leak may be present and the location applies for inspection. The study concludes that there is sufficient cause to perform a field test of the method.

8.7 WP 3.7 Permanent Geophysical Monitoring

WP3.7-D01, Progress report on: Feasibility studies for permanent seismic/EM monitoring

The aim of this deliverable is to investigate the feasibility of permanent monitoring via seismic and (diffusive low-frequency) electromagnetic techniques. These methods address the issue of reliable monitoring and verification of CCS. Since the diffusive electromagnetic (EM) technique is less developed than the seismic technique, the main focus of the work over the reporting period has been on the EM method.

Since no specific site has been chosen yet for CO_2 storage in the Netherlands, use has been made of made of the model resulting from the CO2SINK test site at Ketzin (Germany). Both seismic and controlled-source electro-magnetic data for a 1D layered medium for CO_2 migration under different scenarios with different phases of CO_2 (gaseous, fluid/supercritical) with different reservoir fluid fills (gas, fresh water, saline water) are considered. Since successful field seismic time-lapse studies have been done for the Ketzin site, the discussion on the seismic modelling is very limited and the results will therefore mainly pertain to feasibility of EM.

EM simulations have been done for simplified models. The different scenarios give different conclusions with respect to feasibility. It is going to be dependent on the chosen demonstration site by CATO whether EM will be feasible or not. Analysis of the different EM simulations showed that, for changes due to CO_2 to be optimal, two options are possible. One possibility is using a horizontal electric source and then use should be made of horizontal and vertical electric receivers, and vertical magnetic receivers; the other possibility is using a vertical electric source and then use should be made of only horizontal electric receivers. At shallow depths of the electric source, the difference between pre- and post-CO_2-injection is expected to be a few percent. EM seems feasible when the proper frequencies are chosen to reach the desired depth of CO_2 injection and the case that there is a clear distinction between the resistivities of pre- and post-CO_2 injection.

WP3.7-D02, Progress report on: Development of processing, analysis and interpretation techniques of the data

This report gives the first results obtained from a permanently installed passive seismic array at one of the European demonstration sites used for storage of CO_2 in a saline aquifer near the town of Ketzin, west of Berlin. In June 2008, in the framework of the European CO2SINK project, a two-year-CO_2-injection project has been started. To monitor the migration of the injected CO_2, TNO (although not a partner in the CO2SINK project consortium) installed a multi-component seismic array in Ketzin. Since September 2009, this array has been continuously recording passive seismic data.

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Passive Seismic imaging during reservoir production and injection has become an area of growing interest. The monitored micro-seismic activity (including event magnitude, location, and source mechanics, i.e. moment tensor) gives an indication of how the rocks are actually responding to the pressures, fluid volumes, and gas volumes. Mapping the event locations over time mirrors the development of fracturing, which in turn reflects the dynamics of the process.

Within the framework of CATO-2, more particularly this WP, the recorded passive seismic data have been analyzed, Furthermore a spectrogram based quality control (QC) work flow and an automatic "event" picking procedure have been developed. Results of the automatic signal picking have been tested on known events (such as interruptions of the injection).. In order to map the recorded seismic signals back to their origin, a back-projection algorithm has been introduced. Application of this back-projection algorithm based on a velocity model provided by CO2SINK partners, is work in progress.

Eventually the aim of this WP is to assess the added value of using such a permanent system in the Netherlands for Dutch reservoirs.

WP3.7-D03, Progress report on: Start of a PhD or PD on the improved interpretation of combined EM and seismic data

In the CATO-2a "Beschikking" (AD-01), the following deliverable is mentioned:

- Progress report on: Start of a PhD on the improved interpretation of combined EM and seismic data.

The originally 5 year CATO-2 Program has been divided in CATO-2a (first year) and CATO-2b (second till fifth year). Since the funding for CATO-2b was not guaranteed, universities were not allowed to make a four-year commitment for a PhD. Therefore, the progress on this subject is limited to the PhD description.

8.8 WP 3.8 Laboratory experiments geophysical

WP3.8-D01, Progress report on: The set-up and calibration of specific laboratory measurements regarding complex impedance in the frequency range from 1 kHz to 1 MHz.

This proposed PhD research project has not started yet. However, we have done related research on geophysical monitoring of the behaviour of a subsurface reservoir. Geophysical monitoring of dynamical behaviour of subsurface reservoirs remains an important issue in geophysical research. Among the possible applicable techniques are 4D seismic measurements and off-shore electromagnetic measurements. On-shore monitoring remains an important but not well-resolved issue, as repeated seismic measurements on-land are costly and often suffer from poor repeatability.

A new idea for monitoring based on electrical resistivity tomography was tested by computer simulation in 2009 at TNO. The essential element of the so-called BSEMT (Borehole to Surface

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Electrical Monitoring Technique) technique is the use of one electrode below the reservoir. The computer simulation results were promising, but concerns on the ability to measure the effect also arose. Therefore measurements in a tank in the laboratory were carried out to assess the feasibility of the BSEMT concept. The results of these measurements were that the expected effect of changes in the reservoir can indeed be seen by BSEMT. The surprising part of it is that the effect is bigger than the expectation based on computer simulations. This point has to be clarified further in future.

WP3.8-D02, Progress report on: Preparations for a PhD thesis on electric properties, as a function of pressure, temperature and water saturation, of porous reservoir- and cap-rocks saturated with gas-water mixtures

This proposed PhD research project has not started yet. However, we have done preparatory studies for the research that will be undertaken from the second year by a PhD student. As a result, the research idea has been further refined and progress has been made in understanding the dynamic situation in the reservoir in course of injecting CO_2 and capturing the signature of change through monitoring the electrical properties in association with the seismic properties. From these studies it has been clear that the displacement of brine by CO_2 will cause a change in the electrical resistivity and also changes in seismic velocities and amplitudes. Seismic and perhaps electrical measurements will be sensitive to the CO_2 phase changes occurring at the critical point. Seismic properties may be affected by the quantity as well as the distribution of the phases. We conclude that in the lab experiments and theoretical studies to be carried out by the PhD student the sample behaviour should be tested under reservoir conditions as a function of injected CO_2, the phase of the CO_2, and the brine salinity. This will give us a powerful tool to monitor pore pressure and the CO_2 saturation.

8.9 WP 3.9 Site Specific Monitoring

WP3.9-D01, Progress report on: Preliminary advisory reports on monitoring plans for assigned and potential sites

This report provides an overview of the status of monitoring activities for each subsurface site in CATO-2. Numerous meetings (18) have been arranged with site owners over the past period to discuss and synthesize plans for site specific monitoring activities. The conclusions of these discussions are summarized in this overview. For sites like P18, K12-B and Barendrecht, more detailed separate reports are available.

WP3.9-D02, Progress report on: Preparation and installation of a sounding board committee for the interpretation of Barendrecht data: Meeting reports

Discussions and meetings are summarized in this report to initiate a sounding board committee for Barendrecht. The principal aim of the committee would be to critically follow the monitoring activities of Shell at Barendrecht and to formally provide a reaction on presented results, including potential recommendations.

WP3.9-D03, Progress report on: Monitoring activities at K12-B. If available; Preliminary (raw) results of the monitoring and the downhole

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measurements, preliminary results of chemical and tracer analysis, progress report on the interpretation of the measurements

This report provides an overview of the monitoring activities carried out at K12-B. First a condensed overview of activities prior to the CATO2 project is given, followed by a more detailed description of the tools deployed (or envisaged in the near future) in this WP.
In general the main focus of monitoring at K12-B is on well integrity and on plume tracking including gas mixing.
Activities in 2009/2010 comprise scale sampling & analysis, downhole fluid sampling & analysis and continuous P&T measurements. Furthermore a new (repeated) ElectroMagnetic Imaging Tool (EMIT) is envisaged for well integrity in 2010 as well as the injection of a new type of tracers taking solubility effects (better) into account. Careful planning is required in order not to interfere with ongoing operations on the platform.

WP3.9-D04, Progress report on: Planning/development of site specific monitoring and control programs

This report describes an initial monitoring plan for P18 in providing different monitoring options for various purposes such as plume tracking or migration outside the storage complex. The current version of the monitoring plan is only qualitatively based on current performance assessments and on estimated potential risks. Analysis of the performance of the injection process and of potential risks is subject of investigation in other WPs and in the ROAD project.
A discussion on the monitoring plan in the context of the latest regulatory requirements as stipulated in the EC-directive is included.
In December 2010 an updated plan is expected based on the results of the WPs 3.1-3.4 in CATO-2.

WP3.9-D05, Progress report on: Developing a "Vault" for data storage and a website for: Raw data storage from field locations and experimental work and data collection and (applied) data storage

This report describes a first demo version of data transfer and visualization over the internet, Data from the permanently installed seismic network at Ketzin have been used for demonstration. The data is used and interpreted in WP 3.7. This task is stopped after year 1 due to the 2010 budget cuts in CATO-2

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9 SP 4 Regulation and Safety

9.1 WP 4.1 Legal framework and guidance

WP4.1-D01, Support to the implementation of the proposed Storage

In June 2009, the EU Directive on the Geological Storage of Carbon Dioxide entered into force. The European Member states are obliged to transpose the directive in their national legislations no later than 25 June 2011. The EU legislator has applied a regime of minimum harmonisation when drafting the CCS Directive, amongst others to achieve that an agreement could be reached on the CCS Directive by a majority of Member States. In other words; Member States have considerable discretionary powers while implementing the Directive. The CO_2 Storage Directive is mainly transposed into Dutch legislation by means of adaptation of the Dutch Mining Act. There are, however, still some issues in the implementation of this directive that need further clarification. The way these issues are addressed may impact the deployment of large-scale CO_2 capture and storage (CCS) in the Netherlands and Europe.

This report analyses several of these issues, and aims at providing possible pathways and recommendations on how to resolve them. The issues analysed in detail in this report include:
- Requirements regarding the composition of the CO_2 stream;
- Procedure and criteria for site selection;
- Liabilities with respect to health and property.

Issues addressed in less detail, but which will be researched in more detail in the coming years include:
- Transfer of responsibility;
- Financial Mechanism;
- Monitoring of the site;
- Type of infrastructure access arrangements;
- Supervisory structure.

WP4.1-D02, Practical guidance for monitoring plans for CCS

On 8 June 2010 the Commission Decision amending Decision 2007/589/EC regarding the inclusion of Monitoring and Reporting Guidelines for greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide (EU, 2010) entered into force. The Monitoring and Reporting Guidelines have put a large emphasis on the quantification of CO_2-streams. In the Monitoring and Reporting Guidelines for CCS new emission sources from transfer, capture process, bypasses, fugitive, vented and leakage are required to be monitored. This requires the implementation of monitoring techniques which before were rarely or never used in the EU emission trading system.
This report provides an overview of the present technical status of monitoring equipment and best available technologies for monitoring CO_2-streams and CO_2-emissions.
Monitoring of CO_2-streams from combustion or process installations with CEMS is no common practice. Uncertainty of CO_2 CEMS systems for flow and concentration are larger than the required 2.5% in the MRG. These uncertainty requirements in the MRG for CO_2 (< 2.5%) are far more stringent than for e.g. NOx (< 20%), for which NOx CEMS systems can meet the uncertainty requirement of 20%. This is a point of further study.

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Technical monitoring of compressed CO_2-streams within the MRG uncertainty requirements from capture installations and in transport networks are still in the development stage. Only a few measuring techniques are available for monitoring compressed CO_2-streams. The volumetric flow measurement systems with orifice plates, turbine meters and the Coriolis mass flow measurement systems look the most promising at this moment.
For the orifice plate and turbine measurement systems exact knowledge of the prevailing CO_2 density and viscosity at the point of measurement is needed. Theoretical calculation procedures for density and viscosity at a given pressure and temperature are available, but are rather complicated and not easily available or verifiable. Therefore standardization of these calculation procedures is highly recommended for general application and acceptance by the competent authorities and independent bodies.
For the quantification of fugitive emissions from capture installations, transport networks and at storage sites the EPA method 21 is regarded as the best practice technology. However, no hard data is available on the uncertainties associated with the quantification of fugitive CO_2 emissions. There is very few CO_2 leak detection equipment on the market, which is readily suited for fugitive CO_2 emission measurement. Further development and standardization of measurement methodologies is recommended.
For onshore and offshore storage sites it is difficult to indicate which techniques are most suitable for quantification of CO_2 leakages. There is almost no data about the uncertainty in the quantification of these monitoring techniques. Therefore further research, practical experiences and standardization of methods are needed to establish proven and accepted methodologies for quantifying CO_2 leakages.

WP4.1-D03, Assessment of accuracy required by MRG's for CCS under the EU

On 8 June 2010 the Commission Decision amending Decision 2007/589/EC as regards the inclusion of monitoring and reporting guidelines for greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide (EU, 2010) entered into force. The monitoring and reporting guidelines have a large emphasis on the required uncertainty for the quantification of CO2 emission. In these monitoring and reporting guidelines for CCS new emission sources from transfer, capture process, bypasses, fugitive, vented and leakage are required to be monitored. This requires the implementation of monitoring techniques which have been rarely or never used in the EU emission trading system. If the required uncertainties are not met the operator has to bear large costs for improvement of the monitoring systems or to surrender extra emission allowances to compensate a to large uncertainty.

This report provides an analysis of the uncertainty requirements and provides possible pathways and recommendations how to meet the requirements. The precise implementation of these rules is of great importance for permit holders, as it can ease uncertainty requirements for the monitoring, in particular when the emission sources are relatively small. This also applies for the process and bypass emissions, which are not handled in the CCS monitoring and reporting guidelines. For the uncertainty requirements of these streams the regular annexes of the monitoring and reporting guidelines apply.

The total emission of a capture installation and a transport network could in principle be monitored by the difference between input and output stream of CO_2. But it is shown that measurement of all the emission sources is the preferred option for reaching the lowest uncertainty. For a CO_2-concentration above 95% and an uncertainty in the flow measurement under 2%, it is sufficient to do four analyses a year for the CO_2-concentration.

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The uncertainty requirements for the storage site are too strict in comparison with the capture installation and other installations in the EU-ETS system. It should be considered to base the categorisation of storage sites also on the “emission before transfer”. Then if the overall emission is under 2% of the emission before transfer and under 20 ktonnes, it is a de-minimis source. The operator may then apply approaches for monitoring and reporting using his own no-tier estimation method.

There are many advantages if the transport network plays an important role in the physical monitoring at the CO_2-transfer points of the capture installations and storage sites. Incorporation of the EU-ETS monitoring in the monitoring plan for the storage sites is a requirement. To ease validation and verification it is advised to make also a separate EU-ETS monitoring plan. This contains the limited measurement requirements from the monitoring guidelines for CCS.

9.2 WP 4.2 Permitting and best practice

WP4.2-D01, Progress report on: Best practices in CCS demonstrations

This document is the first report of the five-year (2009-2013) research project, that has been carried out within the framework of the CATO-2 program. The mission of the CATO-2 program is to facilitate and enable the integrated development of CCS demonstration sites in the Netherlands. The program’s ambition is to help support the realisation of two or more demonstration sites where the complete integration of CO_2 capture, transport and storage will be demonstrated in the Netherlands before 2015.

The objective of this research project, CATO-2-WP4.2, is to identify best practices from permitting and certifying CCS activities at designated CCS sites in the Netherlands (offshore as well as onshore urban and rural areas). It will bring together all findings resulting from the project and make these available to a platform consisting of the site operators of the CCS projects, considered within the CATO-2 program. It will help in particular to resolve barriers of regulation, monitoring & verification, and public perception, and thus facilitating and enabling the introduction of CCS demonstrations, as well as a further development of CCS technologies in the Netherlands.

Within the framework of this CATO-2 project a questionnaire to the location managers of the CCS projects in the Netherlands has been prepared by the project partners. It includes questions on general aspects of the operation, permit issues, environmental impact assessments, ETS monitoring, risk management of geological storage, and expectations of the location managers vis-à-vis this project. The questionnaire was made available on-line to 12 location managers, of which 9 did fill in the questionnaire. In order to further an understanding of the responses, additional interviews, including additional questions, were conducted with the location managers.

The results of the questionnaire and the subsequent interviews with the location managers of the CCS projects considered, have led to some conclusions and recommendations, as presented below.

General aspects location

All the projects considered are still in the development phase and none are operational yet. The capture technologies of the CCS projects considered are *post-combustion*, *pre-combustion*, and *oxy-fuel*. In addition, in two of the concerned CCS projects the CO_2 is a 100% pure stream. In

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most of the considered CCS projects, the transport of CO_2 from the capture site to the storage site will take place through newly built pipelines. The majority of the storage sites in the projects considered are related to natural gas production, one site is also related to oil production. None of the natural gas or oil production sites are abandoned yet. In addition, two aquifers are also selected for CO_2 storage.

Permitting of CO_2 capture and storage projects

At least ten Dutch acts and regulations are deemed to be relevant for CCS projects. Based on the responses to the questionnaire, the total length of the permitting procedure seems to be between 2 to 3 years. As a number of interviewees (operators of CCS projects or parts of the chain of a CCS project) pledge for an ‘encompassing package covering CCS activities with a strong involvement of the government’, it is highly important that the authorities involved (government and/or province or municipality) realise that a strong involvement with facilitating of CCS projects does not allow unnecessarily lengthy permitting procedures. There have been unsatisfactory experiences with the permitting of the first few CCS projects. However, this was generally not due to specific laws or regulations but due to conflicting views on the requirements for CSS at different levels. This in itself makes the proposed ‘packaging’ an option to be seriously studied.

Environmental Impact Assessment

From the observations based on results of the questionnaire, it can be concluded that the non-CO_2 environmental impacts are considered relevant, however, are not yet in the picture as a major CCS issue or acceptance risk in the early stages where current CCS pilot projects are in. This assessment is primarily based upon the current properties of power generation technology, the general working mechanisms of CCS technologies and international literature. Nevertheless, information and support in the assessment of non-CO_2 environmental impacts over the full life cycle are welcomed.

Underground storage

Based on the results of the questionnaire it appears that standard procedures and processes for risk management are currently not available in relation to underground storage issues. This is probably due to the early stage of preparation of storage operations. None of the projects have started to operate and therefore knowledge on the procedures and processes, which will be tested during operation, is not yet available. Therefore, mostly general risk assessments have been performed and monitoring plans, abandonment plans and preventive and corrective measures are described in non-specific manners, if available.

Monitoring of emissions for the EU ETS

The general impression is that for most of the projects monitoring for EU ETS is not an important issue yet. Not only because of the stage of the project, but in some cases also because they don't feel responsible for it and leave this to the companies who will transport and store the CO_2.

There is some concern about the effect of a too comprehensive monitoring programme. Implementation of monitoring systems for all imaginable parameters could suggest that processes are not completely understood. And lay people could easily draw the conclusion that when measurements take place, there also something will be measured (think of CO_2 seepage to the surface). Measurements should take place only when it makes sense.

A template of a generic monitoring plan would be very welcome.

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WP4.2-D02, Proceeding Workshop on licensing activities

This document describes the first workshops of the five-year (2009-2013) research project (Mozaffarian *et al.*, 2010), that have been carried out within the framework of the CATO-2 program. The mission of the CATO-2 program is to facilitate and enable the integrated development of CCS demonstration sites in the Netherlands. The program's ambition is to help support the realisation of two or more demonstration sites where the complete integration of CO_2 capture, transport and storage will be demonstrated in the Netherlands before 2015.

The objective of this research project, CATO-2-WP4.2, is to identify best practices from permitting and certifying CCS activities at designated CCS sites in the Netherlands (offshore as well as onshore urban and rural areas). It will bring together all findings resulting from the project and make these available to a platform consisting of the site operators of the CCS projects, considered within the CATO-2 program. It will help in particular to resolve barriers of regulation, monitoring & verification, and public perception, and thus facilitating and enabling the introduction of CCS demonstrations, as well as a further development of CCS technologies in the Netherlands.

Within the framework of this CATO-2 project a questionnaire to the location managers of the CCS projects in the Netherlands has been prepared by the project partners (Mozaffarian *et al.*, 2010). It includes a.o., questions on general aspects of the operation, permit issues, environmental impact assessments, ETS monitoring, and risk management of geological storage. The questionnaire was made available on-line to 12 location managers, 9 of which did fill in the questionnaire.

In order to further an understanding of the responses, additional interviews (workshops), including additional questions, were conducted with the location managers.

In total 9 workshops were organized. The results of both the questionnaire and the subsequent workshops are described and discussed in Mozaffarian *et al.* (2010).

WP4.2-D03, Briefing on identified best practices in relevant networks

This document is the first briefing of the five-year (2009-2013) research project (Mozaffarian *et al.*, 2010), that has been carried out within the framework of the CATO-2 program. The document has been reviewed both by two project partners (TNO, ECN), as well as by the North Sea Foundation[2] (Stichting de Noordzee) and the Netherlands Society for Nature and Environment (Stichting Natuur & Milieu).

The mission of the CATO-2 program is to facilitate and enable the integrated development of CCS demonstration sites in the Netherlands. The program's ambition is to help support the realisation of two or more demonstration sites where the complete integration of CO_2 capture, transport and storage will be demonstrated in the Netherlands before 2015.

The objective of this research project, CATO-2-WP4.2, is to identify best practices from permitting and certifying CCS activities at designated CCS sites in the Netherlands (offshore as well as onshore urban and rural areas). It will bring together all findings resulting from the project and make these available to a platform consisting of the site operators of the CCS projects,

[2] See Appendix B.

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considered within the CATO-2 program. It will help in particular to resolve barriers of regulation, monitoring & verification, and public perception, and thus facilitating and enabling the introduction of CCS demonstrations, as well as a further development of CCS technologies in the Netherlands.

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There is some concern about the effect of a too comprehensive monitoring programme. Implementation of monitoring systems for all imaginable parameters could suggest that processes are not completely understood. And lay people could easily draw the conclusion that when measurements take place, there also something will be measured (think of CO_2 seepage to the surface). Measurements should take place only when it makes sense.

A template of a generic monitoring plan would be very welcome.

9.3 WP 4.3 Environmental performance of CCS chains

WP4.3-D01a, Preliminary environmental performance

The development of carbon capture and storage (CCS) technologies is considered as a key element to achieve significant reductions of CO_2 emissions in the medium and longer term. CCS technologies have been hailed as a clean and efficient means of electricity generation; however, general availability of the technology in a commercial market has yet to be realized. In particular, the development of CO_2 capture technologies for application in stationary power generation is being pursued towards commercialization by a number of global players. While the environmental benefits of the technology during operation are considered particularly attractive with current climate change concerns, it must be expected that these will lead future customers to scrutinize and demand environmental excellence across all aspects of the technology life cycle.

Environmental concerns are becoming an important factor in decision making, as society becomes more aware of the potential for lasting damage. International efforts to limit environmental damage have increased, as the global nature of many environmental concerns becomes apparent. Consequently, decision makers in both government and industry now give additional importance to the relative environmental impacts of their choices, and desire more detailed and accurate environmental information. As the technology moves from R&D to pilots and (larger) demonstration plants, the number of studies considering the potential effects of CCS

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technologies has raised significantly. The diversity in technologies, timelines and aspects treated make it, however, difficult to draw robust conclusions.

In this study an assessment of the existing literature is performed in order to gain insights into potential environmental effects, both negative and positive, of deploying CCS technologies. The results presented by 31 literature studies, that mainly use life cycle analysis (LCA) to evaluate the environmental impacts of CCS, are compared. This analysis has taken into account differences in scope, technology, reference system, time frame, system boundaries, and methodological aspects. The ranges in values reported are analyzed and factors influencing the ranges have been identified.

Most of the studies found in the literature focus on CO_2 capture by means of post-combustion capture with monoethanolamine (MEA) (especially for coal), followed by pre-combustion (IGCC) with Selexol. A number of studies elaborate on novel technologies (e.g. fuel cells, membranes, cryogenics), however, they tend to focus on the technological performance of the option and the level of environmental assessment is mainly limited to a partial LCA (gate-to-gate or cradle-to-gate). None of the literature dealt with the environmental effects of deploying CCS in the industrial sector. The analysis in this report focuses on post-combustion capture with MEA (both coal- and natural gas-fired), oxyfuel power plants with CO_2 capture and IGCC power plants with pre-combustion capture.

The impact of applying CCS on some of the environmental impact categories reported in the literature is summarized in TableTable. The ranges and their analyses are described in more detail in section 6 of this report.

The general trend shows that deploying CCS results on an increase in most environmental impact categories over the full life cycle of electricity production, except for the global warming potential. Several of the environmental impact categories show smaller relative increases for NGCCs compared to PCs. The higher conversion efficiency and the differences in the coal- and natural gas fuel supply chain are the main causes for this.

There are, however, a number of environmental impact categories where no agreement exists on the direction (positive, negative) or the level of the impacts due to CCS deployment (acidification, photochemical oxidation, human toxicity). Furthermore, the small number of data points for oxyfuel power plants and IGCCs with solvents makes it difficult to identify general trends for these technologies.

In terms of global warming potentials, the relative differences show a decrease in GHG emissions by 65-84% for PCs with CCS and by 51-80% for NGCCs with CCS compared to similar plants without CCS. With CO_2 removal rates at the power plant ranging from 88% to 95%, taking into account the complete chain results in a penalty of 14-23 percent points for PCs with CCS and 6-39 percent points for NGCCs with CCS.

Table– Ranges in several environmental impact categories reported for the various technologies with CCS compared to reference plants without CCS

Environmental impact category	PC + CCS MEA	Oxyfuel CO_2 capture	NGCC + CCS MEA	IGCC + solvents
Cumulative energy demand	19-44%	34-38%	19-22%	16-24%
Global warming potential	-65-84%	-78-97%	-51-80%	-68-87%
Eutrophication	19-170%	-43-78%	21-35%	40%
Acidification	-23 to 91%	-80 to 40%	23-150%	30%
Human toxicity	-30 to 260%	-20 to 30%	106%	25%

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Photochemical oxidation	-265 to 524%	-46 to 55%	20-52%	30-40%
PM10	2-60%	21-41%	45-55%	0%
PM2.5	15-23%	17-23%	34-36%	-
Ozone depletion	32-55%	29%	17-100%	24-33%
Abiotic resource depletion	30%	30%	18%	24-30%
Fresh water aquatic ecotoxicity	8-256%	41%	72%	24%
Marine aquatic ecotoxicity	27-93%	62%	-	-
Terrestrial ecotoxicity	42-57%	-17%	140%	24-48%

There are some aspects that play a role in the environmental impacts reported common to all technologies. These issues include:

System boundaries
Differences in system boundaries are found to be an important factor in explaining large variances in results provided in the literature. Not surprisingly, lower values are reported in studies with more limited life cycle boundaries. If indirect impacts, for example related with the transport of fossil fuels, are only partially accounted for, categories such as eutrophication and acidification will show lower values. For other impact categories, such as toxicity, the relation between system boundaries and level of emissions is consequently less distinct.

Energy demand
The energy penalty of CCS technology appears as the main driver for the increase shown for almost all environmental impact categories. For PCs, the increased fuel consumption per kWh, results in more emissions (SO_2, NO_x, methane) during the production and transport of coal. Also the emissions per kWh from the power plant are increased due to the decreased efficiency. And even though plants using MEA require higher removal of SO_2, NO_x, and particulates to avoid interference with the solvent, this higher removal is not sufficient to offset the increase in emissions due to the energy penalty. The increase in SO_2 and NO_x emissions from coal production, transport, and plant operation result in an increase in eutrophication, acidification and photochemical oxidation. Also increases in particulate matter emissions result from the energy penalty. For natural gas-fired power plants, the effect of the energy penalty on these environmental impact categories is generally smaller than for coal-fired power plants, due to their higher efficiency and lower emission levels of SO_2 and particulates.

Furthermore, the increased use of (transport) fuel results in an increase in abiotic resource depletion and ozone depletion. For coal-fired power plants (PC, oxyfuel and IGCC), the energy penalty also results in an increase in heavy metals emissions, mainly formed during coal combustion. This results in increases in toxicity (fresh water, marine, and terrestrial).

The increased consumption of steel for the CCS system (e.g. infrastructure), and especially the metal emissions from its production, results in net increases in toxicity (fresh water, marine, and terrestrial), ozone depletion and abiotic resource depletion.

Coal type
The analysis indicates that the type of coal used (hard coal or lignite) has an effect on both the global warming potential and photochemical oxidation potential of PCs and IGCCs. This effect is already present in power plants without CO_2 capture. A higher CO_2 emission factor and typically lower plant efficiencies of lignite-fired power plants result in about 10% higher GHG emissions compared to hard coal-fired plants.

When equipping power plants with CCS, indirect emissions are typically increased due to the energy penalty of the CO_2 capture process. Lignite-fired plants are often located near-by the

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mining site and therefore have lower transport related emissions than hard coal-fired power plants. For this reason, the GHG emissions from the lignite-fired power plant appear to be further reduced than the emissions from hard coal-fired plants when implementing CCS. This is translated into an average of 30% lower GHG emissions for the life cycle of lignite-fired power plants with CCS compared to hard coal-fired power plants with CCS. The impact of coal winning and transport of hard coal offset the impact at the power plant. The effect of coal type is also seen in the studies focusing on oxyfuel power plants with CO_2 capture.

The larger share in upstream emissions for hard coal-fired plants, partly due to the larger transport distances, is most probably also the main cause for the difference in photochemical oxidation potential observed for lignite- and hard coal-fired power plants. The SO_2 emissions from hard coal transport contribute to the higher photochemical oxidation potential value of hard coal-fired plants. However, the lower sulfur content of lignite and the subsequent lower direct SO_x emissions from the power plant are also contributing factors.

Solvent use

The production and degradation of MEA appears to significantly contribute to increases in several environmental impact categories. The emissions of NH_3 due to the production and degradation of MEA is an important contributor to increases in acidification and eutrophication. Furthermore, human toxicity and fresh water aquatic ecotoxicity are partly increased by the ethylene oxide emissions from MEA production. Metal emissions (from e.g. steel and ammonia production) cause an increase in ecotoxicity (both fresh water aquatic and terrestrial).

Increased consumption of fuel and natural resources due to the MEA production chain (e.g. ammonia, iron ore) contributes to increases in photochemical oxidation, ozone depletion and abiotic resource depletion.

The studies considering other solvents, such as MDEA, Selexol and Rectisol, show not such clear effects. The environmental impact of these solvents seems smaller than for MEA, but the number of studies is considerably lower and therefore further research is needed.

Final remarks

This study aimed to provide a first structured review of literature on the environmental impacts of CCS deployment in the life cycle. The value added of this report lies in the understanding of the key factors that drive an increase or decrease in environmental impacts. From a methodological point of view, life cycle analysis is a valuable tool to identify environmental impacts. Its value, however, is strongly dependent on the quality of the data used and on the ability of the researchers to clearly report the assumptions and parameters that are used. Unfortunately, several studies published in peer reviewed literature are not transparent enough making it difficult to perform a comparative analysis such as the one aimed for in this study.

Nevertheless, the environmental impacts over the full life cycle of the CCS chains researched are for most impacts clear and understandable. In general, we conclude that CCS provides a trade-off between greenhouse gas mitigation in the order of 80% (for coal) and a (moderate) increase of most other environmental impacts due to additional energy consumption for capture, transport of fuels and solvents and emissions from some of the solvents. The sometimes large ranges often indicate that specific regional or technical issues influence the overall environmental performance of a chain. This requires further research.

The analysis in this report covered studies available in the open literature and, therefore, there are geographical and technological characteristics, which do not necessarily fit the specific situation of the Netherlands. However, since the full life cycle is taken into account, many of the

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indirect effects (e.g. fuel exploration, transport, and infrastructure) will be located outside the Netherlands and are likely to follow international trends.

The comparative analysis of literature studies has shown that first generation capture technologies are well studied. The main focus of currently available LCA studies is on pulverized coal-fired power plants using MEA for capture. IGCCs with pre-combustion are studied to a lesser extent. Nowadays a shift in focus is observed towards other solvents (than MEA), which is partly due to the available information on the environmental impacts of MEA.

Finally, the analysis indicates that for many environmental impacts and technologies, especially first generation, there is agreement on the direction of potential impacts due to CCS implementation (i.e. net increase or decrease). Differences in data and or system boundaries result, however, in (sometimes) large uncertainties with regard to the levels of the impacts. Disagreements on the direction *and* level of potential impact are the most evident for categories such as (human, terrestrial, aquatic or marine) toxicity, acidification and photochemical oxidation. For toxicity impact categories this is mainly due to lack of data and knowledge gaps in the behaviour of some (new) substances into the environment. These kinds of uncertainties can only be reduced by a better understanding of the relations present, which can only be acquired by experimental research. In other categories it can be the result of methodological choices, which could be reduced by improving reporting standards

WP4.3-D01b, In depth study of specific themes

A part of CATO-2 Work Package 4.3 aims to find insights in the environmental impacts of carbon capture and storage chains. Certain environmental themes of Carbon Capture and Storage (CCS) technologies such as the emissions related to the production and use of solvents, waste & by-product formation, emissions to water and water consumption are relatively less investigated in the pertaining literature and have not been highlighted in existing overview studies up to now.

It is the goal of this paper to review the existing data on these aspects for CO_2 capture technologies applied on power plants. The review is based on a literature review and is provided with information from ongoing projects to indicate the current standings of knowledge on the subject.

Literature data on these specific subjects appeared to be scarce. Hence, data from field experiments (pilot and demo plants) and expert opinions on these themes are highly recommended and welcomed by the authors.

On the basis of the currently available literature, the following conclusions can be drawn:

Solvent related emissions from the CCS chain

- There is a growing awareness on the possible environmental impacts of CO_2 capture. Focus of the current research in this field is on post-combustion carbon capture using amines, which could lead to the emission of carcinogenic nitrosamines.
- Theoretical studies on the formation of nitrosamines are available. Measurements campaigns are running, but the availability of data is very limited and/or confidential.
- The emissions to air from the production process depend on the type of solvent produced and show a large variation in NH3 emissions.
- Large amounts of waste are produced by CO_2 capture process. As a first estimate, 1 tonne per hour will be produced in an average power plant. From a technical and economic point of view, the incineration does not seem to be a large issue. Although it is important that the

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capacities are available to handle large waste streams when CCS is employed at large scale. The incineration of waste creates additional emissions to air for which legislation maybe needs to be adapted.

Waste and by-products from CO_2 capture

- Waste formation is of relative less interest for gas fired power plants without capture. Post-combustion capture can result in significant additional waste formation depending on the technology variant chosen.
- Waste formation due to volume effects can be assessed accurately with the use of the energy penalty induced by installing the CO_2 capture installation.
- Waste formation due to post combustion capture process depends on solvent selection and process configuration. Detailed data on the formation and composition of wastes from CO_2 capture technologies are not available for most of the technology variants.
- Waste formation in oxyfuel power plants is still uncertain/unknown and is not quantified in the pertaining/consulted literature.
- Waste formation in pre-combustion capture seems to be very limited compared to post-combustion capture processes, but detailed data is lacking.

Emissions to water from CO_2 capture

- Emissions to water are of relative less interest for gas fired power plants without capture.
- There is relatively modest data known to be available on emissions to water bodies due to CO_2 capture, apart from volume effects (due to energy penalty). That is, it is possible to estimate the change in emissions due to increase in primary energy demand. It is however not known what the exact effect is of CO_2 capture technologies on the composition of waste water effluent.

Water consumption from CO_2 capture

- Overall water consumption for power plants depends strongly on the energy conversion technology, process configuration and on the applied cooling technology. It can in principle be assessed with high accuracy. When equipping power plants with CO_2 capture technologies the overall water withdrawal and consumption is expected to increase due to additional cooling water demand and process water demand. This holds to a lesser extent for oxyfuel power plants for which the water balance changes due to changes in the combustion process and flue gas cleaning technologies.

WP4.3-D01c, Economic valuation of environmental impact

The present study provides an overview of methods to assess and evaluate external effects applied within the context of energy-related and environmental issues. External effects from power generation are usually addressed as part of an analysis in order to compare the effects of several technologies. A methodological framework can also be used to compare the effect of a (policy) measure. The present study reviews a number of methodologies to include external effects (from power generation) in the standard economic assessment.

One of the methodologies used to assess external effects (from power generation) is *multi-criteria analysis* (MCA). MCA enables the researcher to include both quantitative and qualitative criteria to evaluate a (power generation) technology. Quantitative and qualitative scores on criteria are neatly summed up to result in an overall evaluation score of different technology options. Another characteristic is that the methodology can show the different valuations for the assessed criteria by all stakeholders involved. By varying the weight of the criteria along with stakeholder or perspective, MCA results in a ranking of technology options.

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MCA has been used until this date predominantly for the assessment of energy policies, e.g. with regard to planning in general, renewable energy, or bio-energy. MCA has several advantages. Firstly, the researcher is able to use all types of input data in the analysis: the input information does not need to be quantitative in nature. Any type of information can be combined: MCA acknowledges the multi-dimensionality of input data. Secondly, MCA allows for policy measures to be assessed with respect to the performance on more than one goal. It can accommodate goals such as sustainability, health and equity. This feature is especially important when issues are adressed where other goals than efficiency (affordability) are highly relevant. This could for example hold for issues of sustainability where the equity across current and all future generations is deemed relevant.

Thirdly, the method can explicate the valuations of different stakeholders for a particular ranking of policy measures based on different weighings being attached to the defined criteria. For example, regarding the evaluation of allowing for oil and gas production in the Waddenzee, Greenpeace and the NAM are likely to have different valuations of the criteria defined under the policy goals of efficiency and affordability on the one hand, and sustainability on the other. Normally, when applying other types of evaluation methodologies, these preferences remain implicit and result in for example a different calculation of the ‘probability times effect’ of oil production permanently damaging the environment.

MCA is a useful tool for setting priorities in energy policies. Therefore, it is possible that MCA may give a view on advantages and disadvantages of including CCS in the policy mix. Comparison between different options within the scope of Carbon Capture and Storage (CCS) technologies may, however, not be easily addressed based on MCA.

Alternatively, the researcher may use the *cost-benefit analysis* (CBA) methodology. CBA is a well-known framework for evaluation of impacts of technologies. It is a monetary evaluation of the expected costs and benefits of a technology. CBA not only analyses the internal direct costs and benefits of the technology, but also the indirect and external costs and benefits. Cost-benefit analysis is a useful and rather straighforward tool in case of monetary *quantification* of external costs and benefits. The extent to which CBA provides a useful tool for evaluation of a specific (power generation) technology depends on the availability of data, methodologies to quantify external costs and benefits, etc.

CBA has been used for various energy and climate related issues, such as the relationship and synergy of policies focused at reduction of GHG emissions and local air pollution, the costs and benefits of nuclear power to the UK, etc. CBA is widely applied in the field of energy and the environment due to several advantages, although it also contains some serious drawbacks. The general beauty of CBA is the clear rationality behind it and the general transparency with regard to its underlying assumptions and methodological framework. In addition, it appeals to decision-makers because of the capability of bringing together all sorts of qualitative and quantitative information into one monetary value. And finally, the discipline with which the CBA lists the different costs and benefit items, covering all internal and external, and direct and indirect effects is considered an amenity.

CBA is useful for evaluating the costs of various energy alterntives based on quantification of external costs and benefits. Therefore, CBA may be a straigtforward way to detemine the costs and benefits of fossil fuel based electricity generation *with* and *without* CCS. The accuracy of the resulting costs and benefits depends not only on the methodology used but also on the accuracy of the cost data, which may be a problem for some external costs.

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Besides, there are *methodologies* to assess or evaluate potential impacts during stages of the life cycle of a power plant. If there is a need for monetarisation of impacts, the methodologies used for economic valuation that are distinguished are based on *avoidance costs* or *damage costs*. Traditionally, the policy debate on climate change has focused on the cost of emission mitigation, e.g. the cost of GHG emission reduction. Whereas the costs of emissions of local/regional pollutants may be based on *damage costs* as the impacts are mainly local or regional by nature, and the temporal extent may also be limited, the impacts of GHG emissions are global and long-lasting (up to hundreds of years).

The methodology denoted as 'avoidance costs' focuses on quantification of the *abatement costs* (instead of damage costs). Mitigation costs of GHG emissions use to be based on abatement costs, e.g. in the updated impact pathway approach or ExternE methodology, as a proxy for environmental cost (external cost) analysis. For the determination of damage costs a methodology was developed on behalf of the European Commission to quantify the *energy external costs* (ExternE). The research resulted in the development of a methodology called the *Impact Pathway Approach*. This approach to quantify environmental impacts is described in the ExternE research program (Externalities of Energy).
Four main steps are distinguished:

- Emission: specification of the relevant technologies and pollutants.
- Dispersion: calculation of increased pollutant concentrations in all affected regions.
- Impact: using exposure-response functions for calculation of impacts cumulated exposures.
- Cost: valuation of impacts in monetary terms.

Therefore, the methodology denoted as 'damage cost' aims to quantify potential environmental impacts based on quantifiable damage costs incurred by humans, flora and fauna, buildings, etc. from emissions (to air, water, soil) that arise in case of a specific (power generation) technology. Whereas the ExternE methodology originally focused on GHG emissions, (local) air pollution and radio nuclides, recent extensions of the methodology address land use change, cultural heritage, impacts on building materials, biodiversity, visual impact, and noise.

The ExternE methodology may be applied to CCS. 'ExternE' has the advantage that it draws on a relatively long history of quantification of external effects (from power generation). It is used as a corner stone for development of sustainable energy policies. Also, it enables the researcher to take into account long-term effects from power generation, e.g. the effects of GHG emissions. Limitations of the ExternE methodology relate to the geographical area considered, limitations with regard to dispersion and with regard to impact category.

WP4.3-D02a Monitoring and exchange plan

This report was aimed to be the second deliverable "Environmental monitoring and exchange plan for the CATO-2 sites" (CATO-2-WP4.3-D02) of Work Package 4.3 "Environmental performance of CCS chains".

In contact with partners from the pilot projects in the CATO-2 project and the project management of CATO-2 (Jan Hopman), it appeared that an environmental monitoring and exchange plan for the CATO-2 sites is premature. Instead, it was proposed to select a number of relevant issues to perform in-depth focus studies on. In the modified work plan of WP4.3 (as in the AD-03 Program Plan of 2009.09.29), the deliverable for year 1 has been formulated as follows:

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"Definition study of in-depth cases: description of selected case studies on specific environmental issues such as amine impacts, LCA of solvents and measurements of toxicity of emissions and waste."

However, the list of deliverables had not been updated, incorrectly referring still to an "Environmental monitoring and exchange plan for the CATO2 sites". Hence, this deliverable CATO-2-WP4.3-D02a is fulfilling the administrative requirements for that.

Deliverable CATO-2-WP4.3-D02b "Focus issues for further study" is meeting the ideas and planned deliverable of the modified work plan of WP4.3 (as in the AD-03 Program Plan of 2009.09.29).

WP4.3-D02b Monitoring and exchange issues

This report describes the way how we gathered and selected in-depth environmental focus issues for further study in CATO2 WP4.3 in the next years.

A list of possible in-depth environmental focus issues for study in the next years of WP 4.3 Environmental performance was presented to and supplemented, discussed and ranked by a group of stakeholders from the CATO-2 project in a computer supported environment (the so called Policy Lab). The group of 8 persons present represented a variety of stakeholders stemming from pilot plants on capture and storage, research institutes as well as NGO's. However, the group was too small for being a representative group. So, the input from the group should be considered more as useful information and arguments, not as "the truth".

The results of this session can be summarised as follows.
The following items on the list of possible focus issues already have been and in the next phase will continue to be taken into account in the WP 4.3 tasks:

- A thorough environmental comparison of pre-, post- and oxyfuel combustion capture technologies,
- an assessment of most important environmental aspects for CCS, including weighting, as an input for a strategic Environmental Impact assessment and
- a verification of the large effects of methane leakage on GWP over the lifecycle of CCS at natural gas fired power plants.

We consider it as a support that the first two subjects are scored as so relevant, since these are at the core of the WP 4.3 research.

A number of other issues on the list will be taken into account explicitly in the tool to perform an environmental performance analysis for user defined CCS chains:

- chemical emissions and waste from amines,
- water use, depletion and pollution,
- environmental impacts due to leakage of CO_2 and
- the valuation of by-products (ashes, sulfur, gypsum) of different types of coal fired power generation.

Main reason is that these impacts (waste, water, leakage) were scored as important for CCS and we are able to include these in the tool. Additional attention should be paid to inclusion of risk concepts as investigated in WP 4.4 Risk management of CO_2 transport and WP 4.5 Risk management of CO_2 storage.

From the list, two in-depth focus issues have been selected. These focus issues will be researched in an in-depth study by literature study, in interaction with the relevant CATO-2 Work

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Packages. Also, several international programmes and projects on these issues will be taken into account.

The selected in-depth focus studies are:
a) Environmental screening of second generation CO_2 capture technologies;
b) Assessment of environmental impacts over the life cycle of solvents used in CO_2 capture.

For both issues, the research will be conducted by the following tasks:
1. International literature survey on different technologies / solvents (year 2 and 3)
2. Collection of data in database per life cycle stage (year 3)
3. Technology outlook for short and long term (year 3)
4. Presentation of intermediate results to CATO-2 stakeholders (year 3)
5. Environmental performance assessment in terms of environmental legislation and environmental and health impacts (year 4)
6. Criteria setting for future developments (year 4)

According to the work plan, the in-depth focus issue reports for the selected environmental research subjects will be published at the latest at the end of year 4.

WP4.3-D03, information exchange platform

The WP 4.3 (Environmental performance of CCS chains) aims to:
- Assess the environmental performance of CCS technologies over the complete life cycle
- To deepen the insight of all CATO2 partners in the other (non-CO_2) environmental aspects of CCS in general and capture in particular by enlarging the amount of available and accessible data
- Provide input that would be required to carry out a strategic environmental impact assessment (SEA) for CCS in the Netherlands

An Information Exchange Platform is created on the CATO-2 SharePoint. The SharePoint is hosted by TNO on a secure TNO server, facilitated by TNO IT services.

The Information Exchange Platform offers the possibility to organize and exchange location and/or technology specific data on environmental performance and regulation on a confidential data exchange platform where specific parts are accessible by specific CATO-2 partners only. Up to now, all WP4.3 information and data is available on the Information Exchange Platform. The intensity in usage will increase in the years 2- 5 when more and more location specific information data will be gathered.

WP4.3-D04 Environmental database

In this document we present an overview of the role, structure and content of the environmental performance database of energy conversion supply chains including carbon capture and storage. The database is an important part of Work Package 4.3 on the environmental performance of CCS chains. The database functions as a platform where the data on the environmental performance of CCS technologies and the other steps in the life cycle will be gathered, prepared and stored. Several chains will be analyzed in the environmental performance tool, which will also be developed within this WP. The database forms the basis of this tool.

In the database, we collect the data for several environmental performance indicators for a broad set of environmental themes. The themes that are currently considered in the database are

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Energy and Climate, Air, Water (consumption and pollution), Waste and by-products, and Land use. The data is derived from literature and monitoring results of worldwide CCS demonstration sites.

The database is designed so that it should be easy accessible for the WP partners and for third parties that request data on the environmental performance of (parts of) the life cycle of CCS chains. The database is not directly publicly available and not available for other CATO-2 partners during the development phase. Data requests can however always be submitted to the WP partners. CATO partners and others are very much encouraged to share environmental information with the WP partners so that it can be included in the database

9.4 WP 4.4 Risk management of CO_2 transport

WP4.4-D01, Literature study on release and dispersion models for accidental releases from CO2 pipelines

In CCS (Carbon Capture and Storage) the CO_2 that is produced by (large) power plants is captured and transported to a location where it can be stored. Most likely the production and storage are not at the same location. The produced CO_2 needs to be transported; one of the options for transport is by pipelines.

For the transport of hazardous substances, risk analysis studies need to be performed. For these studies standard procedures and models have been developed. In principle these should also be used for CO_2. However, this is not straightforward. CO_2 behaves differently on outflow than most other substances as no liquid CO_2 exists at room temperature and ambient pressure. In addition, some physical properties of CO_2, like the probit function, are unknown. This complicates the calculation of the risks to which the population is exposed with the currently available models.

A literature search has been done on modelling the physical effects and the subsequential risk of the accidental release of CO_2. The state of the art is described and open issues with respect to modelling the effects of CO_2 are documented.

The most important open questions within the modelling of the effects are all related to solid CO_2:
- Where and when is solid CO_2 formed, inside or outside the pipe?
- Is a meta-stable liquid possible, so that solid CO_2 is only formed outside the pipe?
- How does solid CO_2 influence viscosity, surface tension and other fluid properties?
- If solid CO_2 is formed, in what shape (pallets or flakes) will it be and what is the size? And will the formed solid CO_2 rain out or remain air borne?
- Does the discharge of CO_2 require other models than normal or will it only require a change of model parameters?

Also more general open questions are found on atmospheric dispersion:
- Which type of model to use: more complicated CFD or more standard dense gas dispersion model?
- How to incorporate the atmospheric boundary layer in CFD calculations?

For QRA studies on CO_2, the following data is not readily available:
- Dose-effect relation or probit function

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- Failure frequency of pipelines

Based upon these open questions on modelling the release and dispersion of CO_2 the following recommendations are made.

- First, experiments on the discharge and dispersion of CO_2 should be performed. This will give insight into the physical processes. These experiments should be done both on a large, real-life scale as well as on a smaller, lab-scale. The results can be used to validate existing models that have been adapted to perform calculations on CO_2 or for newly developed models.
- The adaption and development of the models is the second area where work should be continued. This is not just a scientific or academic exercise, it will lead to better models for risk assessment in concrete situations where CCS is likely to be implemented.

WP4.4-D02, Literature review of CO2 impacts on humans and the environment

The aim of this CATO-2 study is to provide an overview of the current status of knowledge of the impact of (accidental) CO_2 release on the environment. An additional focus of this report is to gather all available environmental (terrestrial and marine) effect data. This data is to be used in an impact assessment based on a probabilistic approach using so-called probit functions and species sensitivity distributions (SSD).

It has been found that the reviewed effect studies are seldom focused on release from reservoir storage, but on ocean storage or increased atmospheric concentration (greenhouse effect). This limits the suitability of the data for risk assessment, because of e.g. different routes of exposure and exposure concentrations.

The available studies cover only a limited part of the potential exposure of the terrestrial and aquatic environment to CO_2 caused by release from reservoir storage. The scenario's that can be drawn for leakages of CCS show that not only the effect of CO_2 will be imported but also the effect of less O_2, the effect on pH and redox. As many of these parameters also show variation in time and space and are not in all cases detrimental, it is important to make a distinction in risks of CO_2 (additional stress due to CO_2 leakages).

A database with CO_2 effects on aquatic species is composed. Effect values based on acid toxicity, i.e. exposure to decreased pH by acids such as HCl instead of CO_2, are not included in the database. Based on these data and existing guidelines, a quality assessment of effect data is developed for the use in probabilistic ecological risk assessment (i.e. SSD) of CO_2 exposures.

Cut-off criteria have not been developed in this study. Instead, the elements for quality assessment are given, including a preference for the required data. Based on these elements and preferences, cut-off criteria could be developed in a follow up study. By applying cut-off criteria, all values that are considered unsuitable are discarded.

It is concluded that the results of a probabilistic ecological risk assessment of CO_2 exposures can thus only be used as an indicative tool but should not be used to estimate or correlate to field effects.

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WP4.4-D03, Detailed proposal for the release and dispersion

In WP4.4 a risk assessment model for the accidental release of CO_2 from high pressure pipelines will be developed. Important in the risk assessment model is the development of model for the accidental release of CO_2 from high pressure CO_2 pipeline and the modelling of the dispersion of the released CO_2. This document describes the set up of a release and dispersion experiment to validate the models that will be developed. The basis of this document is the literature study on release and dispersion model for accidental releases from CO_2 pipelines (D.4.4.01, RD-01). In the literature study an overview is given of missing data and interesting experiments, that have been be used as input for this global proposal for release experiments.

This proposal for a validating experiment is also based on an exchange of information between WP2.1 and WP4.4. In WP2.1 experiments are being developed to study the behaviour of CO_2 inside the pipe line or near a hole in the pipe. With a small extra effort also information on the dispersion of CO_2 in air can be obtained, which is of interest for WP4.4. The current document is meant as a starting point for further discussions with WP2.1 on the actual experimental set-up and test-plan.

In this document it is proposed to have a lab-scale experiment with a release time long enough to measure transient phenomena. A large vessel (or pipe) with a small hole will meet these requirements. Typically the vessel should be $1m^3$ and the hole 10 mm diameter. With these numbers reasonable measuring times can be obtained, the total outflow process will take about 100 sec for this geometry. Increasing the hole size decreases the release time. Decreasing the hole size may make the situation less realistic and applicable.
It would be interesting to be able to measure with a few sizes of outflow diameter.

The physical conditions in the experiment should represent actual operating conditions in a pipeline, i.e. around 100 bar and 20℃. Ideally bot h temperature and pressure should be variable in the experiments.

A more detailed design of the experiment will be made in cooperation with WP2.1. in the 2nd year of CATO-2.

WP4.4-D04, Theoretical model for outflow of CO_2 and dispersion

Based on WP4.4.D01 the development of new physical models for the release and dispersion of CO_2 is started. The whole release process is divided into 5 steps:

- source region, inside the pipeline
- expansion region
- turbulent jet, entrainment
- passive, dense gas dispersion
- dry ice bank sublimation.

Each of these processes has its own open questions. These can be specific for CO_2 or more general. Each process will be studied in turn to improve the existing models to apply them to CO_2. When this is not possible a new model should be developed.

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This progress report describes the results of the first process that has been studied: the dry ice bank sublimation. Two methods for calculating the sublimation of a dry ice bank have been studied: models in the software Effects 8.1 and the model described in [Mazzoldi2008]. The results from the two methods are in the same order of magnitude and differ at most a factor of 2. Unfortunately no experimental data are available to compare them with.

Experiments are needed to validate both methods. Until experimental data become available the current models are sufficient to give an estimation of the amount of CO_2 that sublimates.

9.5 WP 4.5 risk management of CO_2 storage

WP4.5-D01, Technical report describing the draft workflow and tools for qualitative and quantitative risk management including uncertainty analysis

CATO-2 program's mission is to facilitate and enable the integrated development of CCS demonstration sites in the Netherlands. Work Package 4.5 aims to develop and test risk management methods and tools supporting the qualification and certification procedures for long-term safe and effective CO_2 storage during all phases of the storage lifetime. During the first project year (CATO-2A Programme Plan) the concept of risk management and the overall workflow and related tools were described (ECN). The procedure for developing a monitoring plan was elaborated the concept for a monitoring planning tool was developed including the evaluation of the tool concept on the basis of the Barendrecht monitoring plan (TNO).

Risk management acts as the central driver for all safety related activities, just as stipulated by the EU guidelines. Although developing a risk management plan in itself is not a legal requirement, most of the components (Site characterisation and risk assessment, Monitoring, Preventive and corrective measures) are required or will be required once the CCS Directive is ratified. The CCS Directive as such does not include a definition of risk management; nevertheless most technical elements of the ISO 31000 definition of risk management are included in the Directive. The ISO 31000 communication and consultation plan, and the context for the risk management process need more visibility in the CCS Directive, since they are not addressed.

In setting up a *monitoring plan* the following main categories were identified:

- Mandatory (for all sites) monitoring: A number of parameters to be monitored is mandatory based on the storage directive.
- Required (site specific) monitoring: This monitoring group is directed to gathering evidence for containment in the reservoir and to demonstrate integrity of seal, fault and wells in case of regular development.
- Optional contingency monitoring: The third group refers to a contingency monitoring system which will only be called in action if irregularities show up.

The *concept* for the monitoring planning tool, which will be built around a database with risk factors and parameters and a database with monitoring techniques and parameters is supporting the development of risk-based monitoring plans. The tool is driven by site-specific characteristics, selected Scenarios with risk factors (FEPs), risk index and the time and space frames of the scenarios/FEPs. The analysis of the Barendrecht monitoring plan shows that a risk assessment based work flow is feasible. The mitigation action plan might be a useful addition to the

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Monitoring Planning Tool that we are proposing here. In that case we have a complete Plan-Do-Check-Mitigate cycle.

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10 SP 5 Public Perception

10.1 WP 5.1 Local communication near CCS

WP5.1-D01, Progress report on the procedure and the resulting information on attributes of the CCS demonstration project which is according to the SSC (Stakeholders and Scientists Committee) balanced, relevant and comprehensible information (actual report to be delivered in Month 15 after start, that is, after decision on onshore CO2 storage location/transport route

This progress report describes activities and developments within WP5.1 in the period June 2009 – August 2010. After various meetings with location managers, companies, and government officials, it was decided that the full WP5.1 intervention program will be applied (research and public communication and (when needed) public mediation) in the Northern Netherlands, and that repeated surveys on public awareness, public perception and/or public opinion will be conducted at two locations in the Western part of the Netherlands. However, the selection of 1 CO_2 storage location in the Northern Netherlands will be known by the end of 2011. Therefore, we are not able to report on the developments of the proposed SSC - Stakeholder and Scientists Committee - procedure, which can only start after the ultimate choice of 1 location has been made (note that a progress report on these developments is scheduled for 12 months after the ultimate choice of 1 location has been made). Nevertheless, we have already started some of the WP5.1 activities in the Northern Netherlands, namely with respect to identifying criteria and preconditions for setting up this Stakeholders and Scientists Committee.
Furthermore, we have conducted a first survey on public awareness, public perception and public opinion about CCS in the Northern Netherlands (administered by TNS-NIPO to a representative sample of the Dutch general public – N = 1109) – and a sample of people living in the Northern provinces – N = 349), and we designed and conducted two other surveys in the Western part of the Netherlands (N = 801 and N = 811), again administered by TNS-NIPO. Finally, in this progress report we discuss the developments of the media log (started in June 2009 and ongoing) that covers local media attention at the selected locations.

WP5.1-D02, Report on survey among residents: results and implications for decision procedure and communication campaign

This report presents the results of the first study on public knowledge and awareness of CCS in general, public trust in CCS stakeholders, and initial public perceptions of CCS activities planned for the Northern Netherlands. Because the location for CO_2 storage in this region is not yet known, it was not possible to administer a survey to people living near such a planned storage location and ask them about their perceptions of these plans in the context of other local issues. Therefore, we administered a traditional survey to a representative sample of the Dutch general public (N = 1109) and to an additional broad sample of people living in the Northern Netherlands (N = 349) to examine levels of public knowledge and awareness of CCS, trust in CCS stakeholders, and *initial* public attitudes toward CCS activities planned for the Northern Netherlands. Such initial public attitudes are proven to be highly unstable because they are based only on the very little amount of information people had at their disposal when they were asked about their opinions, which is

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why a traditional survey is not particularly suited to assess public opinions on CCS. However, the survey is suited to examine public knowledge and awareness, and public trust in stakeholders. The results of this survey show that public knowledge and awareness of CCS is quite low; 50% of the respondents indicated to have never heard of CCS, and only 2.6% of the entire representative sample is able to correctly indicate both which environmental problem CCS aims to address and which environmental problems CCS does *not* address (for more details on public knowledge and awareness, see Sections 1 and 2).

Second, the results show that on average, both people living in the Northern Netherlands and people living in the other Dutch provinces trust knowledge institutions most (with a mean score of M = 5.09 on a 7-point scale ranging from 1 = *no trust at all* to 7 = *very much trust* for the Northern sample and M = 5.04 for the other Dutch provinces), followed by environmental NGOs ($M_{northern}$ = 4.50 versus $M_{other\ provinces}$ = 4.62), while government bodies ($M_{northern}$ = 4.30 versus $M_{other\ provinces}$ = 4.20) and companies ($M_{northern}$ = 4.36 versus $M_{other\ provinces}$ = 4.15) are trusted least. With regard to specific companies, people living in the Northern Netherlands tend to be relatively trusting the companies involved in CCS activities in the Northern Netherlands (e.g., Essent, Gasunie, NAM, NUON) with mean trust scores varying between M = 4.69 and M = 4.96, although RWE is trusted less (M = 4.08). Also, while trust in environmental NGOs on average is quite high, people living in the Northern Netherlands are particularly trusting WWF (M = 5.26; for more details on public trust in specific CCS stakeholders, see Section 3). Finally, the results indicate that initial public attitudes toward CCS (i.e., toward CCS in general and toward CCS activities planned for the Northern Netherlands) are, on average, neither extremely negative nor extremely positive (mean score around 4 on a 7-point scale). People living in the Northern Netherlands seem a bit more negative about CO_2 transport and storage (but not about CO_2 capture) in this region as compared to people living in the other Dutch provinces (for more details on initial public attitudes, see Sections 4 and 5). All in all, this study is a relevant first step for future research and interventions within WP5.1 and provides support for the proposed procedure how to introduce a CCS project in a local community and how to communicate on this project. Within WP5.1 subsequent surveys will repeatedly be conducted once the actual CO_2 storage location is known.

WP5.1-D03, Only in case of a strong public controversy, a progress report on the convening assessment as a start for an integrated approach (planning procedures and research) for public mediation regarding decision making on CCS

The decision where CO_2 will be stored in North Netherlands is expected not (long) before summer 2010. Only after this decision, the local SSC procedure can be started. On 31 August (due date), the SSC procedure (duration 1 year) just started so a progress report might be premature.

10.2 WP 5.2 Framing effects in communication about CCS

WP5.2-D01, Progress report on first (half) year of this PhD project (including detailed research plan written by senior researchers)

This document contains the progress report on the first half year of the CATO-2 WP5.2 PhD project “Framing effects in communication about CCS”. In the first few months, PhD student De Vries has conducted a literature study, both on (factors that influence) public perceptions and acceptance of CCS, and on framing. In the last two month, De Vries has designed a first study. This study consists of an experiment designed to examine how framing a company’s involvement in CCS in terms of economic benefits and/or CSR of the organization affects the corporate image,

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trust, and perceived "greenwashing" (deceit). Furthermore, this experiment serves to test the quality of newly developed questionnaires to measure these variables.
In addition, this document contains a detailed description of the research planned for WP5.2 written by senior (CATO-2) researchers from January on. The objective of the research planned for WP5.2 is to examine whether framing of communications by an organization can improve the perceived credibility and trustworthiness of the organization and the information provided. This issue will be examined by a combination of experimental studies and a survey-type study.

10.3 WP 5.3 Trends in public opinions on CCS

WP5.3-D01, Progress report on the public's awareness and knowledge regarding CCS and on shared misconceptions with implications for targeted communication to refute false beliefs

Public support can be crucial for the success of CO_2 mitigation policy, as recently demonstrated by the public's reaction to a CCS project in the Netherlands. It is imperative therefore to further study the public's perception of CCS in order to better understand their concerns and communicate more effectively.

Earlier research, both international as well as in the Netherlands, has shown people have limited awareness and knowledge of CCS (e.g. Reiner et al, 2006; De Best-Waldhober et al, 2008). In previous studies therefore researchers presented the respondents with information on CCS technology before asking for their opinion of CCS technology. In one of those studies in the Netherlands De Best-Waldhober et al (2008) used an Information-Choice Questionnaire (ICQ) to get insight into deliberated, informed opinions on CCS technology. Respondents were confronted with a policy-relevant decision problem where two CCS options were compared with other mitigation options such as improved energy efficiency, biomass, wind and nuclear energy. However, before choosing which mix of options they found most suitable, respondents were provided with well-balanced expert information on the most important consequences of each option. Results showed most people were slightly negative about this new technology, but hardly rejected possible implementation. Their evaluation of CCS was based to a large extent on the expert information about the consequences of CCS. Nevertheless, part of their evaluation is not explained by this information. Apparently, people base their opinion in part on other factors than the information provided.

These results raise several questions. First of all, if people are not informed, which beliefs do people hold about CCS? Which associations and misconceptions play a role in their evaluation of CCS? Also, which of these beliefs are commonly held by a substantial part of the public? Thirdly, how are these beliefs affected by expert information? Work Package 5.3 of CATO-2, "Trends in public opinion", inter alia aims to generate more insight into the beliefs and misconceptions the public currently holds regarding CCS and CO_2. This document reports the activities in year 1 of this Work Package. During this first year, several measures were developed to gather the first data on these issues, which will be analyzed in year 2. The use of a large sample of the Dutch population allows detection of the prevalence of perception and beliefs regarding CCS amongst the public. Additionally, the effects of balanced expert information on pre-held beliefs are being studied, using an Information-Choice Questionnaire that was developed in CATO-1.

Furthermore, we are investigating the possible link between both media-events related to CCS and media use in general, and beliefs of the general population about this technology. In year 1,

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25 members of the general public were interviewed in-depth, 134 filled in the Information-Choice Questionnaire online and were interviewed face-to-face immediately afterwards, and 401 took the knowledge and beliefs test online. The first results show a substantial percentage of people have a lack of knowledge and quite a few misconceptions on CO_2, climate change, energy technology and the relations between the three.

10.4 WP 5.4.Resistance of valid beliefs about CCS against low quality information

WP5.4-D01 Progress report on first (quarter) of this PhD project (including detailed description of planned research written by senior researchers

This document contains the progress report on the first quarter of the CATO-2 WP5.4 PhD project “Resistance of valid beliefs about CCS against low quality information”. In addition, this document contains a detailed description of the research planned for WP5.4 written by senior (CATO-2) researchers from January 2010 on. The planned work for this work package is fundamental in nature, and aims to identify factors (i.e., communication procedures) that determine the resistance of valid beliefs about CCS against low quality information (e.g., in media reports) about potential consequences of CCS

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