

CO₂ CAPTURE, TRANSPORT, STORAGE AND UTILISATION



TNO innovation
for life

Reducing CO₂ emissions requires an integrated CO₂ management approach. The dependency between the different industry sectors is higher than commonly acknowledged and covers all areas; capture, transport, storage and utilisation. TNO is one of Europe's largest independent research organisations and provides applied science and technical and techno-economic consultancy services in a broad range of areas. TNO supports both industry and governments to develop innovative technologies that reduce emissions, reduce cost and increase efficiency, reliability and availability.

At present there is consensus that the global climate is changing as a result of increased atmospheric concentration of greenhouse gases such as CO₂. The emissions of CO₂ are directly linked to the abundant application of fossil energy sources.

Despite the efforts directed at the development and large scale application of sustainable energy, the world still heavily depends – and will depend in the next decades – on fossil fuels. The challenge is to develop technology options that allow for continued use of fossil fuels without substantial emissions of CO₂ through cost-effective capture and storage while maintaining industrial competitiveness in global markets. CO₂ capture, transport and storage (CCS) in geological systems could bridge the transition period required to further develop and implement sustainable

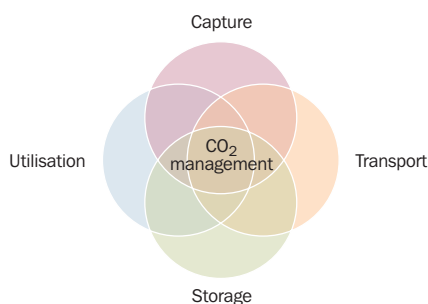
sources of energy. With renewable energy and energy efficiency, CCS constitutes a 'Trias Energetica' portfolio.

Although promising, CCS is not yet a mature, commercially available technology. The individual segments of the CCS chain build on proven technology that has been used in industry for years. However, operating and upscaling the integrated CCS chain requires additional research effort. CO₂ abatement, health, safety and environment (HSE), and cost-efficiency issues are the main factors determining the feasibility of CCS.

In the Netherlands, small-scale, mostly independent capture pilots and demonstrations of CO₂ storage are currently planned, under construction or ongoing. At present also large-scale demonstration projects are being prepared. These pilots and demonstration projects

provide the required knowledge and expertise for the commercialisation of CCS technology, which is due around 2020.

TNO holds extensive knowledge on the complete CCS chain and utilisation of CO₂ and TNO offers integrated CO₂ management services. TNO has tools available to simulate and test different scenarios and to deliver extensive in-depth support on the individual segments.



CAPTURE

In the transition to a low carbon-emitting economy by 2020, large scale deployment of post-combustion CO₂ capture is the most promising route to reduce greenhouse gas emissions from power plants, petrochemical, cement and other industries.

FAST DEPLOYMENT OF CO₂ CAPTURE SYSTEMS

The coming years are crucial to prove the overall performance and feasibility for large scale deployment of CO₂ capture. Instead of gradually implementing medium-sized capture plants, full scale units are constructed from 2011 onwards. This requires continuous evaluation and improvement of techno-economic objectives, assessment of HSE risks and fast response to emergencies.

- Technical and economic evaluation
- Validation of design using experimental testing and/or mobile mini plant
- Debottlenecking and troubleshooting.

INCREASE EFFICIENCY AND REDUCING COST

Optimisation of current capture processes is required to make CCS feasible. In co-operation with industry TNO develops new generation technology that will have a major impact on the energy efficiency and reduce overall capital and operational cost.

- Conceptual design of next generation capture systems
- Process and equipment optimisation
- Technical modelling and process design
- Economic modelling and value chain analysis.

HEALTH, SAFETY AND ENVIRONMENT

Similar to any other industry certain risks are associated with CO₂ capture. The main risk is the unintentional release of volatile chemical components or more hazardous reaction products.

- Chemical reaction and degradation mechanism studies and pilot plant validation
- Unwanted emission measurement
- Environmental impact analysis
- Life cycle analysis.



TRANSPORT

Where CO₂ capture is the most capital-intensive part of the CCS chain, transport – either by ship or pipeline – and storage are likely to define the critical path in the development of both small-scale and large-scale projects. The long lead time associated with the construction of pipeline systems, especially for cross-border projects, requires that planning starts well ahead of the capture, transport and storage of the first CO₂.

UPSCALING AND NETWORK MANAGEMENT

Future CCS infrastructure is expected to be a combination of single pipelines, connecting one capture plant with a single storage location, and more complex, networked solutions. TNO is working with industry to understand the behaviour of CO₂ in pipeline systems, to prepare for managing large-scale network systems.

- Upscaling transport solutions to the megatonnes per year level
- Understanding the behaviour of CO₂ in pipeline systems
- Developing requirements on mixture composition
- Network management and operations.

HEALTH, SAFETY AND ENVIRONMENT

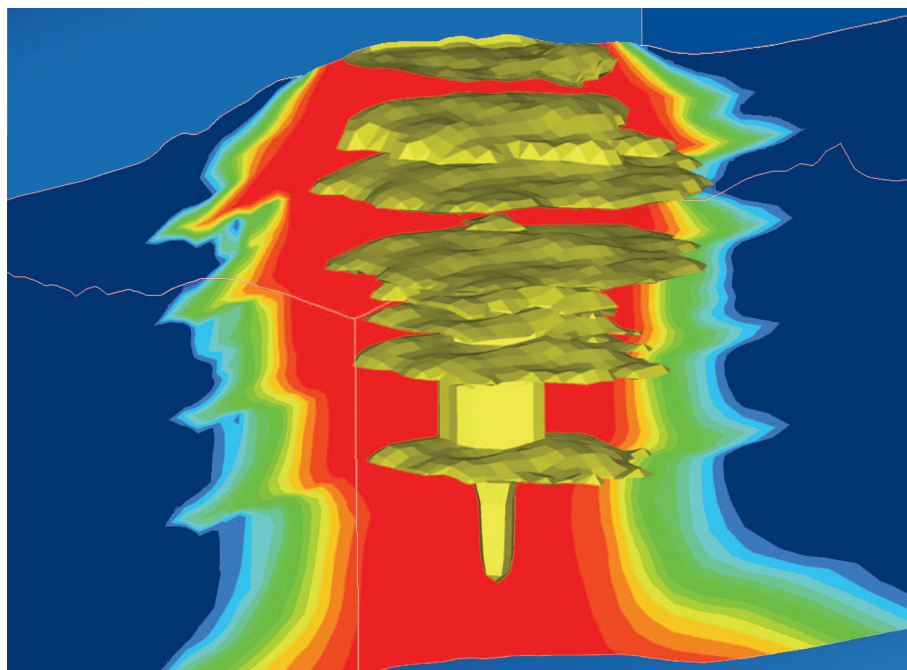
Cost-effective transport of CO₂ requires the CO₂ to be in dense phase, at pressures typically over 80 bar. In co-operation with industry, TNO is performing tests to further validate models of leakage and dispersion. Liability is an issue that needs to be solved in regulations, for multi-party CCS systems to become reality.

- Ongoing validation of dispersion models
- Recommendations on improving transport safety regulations
- Resolving liability issues in large-scale networks

PLANNING

The construction of networks to transport CO₂ requires careful planning and forecasting of current and future volumes. Minimising costs means over-sizing pipeline capacity, to accommodate future volume increases. On a longer term, cross-border transport requires different systems to be combined and to cooperate. A network linking multiple capture installations and several storage locations demands advanced management systems. TNO conducts long-term outlook studies on CO₂ capture and storage options, to alert current CCS projects on future developments and requirements relevant to CO₂ transport.

- Cost-effective development of CCS transport infrastructure
- Optimised exploitation of available storage capacity
- Development of integrated transport and storage strategies.



STORAGE

Geological strata provide the most favourable conditions for largescale, permanent storage of CO₂, comprising depleted oil and gas reservoirs, deep saline aquifers and unmineable coal seams.

STORAGE CAPACITY AND INJECTIVITY

Both CO₂ storage capacity and injectivity in a given storage reservoir determine the operational feasibility of a project. TNO has an extensive track record of reservoir studies, comprising static and dynamic modelling expertises originally stemming from oil and gas reservoir evaluation. At present these are customised to the specific demands that CO₂ storage poses on the geological system as well as the singular reservoir behaviour of CO₂ relative to oil and gas. TNO adjusted a conventional reservoir simulator to enable modelling of combined thermal and compositional effects of cold CO₂ injection.

- Geological characterisation
- Reservoir simulation
- Pseudo-thermal reservoir modelling.

HEALTH, SAFETY AND ENVIRONMENT

Specific to CO₂ storage are long-term containment and potential chemical reactivity of aqueous CO₂ with reservoir and caprock. TNO developed site-specific performance assessment methodology, involving a multi-disciplinary investigation of the integrity of the containment reservoir, caprock and faults, as well as of boreholes and surface facilities – an approach that proved its value in numerous feasibility studies. Furthermore, monitoring programs are developed and matched against modelling results to ensure safe and reliable long-term storage.

- Comprehensive risk assessment
- Integration of fluid flow, geomechanics and geochemistry expertises
- Monitoring.

IMPLEMENTATION

TNO offers support to the development and implementation of regulations on geological CO₂ storage, both on a national and international level. To build a favourable business case for CO₂ storage, TNO investigates the application of additional energy benefits to improve cost-efficiency and the overall economics of storage operations. Evaluation of the timing of depletion of hydrocarbon reservoirs and abandonment of associated infrastructure provides support to 4-dimensional planning of large-scale CO₂ storage within the Netherlands and across borders.

- Policy support
- Economic evaluation
- Spatial and temporal planning.



UTILISATION

CO₂ FOR BIO-REFINERY

Biomass is the feedstock of the future for many applications. Highvalue products, such as chemicals, fuels and building materials can be derived from biomass. The concept of converting biomass into useful products is known as bio-refining. In a bio-refinery system using micro-algae, the ability exists to simultaneously mitigate CO₂ and produce high-value intermediate and end products.

TNO recently developed an Integrated Chain Assessment (ICA) tool for sustainable feedstock technology. When applied to an entire process chain, this tool assesses the system's level of technological, economic and environmental sustainability. The ICA tool identifies areas where innovative technology can be further developed to optimise systems for sustainability and profitability.

CO₂ FOR ENHANCED OIL RECOVERY (EOR)

Displacement and enhanced production of oil by carbon dioxide injection relies on the phase behaviour of the mixtures of that gas and the crude, which is strongly dependent on reservoir temperature, pressure and crude oil composition. Using EOR, 30 to over 60 % of the reservoir's original oil can be extracted, compared to 20-40% using primary and secondary recovery. In this application, typically up to two-thirds of the injected CO₂ returns with the produced oil and is usually re-injected into the reservoir to minimise operating costs.

CO₂ FOR CROP NOURISHMENTS

The photosynthesis process requires CO₂. As a result CO₂ concentrations higher than the natural concentration in air, provide improved crop growing conditions. Therefore, flower, fruit and vegetable production in greenhouses can be optimised using clean CO₂. As a consequence plants will be stronger and of higher quality, which leads to a higher market value.



INTEGRATED CCS: FROM SOURCE TO SINK

The different segments of the CCS chain cannot be evaluated independently as the developments and changes in one of the segments affect the others.

Different gas treatment and carbon capture technologies pose different requirements on transport, storage and processing of the output streams. A change in the gas treatment process that results in more efficiency on the front-end might have a larger negative effect on the back-end. Efficient process improvement requires a good understanding of the front- and back-end processes as well as the static and dynamic mechanical behaviour of the connecting grids. TNO holds extensive knowledge on the different segments of the CCS chain, facilitating an integrated approach for CO₂ capture, transport, storage and utilisation.

Although theoretical CO₂ storage capacity of the Netherlands is large, the timing of planned storage in relation to abandonment of oil and gas fields and infrastructure results in a narrow window of opportunity for commencing CO₂ storage in depleted oil and gas fields. Moreover, in order to fully utilise the available storage capacity, the capture and transport rates of CO₂ should match the optimal injection scheme. Therefore, temporal and spatial aspects have to be considered when planning large scale CCS. To support policy development, TNO is developing a 'Masterplan' for application of the subsurface for production of oil, gas or geothermal energy, temporary storage of natural gas or permanent storage of CO₂.

CATO-2

CCS has obtained a promising position in the Netherlands. The national CATO R&D programme, executed between 2004 and 2009, created an extensive knowledge network on CCS in the Netherlands. The conclusion that many aspects of CCS still required further research and development laid the foundation for its follow-up CATO-2 (2009-2014). The CATO-2 programme is co-ordinated by TNO.

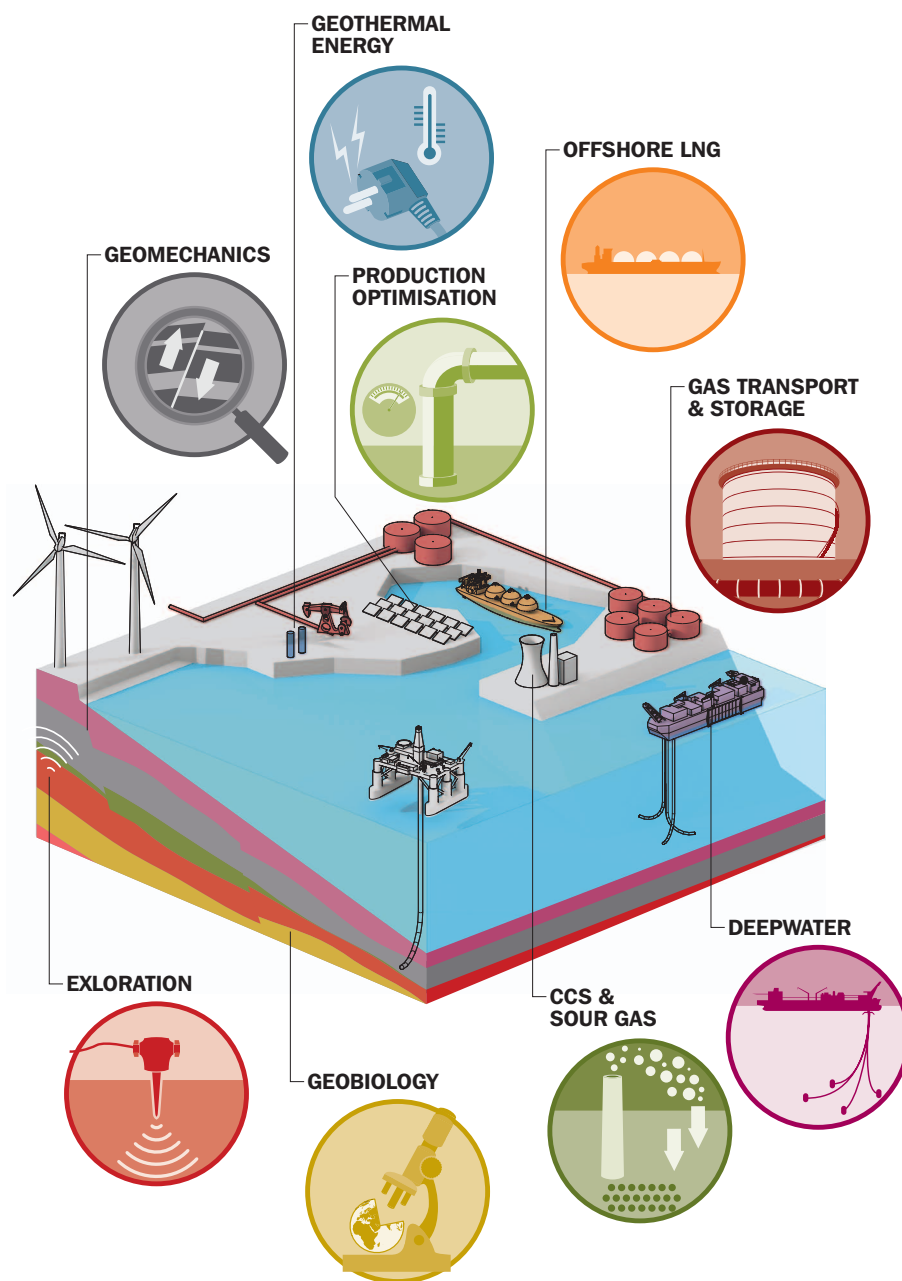
CATO-2 concentrates on enabling commercial CCS technology implementation as of 2020. At the current stage, site-specific research is very important. Experience from pilots and demonstration projects are essential for upscaling and integrating CCS technology.



TNO pilot plant at E.on, the Netherlands

The co-operation between industry and research institutions ensures that CATO-2 is a demand-driven and effective program. Research priorities are aligned with future requirements. Applied research on capture, transport and storage is planned on a number of demonstration sites. Meanwhile, another important topic within CATO-2 forms fundamental research, focusing on innovative technologies, processes and procedures that can be applied within 5 to 10 years.

Research topics are not only technological. Moving towards the demonstration and commercialisation phase, issues like public perception, financing and costs are of increasing importance and also covered



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