Overview European CCS activities and R&D work at ECN

CCS Workshop RITE
February 15th and 16th, 2007
Overview presentation

Introduction ECN (Energy research Centre, The Netherlands)

• European CCS Projects
  ➢ CASTOR
  ➢ ENCAPE
  ➢ CACHET

• Activities in the Netherlands
  ➢ CATO
  ➢ Other initiatives

• ECN CCS activities
  ➢ Membrane reactors
  ➢ Sorption enhanced reactors
ECN key data

Employees: 620 fte
Annual turnover: 68 Meuro
Government funding: 24 Meuro
patent portfolio: 78 (34 granted, others pending)
External publications: 617 (90 peer reviewed)
ISO 9001 & 14001 certified
ECN programme units

- Hydrogen & Clean Fossil Fuels
- Solar Energy
- Wind Energy
- Energy In the Built Environment
- Energy Efficiency in Industry
- Biomass, Coal & Environmental Studies
- Policy Studies

ECN programme units
European initiatives

Depleted reservoirs

EOR/EGR /ECBM

Deep saline aquifers

No storage

Gas separation or no Capture

Post Combustion

Pre-Combustion

Oxy-fuel
European Capture Projects

**CASTOR**: *CO$_2$, from Capture to Storage*
- Post combustion capture technology development
- CO$_2$ geological storage

**ENCAP**: *Enhanced capture of CO$_2$*
- Research and development on pre-combustion CO$_2$ capture mainly for hard coal and lignite
- Oxy fuel also seen as pre combustion CO$_2$ capture

**CACHET**
- Pre combustion capture technologies for gaseous fuels (natural gas)

Reduce cost of CO$_2$ capture to EU target of 20 to 30 €/tonne at 90% capture rate
Objectives

- Development of absorption liquids, with a thermal energy consumption of 2.0 GJ/tonne CO₂ at 90% recovery rates
- Resulting costs per tonne CO₂ avoided not higher than 20 to 30 €/tonne CO₂, depending on the type of fuel (natural gas, coal, lignite)
- Pilot plant tests showing the reliability and efficiency of the post-combustion capture process
Post-combustion capture

WP 2.1: Evaluation, Optimisation and Integration of post-combustion capture

WP 2.2: New solvent development

WP 2.3: Membrane contactor development

WP 2.4: Advanced process development

WP 2.5: Pilot plant validation with real flue gases
# Post-combustion capture

<table>
<thead>
<tr>
<th>Current costs contribution</th>
<th>Cost contribution by advanced process</th>
<th>Effected by</th>
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<tbody>
<tr>
<td><strong>Investment costs</strong></td>
<td></td>
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<tr>
<td>Absorber</td>
<td>25 %</td>
<td>10 – 15%</td>
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<tr>
<td>Rest of equipment</td>
<td>25 %</td>
<td>10 – 15%</td>
</tr>
<tr>
<td>(desorber, heat exchangers)</td>
<td></td>
<td></td>
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<tr>
<td><strong>Total investment</strong></td>
<td>50 %</td>
<td>20 – 30 %</td>
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</table>

| **Operational costs**     |                                       |             |
| Thermal energy            | 25%                                   | 10 – 15%    | Halving of energy consumption through use of advanced solvents (novel chemicals, additives with low vaporisation enthalpy)  |
|                           |                                       |             | Integration of heat exchanger in desorber  |
| Rest (cooling, electricity, chemicals) | 25%                                   | 10 – 15%     | Halving of solvent flow rate  |
|                           |                                       |             | Optimised operational conditions for advanced process technologies and solvents  |
| **Total operation**       | 50%                                   | 20 – 30%    | Solvent stability improvements  |

| **Total costs**           | 100%                                  | 40 – 60%    |             |
European post-combustion test facility: the CASTOR pilot plant

Capacity: 1 t CO₂ / h

5000 Nm³/h fluegas
(coal combustion)

In operation since early 2006

The greatest post-combustion pilot worldwide
CASTOR pilot plant (3)

January - March 2006: MEA-testing for 1000 hrs
September - November 2006: 2nd MEA-testing for 1000 hrs
December 06 – May 2007: CASTOR1-testing 5000 hrs
January - November 2007: CASTOR2-testing 5000 hrs
CASTOR CO₂ storage initiatives

- Spain: offshore oil reservoir (Casablanca, REPSOL)
- Norway: offshore aquifer (Snøhvit)
- Austria: offshore gas field (Atzback, Rohwet)
- The Netherlands: offshore gas field (K12b, Gaz de France)

Ketzin (Germany) – CO2Sink EU project
In-Salah (Algeria)
European Capture Projects: ENCAP

Objective:

- ENCAP aims at technologies that meet the target of at least 90% CO2-capture-rate and 50% CO2-capture-cost reduction.
- Pre combustion decarbonisation
  - IGCC for hard coal and lignite
  - IRCC for natural gas
- CO$_2$/O$_2$ combustion technologies (oxy fuel)
  - PC for hard coal and lignite
  - CFB for hard coal, lignite and pet-coke
- Chemical looping
European Capture Projects: ENCAP

**ENCAP activities**

- **ENCAP SP2**: Development of power plants with pre-combustion decarbonisation (for bituminous coal, lignite and natural gas)
  - Process outline
  - Optimised gas processing
  - H$_2$-rich combustion in gas turbines (Siemens, Alstom)
  - Integration of cryogenic oxygen production, CO$_2$ capture, gas and steam turbines into functioning power plants

- **ENCAP SP5**: High-temperature oxygen generation

- **ENCAP SP6**: Novel concepts

- SP5 and SP6 investigate pieces that can be inserted in the SP2 plant beyond year 2020
European Capture Projects: ENCAP

ENCAP activities on oxyfuel combustion

- Coal Boiler technologies
  - Oxyfuel combustion for bituminous coal and lignite plant
    - PF and CFB combustion technology
  - Integration and optimisation in combination with economic evaluation
  - Operational characteristics, risk analysis
- Natural gas combined cycle technologies
  - Novel process concept for increased efficiency
European Capture Projects: ENCAP

Air separation: Development within the ENCAP project

- High temperature oxygen separation with ceramic materials
  - oxygen transfer membranes
  - high temperature oxygen adsorbent (CAR)

- Development of materials, cost, integration into power plant
European Capture Projects: ENCAP

New Developments – Chemical Looping Combustion

- Combustion with a solid "oxygen carrier"
  - avoids energy penalty of air separation
- Developments within the ENCAP project
  - Chemical looping combustion for solid fuels
  - Evaluation of oxygen carrier materials
  - Novel reactor concepts
  - Process design, integration optimisation and economics
- Phase 2 decision on pilot testing

\[
\text{CH}_4 + 4\text{NiO} \rightarrow 4\text{Ni} + \text{CO}_2 + 2\text{H}_2\text{O}
\]

Courtesy Jens Wolf, Vattenfall Utveckling AB
European Capture Projects: CACHET

Objective:

- Develop technology to reduce cost of CO$_2$ capture to EU target of 20 to 30 €/tonne at 90% capture rate
  - Industrial application to natural gas fired 400 MWe CCGT with (H$_2$ side-stream)
  - 4 main technology areas:
    - Advanced SMR
    - Chemical looping and One-step
    - Membranes
    - SEWGS
- Novel technology evaluation, HSE and dissemination
- 3 year project duration, commencing 1$^{st}$ April 2006

15 M euro, 50 % from EU, 20% from CCP
European Capture Projects: CACHET

LP Fuel gas → Secondary combustion → After burner

Jet Engine Gas Generator

NG + Steam → Reforming Steam → Tertiary combustion

H₂ + CO...

Catalytic Reactor / Exchangers

Power

Reforming Steam

BFW
European Capture Projects: CACHET

chemical looping reforming

**autothermal**

1) Air reactor/riser, 2) cyclone, 3) fuel reactor,
4) fluidized bed heat exchanger/reformer (FBHE/R), 5) shift reactor
6) hydrogen separation (one pure hydrogen flow, one CO₂/H₂ flow)

NOTE: return of particles from 4 to 1 not shown because of 2 D view.
Fluidizing gas for FBHE/R can be gas recycled from outlet of fuel or air reactor or air.

**smr**

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One-step decarbonisation

Circulating "redox" solid material that can be oxidized via water splitting thereby producing H₂, and reduced by a carbon-containing stream, typically hydrocarbons, producing CO₂
European Capture Projects: CACHET

- Water gas shift catalyst + high temperature CO\(_2\) adsorbent
- Removes CO\(_2\) from hot syngas (400-500\(^\circ\)C), drives CO towards extinction
- Multiple beds undergo cyclic process steps (reaction/adsorption and regeneration)
European Capture Projects: CACHET

combined reaction and separation

CO₂

Capture

CO or CH₄

H₂O or O₂

reaction

H₂

Hydrogen Utilisation

Membrane reactor

Operating temperature | Type of reaction                         | Active membrane     |
----------------------|-----------------------------------------|---------------------|
300-400°C             | Water gas shift                         | Metal membrane      |
400-600°C             | Low temperature reforming of methane    | Metal membrane      |

thin palladium supported membranes
CCS projects in The Netherlands

- CATO project
- CRUST of-shore storage project GdF
- OCAP re-use project
- New initiatives
CCS projects in The Netherlands

Unique Dutch knowledge network in the area of CO₂ capture, transport and storage

- Partners: 17
- Budget: 25.6 million € (50% govt. support)
- In line with Dutch government policy: Ministries EZ (Economic Affairs) and VROM (Environment)
- Embedded in international networks (CO2NET, IEA, CSLF)
- Over 15 PhD students
- Period: 2004-2009
- Manager: UCE (within Utrecht University)
<table>
<thead>
<tr>
<th>WP Subject</th>
<th>WP Leaders</th>
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<tbody>
<tr>
<td>1 System analysis &amp; Transition</td>
<td>UU-Copernicus, Ecofys and ECN</td>
</tr>
<tr>
<td>2 Capture of CO₂</td>
<td>TNO S&amp;I, ECN, TNO S&amp;I</td>
</tr>
<tr>
<td>2.1 Post-combustion</td>
<td>TNO S&amp;I</td>
</tr>
<tr>
<td>2.2 Pre-combustion</td>
<td>ECN</td>
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<tr>
<td>2.3 Denitrogenated conversion</td>
<td>TNO S&amp;I</td>
</tr>
<tr>
<td>3 Storage of CO₂</td>
<td>TNO-NITG, Shell (SIEP)</td>
</tr>
<tr>
<td>3.1 Storage gas fields</td>
<td>TNO-NITG</td>
</tr>
<tr>
<td>3.2 Storage coal fields (ECBM)</td>
<td>Shell (SIEP)</td>
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<tr>
<td>4 Mineralisation</td>
<td>Shell (SIEP), ECN, TNO S&amp;I</td>
</tr>
<tr>
<td>4.1 Subsurface mineralisation</td>
<td>Shell (SIEP)</td>
</tr>
<tr>
<td>4.2 Surface mineralisation</td>
<td>ECN, TNO S&amp;I</td>
</tr>
<tr>
<td>5 Monitoring, safety and regulations</td>
<td>TNO-NITG</td>
</tr>
<tr>
<td>6 Communication</td>
<td>Leiden University</td>
</tr>
<tr>
<td>7 Management and knowledge transfer</td>
<td>UU-UCE</td>
</tr>
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</table>
CCS projects in The Netherlands

System analyses

- North Sea Gasfields (816 Mt) Aquifers (~350 Mt)
- West Aquifers (570 Mt)
- Southwest Aquifers (200 Mt)
- Central Aquifers (155 Mt)
- Southeast Aquifers (204 Mt)
- North Aquifers (85 Mt) Groningen gasfield (7512 Mt)

- Large scale hydrogen plant
- Large scale power plant
- CO₂ grid/pipeline
- Hydrogen pipeline
- Residential hydrogen market
- Industrial hydrogen market
- Automotive hydrogen market

UU, van Troost & Daamen

Energy research Centre of the Netherlands www.ecn.nl
CCS projects in The Netherlands

Post combustion capture

- CO$_2$ capture with solvent and membrane contactors

- CATO pilot plant in E.on PC boiler Maasvlakte in the Roterdam area

- 50% capture cost reduction

- Design for membrane absorber which is 4 times compactor the conventional absorbent
CCS projects in The Netherlands

Pre combustion capture; Pd alloy membrane reactor

Steam reforming: \[ \text{CH}_4 + \text{H}_2\text{O} \rightleftharpoons 3 \text{H}_2 + \text{CO} \ (\Delta H = 206 \text{ kJ/mol}) \]

Water-gas shift: \[ \text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{H}_2 + \text{CO}_2 \ (\Delta H = -41 \text{ kJ/mol}) \]

\[ \text{CH}_4 + 2 \text{H}_2\text{O} \rightleftharpoons 4 \text{H}_2 + \text{CO}_2 \]

Shifting the equilibrium to the product side

- System analyse
- Membrane development
- Membrane reactor design
- Catalyst screening
- PDU tests
CCS projects in The Netherlands

Pre combustion capture; Sorption Enhanced Reaction Process

Steam reforming: \( \text{CH}_4 + \text{H}_2\text{O} \rightleftharpoons 3 \text{H}_2 + \text{CO} \) (\( \Delta H = 206 \text{ kJ/mol} \))

Water-gas shift: \( \text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{H}_2 + \text{CO}_2 \) (\( \Delta H = -41 \text{ kJ/mol} \))

\( \text{CH}_4 + 2 \text{H}_2\text{O} \rightleftharpoons 4 \text{H}_2 + \text{CO}_2 \)

Shifting the equilibrium to the product side

- Hydrotalcite materials suitable for SE water gas shift reaction, not for SE reforming
- Hydrotalcites not stable > 450 °C
- Temperatures between 550 en 750 °C are needed for steam reforming
- New HT sorbents under development
CCS projects in The Netherlands

System evaluations: Pre combustion capture technologies

Results

Performance of selected systems

Reference power plant without CO₂ capture: 57.1% efficiency
CCS projects in The Netherlands

The K-12B gas field

1st test: K12-B8 - Injector
2nd test: K12-B5 - Producer
2nd test: K12-B1 - Producer
2nd test: K12-B6 - Injector

courtesy GdF Netherlands
CCS projects in The Netherlands  
Industrial CO₂ re-use in greenhouses

• CO₂ from Shell Pernis,
• 170 kton CO₂ reduction
CCS Initiatives in The Netherlands

- Nuon MAGNUM capture ready IGCC
- SEQ oxy fuel ZEPP in Drachten
- Nuon WAC Pre-combustion demo
- NAM CO₂ storage in de Lier
ECN CCS activities

- Pre-combustion decarbonisation
  - Sorption-enhanced reaction
  - Hydrogen-selective membrane reactors
  - $\text{CO}_2$ selective membrane reactors
- Oxyfuel combustion
  - SOFC + afterburner
  - Oxygen conducting membranes
- $\text{CO}_2$ re-use/storage
  - Mineralisation
Participation ECN in programs & projects

- **CATO**: Dutch national CO₂ program  
  - Co-ordination Utrecht University  
  - Running time 2004 – 2009  
  - ECN co-ordinates the pre-combustion CO2 capture work package: hydrogen membranes and CO₂ sorbents

- **CACHET**: EU FP6 Integrated Project  
  - Co-ordination BP  
  - Running time 2006 until 2009  
  - ECN co-ordinates membrane WP and participates in WP on sorption-enhanced Water Gas Shift coordinated by Air Products and is co-financed by CCP.

- **GCEP** (Global Climate and Energy Program)  
  - Co-ordination: Stanford University  
  - Running time 2005 -2008  
  - Sponsors: ExxonMobil, Toyota, Schlumberger, GE  
Participation ECN in programs & projects

National EOS projects
- **C- CLEAR**
  - Continuous SERP for “ZEPP”
  - Co-ordination: ECN
  - running time 2005-2008
- **CATHY**
  - Catalysts for Separation enhanced reformers
  - Co-ordination: ECN
  - running time 2006-2009
- **CAPTECH**: extension to CATO
  - Capture technologies for IGCC and PC
  - Co-ordination: ECN
  - running time 2006-2009

EU IP projects
- **CO2ReMOVE** (Policy studies, H₂&CFF)
  - CO₂ monitoring and verification
- **ACCEPT** (Policy studies)
  - Public Acceptance of CO₂ storage, economics, Policy and technology
SERP for hydrogen production with CO$_2$ capture

steam natural gas

SERP reactor in adsorption mode

water knock out

CO$_2$

SERP reactor in desorption mode

PSA

Pure hydrogen

steam
SERP for electricity production with CO₂ capture

Steam
Natural gas

SERP reactor in adsorption mode

H₂ + steam

Air
Gas turbine
Generator

SERP reactor in desorption mode

Steam

Water knock out

CO₂
Shifting the equilibrium

Steam reforming

$$\text{CH}_4 + 2\text{H}_2\text{O} \rightleftharpoons 4\text{H}_2 + \text{CO}_2$$

$$K_{eq} = \frac{[\text{CO}_2][\text{H}_2]^4}{[\text{CH}_4][\text{H}_2\text{O}]^2}$$

CO, CH₄ conversion

CO₂ slip [ppm]
Steam reforming
\[ CH_4 + 2H_2O \leftrightarrow 4H_2 + CO_2 \]

\[ K_{eq} = \frac{[CO_2][H_2]^4}{[CH_4][H_2O]^2} \]

Water gas shift
\[ CO + H_2O \leftrightarrow H_2 + CO_2 \]

\[ K_{eq} = \frac{[CO_2][H_2]}{[CO][H_2O]} \]
ECN CCS activities
Hydrogen-selective membrane reactors

DECAFF

Low-CO₂ flue gas

Heat recovery steam generator

Heat

CO₂ to cleanup and compression

Membrane reactor

H₂, H₂O

Natural gas

H₂O

GT turbine

GT compressor

Generator

Air

CO₂ to clean-up and compression

H₂, H₂O

Heat

H₂O

Natural gas

H₂O

Heat recovery steam generator

GT turbine

GT compressor

Generator

Air

CO₂ to clean-up and compression

H₂, H₂O

Heat

H₂O

Natural gas

H₂O

Heat recovery steam generator

GT turbine

GT compressor

Generator

Air

CO₂ to clean-up and compression

H₂, H₂O

Heat

H₂O

Natural gas

H₂O

Heat recovery steam generator

GT turbine

GT compressor

Generator

Air

CO₂ to clean-up and compression

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H₂O

Natural gas

H₂O

Heat recovery steam generator

GT turbine

GT compressor

Generator

Air

CO₂ to clean-up and compression

H₂, H₂O

Heat

H₂O

Natural gas

H₂O

Heat recovery steam generator

GT turbine

GT compressor

Generator

Air

CO₂ to clean-up and compression

H₂, H₂O

Heat
ECN CCS activities

Power generation in SOFC with H2-MR

- Efficiency up to 62% LHV
- Fuel utilisation SOFC is key parameter
CCS projects at ECN

CO₂ separating membranes for advanced energy systems

- Part of the GCEP project managed by Stanford University
  - Sponsors: GE, EXXON, Toyota, and Schlumberger
  - 3 years (2.3 million $) project in cooperation with TU-Delft

Task 1. System analysis and thermodynamic evaluations
Task 2. Hydrogen membrane research & development
Task 3. CO₂ membranes research & development
Task 4. Catalyst screening
Task 5. Reactor modelling and design

Executed by ECN
Executed by TUD
Executed by ECN+TUD
Executed by ECN
Executed by ECN
Steam Reforming

Conversion relatively easy enhanced by separation of $H_2 \rightarrow$ favourable kinetics

$CO_2$ selective membranes show a too low conversion and are therefore not suitable, as opposed to $H_2$ selective membranes

Membrane reformer: Residual partial pressure of permeating component in retentate as a function of conversion.

@ 600 °C, 40 bar, S/C = 3, Sweep: steam 5 bar, 600 °C, Sweep flow/Feed flow = 0.11 (mole/mole)
ECN CCS activities

Mineral CO₂ sequestration in alkaline solid waste

Main route of natural CO₂ sequestration:

→ weathering of (Ca,Mg)-silicates

\[
\text{CaSiO}_3 (s) + \text{CO}_2 (g) \rightarrow \text{CaCO}_3 (s) + \text{SiO}_2 (s)
\]

\[\Delta H_r = -87 \text{ kJ/mol} \quad \text{and} \quad \Delta G_r = -44 \text{ kJ/mol}\]

\[\text{d} < 106 \mu\text{m}, \quad p_{\text{CO}_2} = 20 \text{ bar}\]
ECN CCS activities

IPCC special report CCS

Download: WWW.IPCC.CH
Overview European CCS activities and R&D work at ECN

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