ECN

Energy research Centre of the Netherlands

Overview European CCS activities and R&D work at ECN

CCS Workshop RITE

February 15th and 16th, 2007

Overview presentation

Introduction ECN (**E**nergy research **C**entre, The **N**etherlands)

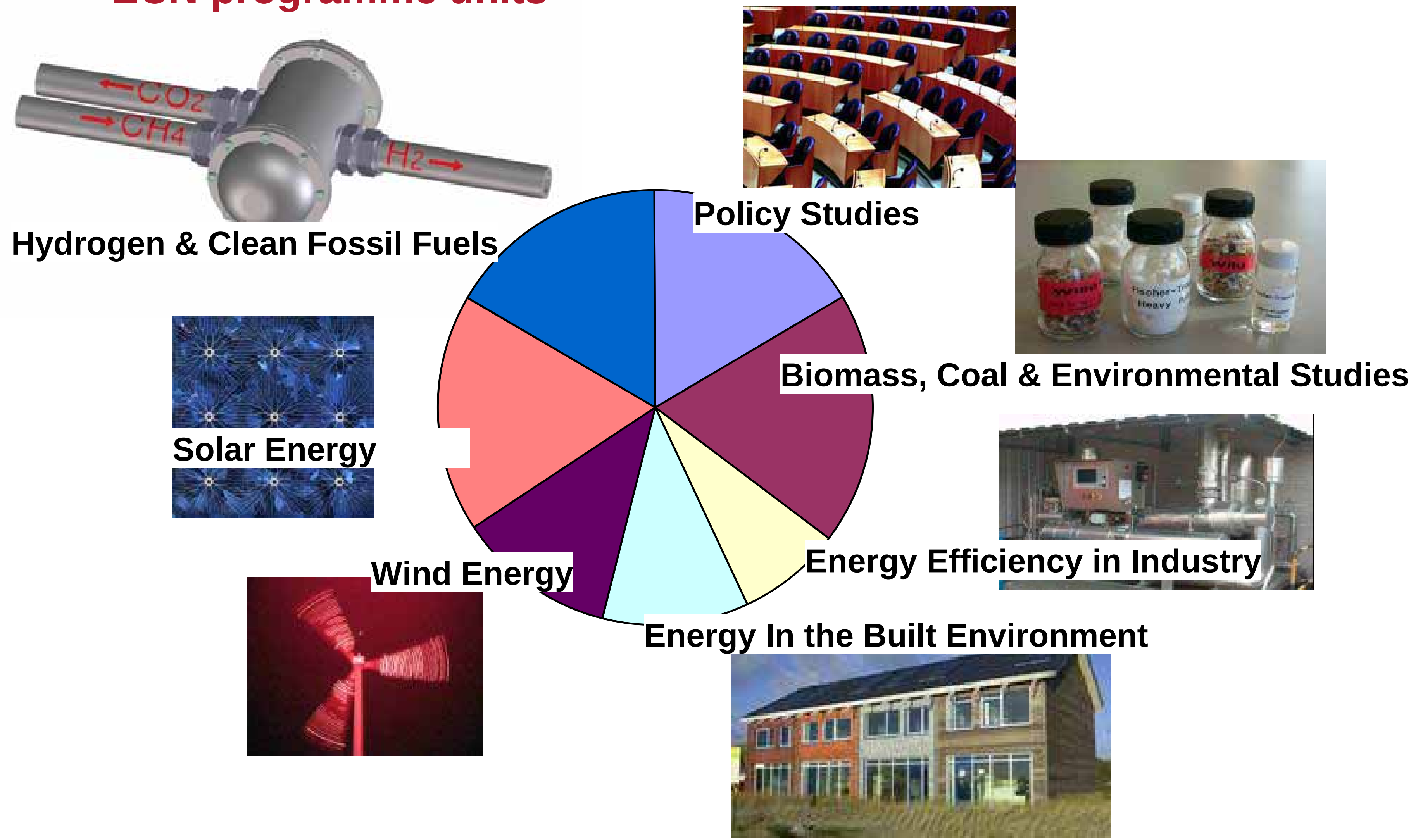
- European CCS Projects
  - CASTOR
  - ENCAPE
  - CACHET
- Activities in the Netherlands
  - CATO
  - Other initiatives
- ECN CCS activities
  - Membrane reactors
  - Sorption enhanced reactors

ECN key data

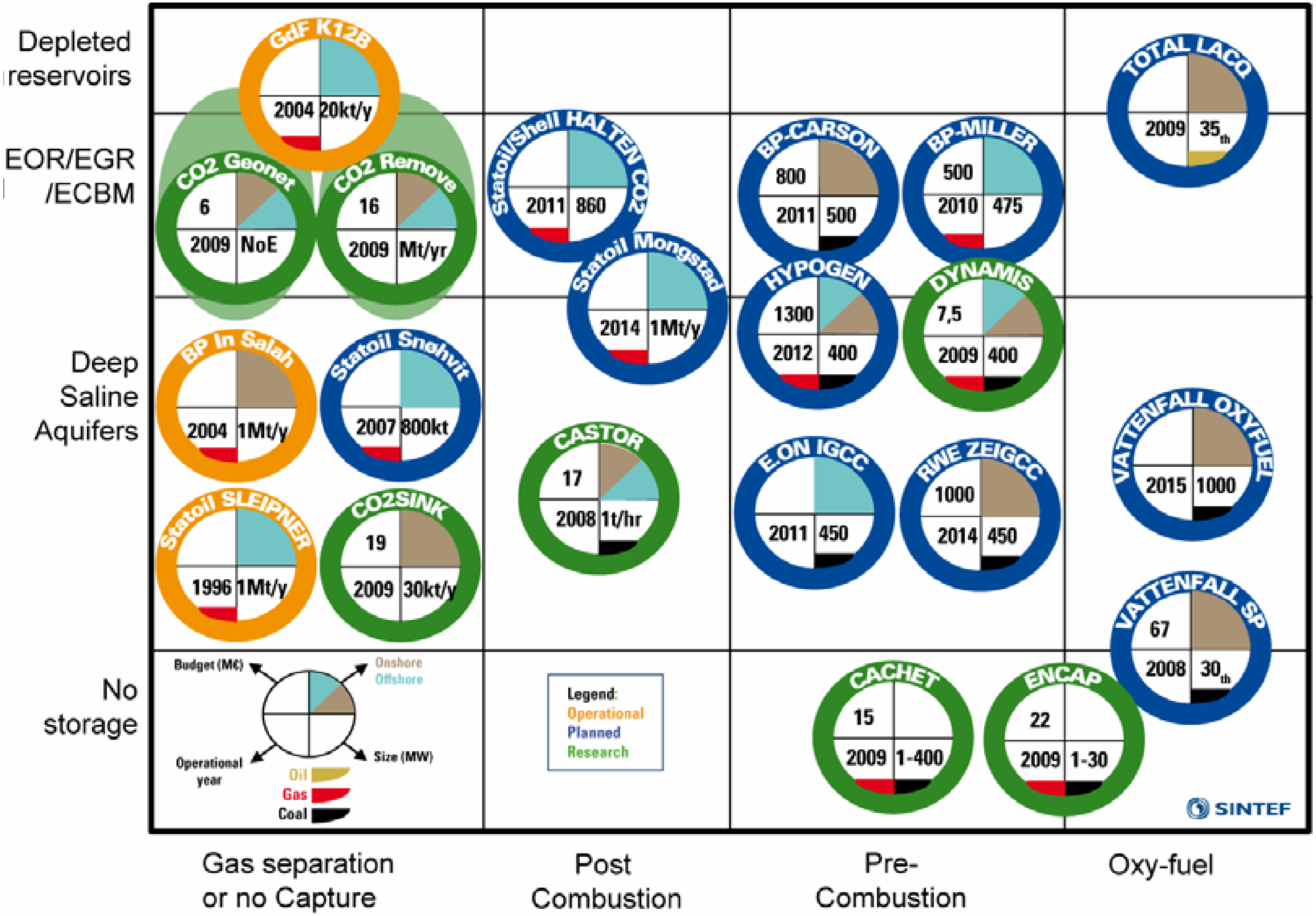
Employees:	620 fte
Annual turnover:	68 Meuro
Government funding:	24 Meuro
patent portfolio:	78 (34 granted, others pending)
External publications:	617 (90 peer reviewed)

ISO 9001 & 14001 certified

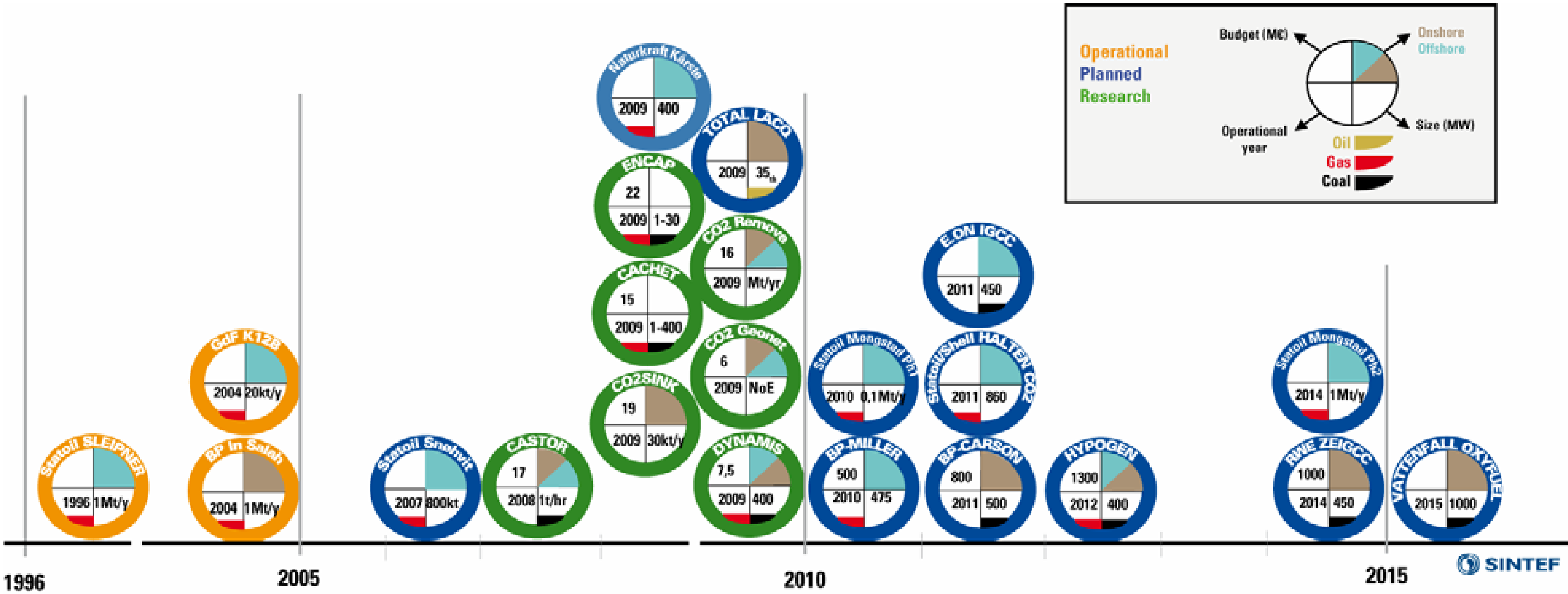
ECN programme units



European initiatives



Timing


Operational
Planned
Research
Budget (M€)
Onshore
Offshore
Size (MW)
Operational year
Oil
Gas
Coal
Statoil SLEIPNER
1996 1Mt/y
GdF K12B
2004 20kt/y
BP In Salah
2004 1Mt/y
Statoil Snøhvit
2007 800kt
CASTOR
17
2008 1t/hr
Naturkraft Kårstø
2009 400
ENCAP
22
2009 1-30
CACHET
15
2009 1-400
CO2SINK
19
2009 30kt/y
TOTAL LACQ
2009 35
CO2 Remove
16
2009 Mt/yr
CO2 Geonet
6
2009 NoE
DYNAMIS
7,5
2009 400
Statoil Mongstad Ph1
2010 0,1Mt/y
BP-MILLER
500
2010 475
E.ON IGCC
2011 450
Statoil/Shell HALTEN CO2
2011 860
BP-CARSON
800
2011 500
HYPOGEN
1300
2012 400
Statoil Mongstad Ph2
2014 1Mt/y
RWE ZEIGCC
1000
2014 450
VATTENFALL OXYFUEL
2015 1000
1996
2005
2010
2015
SINTEF

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

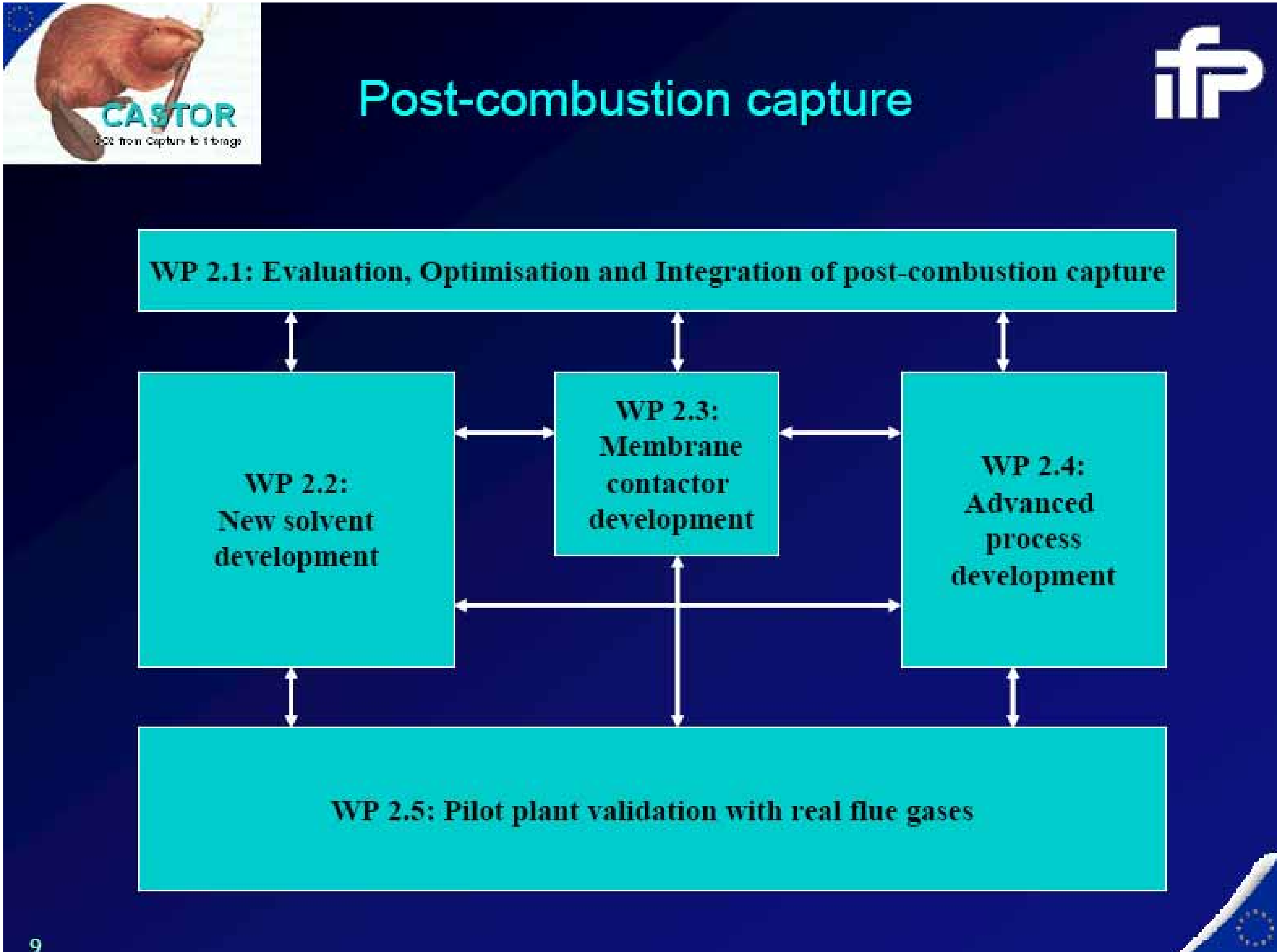
- Pre combustion capture technologies for gaseous fuels (natural gas)

Reduce cost of CO_2 capture to EU target of 20 to 30 €/tonne at 90% capture rate

Post-combustion capture

- Objectives
  - Development of absorption liquids, with a thermal energy consumption of 2.0 GJ/tonne CO_2 at 90% recovery rates
  - Resulting costs per tonne CO_2 avoided not higher than 20 to 30 €/tonne CO_2, depending on the type of fuel (natural gas, coal, lignite)
  - Pilot plant tests showing the reliability and efficiency of the post-combustion capture process

7

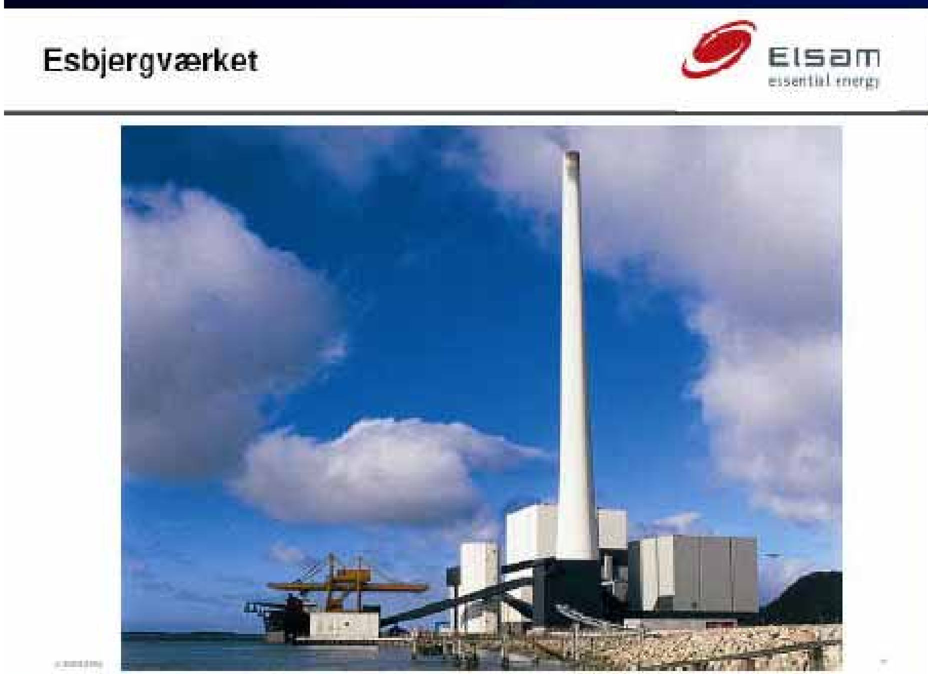

CASTOR
Post-combustion capture
WP 2.1: Evaluation, Optimisation and Integration of post-combustion capture
WP 2.2: New solvent development
WP 2.3: Membrane contactor development
WP 2.4: Advanced process development
WP 2.5: Pilot plant validation with real flue gases
9

Post-combustion capture

	Current costs contribution	Cost contribution by advanced process	Effected by
Investment costs			
Absorber	25 %	10 – 15%	Compact contactor Simplified cost-optimised contactors Membrane contactors
Rest of equipment (desorber, heat exchangers)	25 %	10 – 15 %	Halving of solvent flow rate Optimised operational conditions for advanced solvents
Total investment	*50 %*	*20 – 30 %*	
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 Solvent stability improvements
Total operation	*50 %*	*20 – 30 %*	
Total costs	**100%**	**40 – 60 %**	

9

European post-combustion test facility: the CASTOR pilot plant



Capacity: 1 t CO_2 / h

5000 Nm3/h fluegas
(coal combustion)

In operation since early 2006

The greatest post-combustion pilot worldwide

12

CASTOR pilot plant (3)

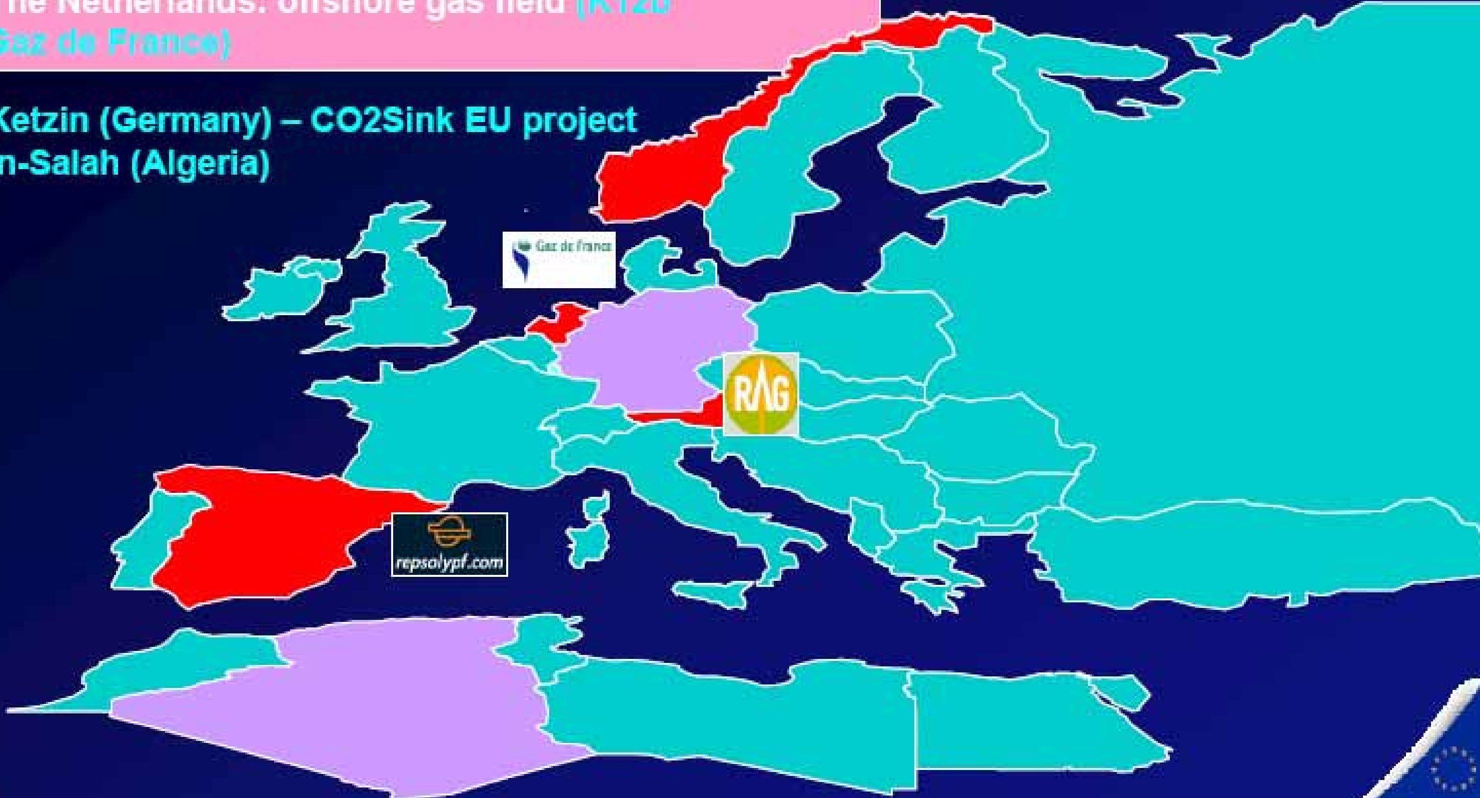
January - March 2006: MEA-testing for 1000 hrs
September - November 2006: 2nd MEA-testing for 1000 hrs
December 06 – May 2007: CASTOR1-testing 5000 hrs
January - November 2007: CASTOR2-testing 5000 hrs

14

CASTOR CO_2 storage initiatives

- Spain: offshore oil reservoir (Casablanca, REPSOL)
- Norway: offshore aquifer (Snohvit)
- Austria: offshore gas field (Atzbach, Rohoel)
-The Netherlands: offshore gas field (K12b Gaz de France)

Ketzin (Germany) – CO2Sink EU project
In-Salah (Algeria)



17

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

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

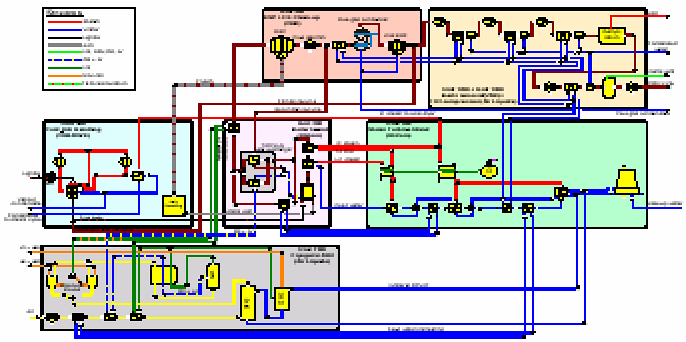
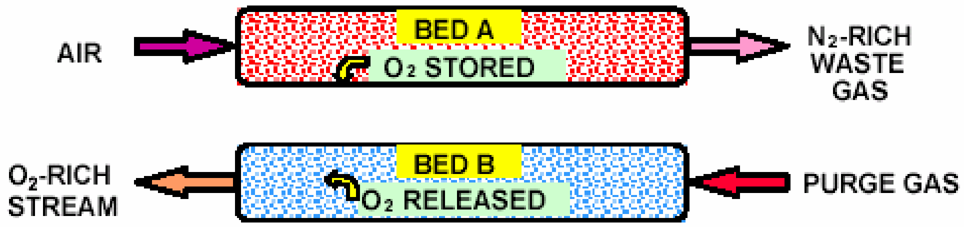


FIGURE 3.1: High Level Conceptual PFD, 1000 MWe Lignite Fired Oxy-Combustion Power Plant

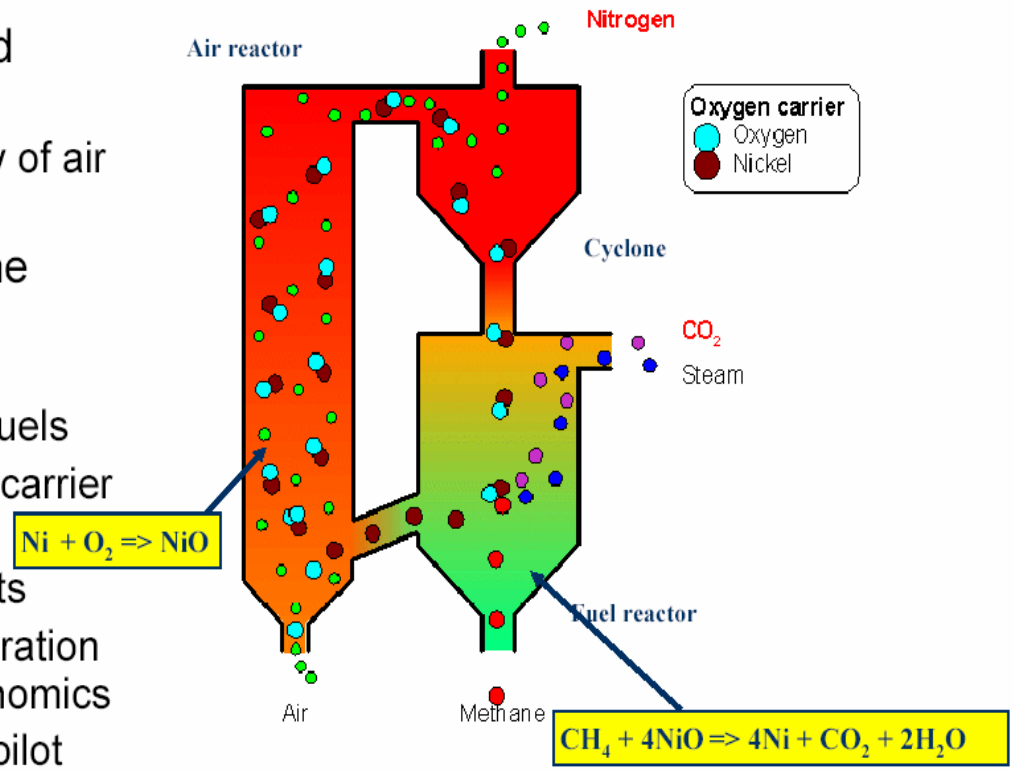
Air separation: Development within the ENCAP project

- High temperature oxygen separation with ceramic materials
  - oxygen transfer membranes
  - high temperature oxygen adsorbent (CAR)
- Development of materials, cost, integration into power plant



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



Courtesy Jens Wolf, Vattenfall Utveckling AB

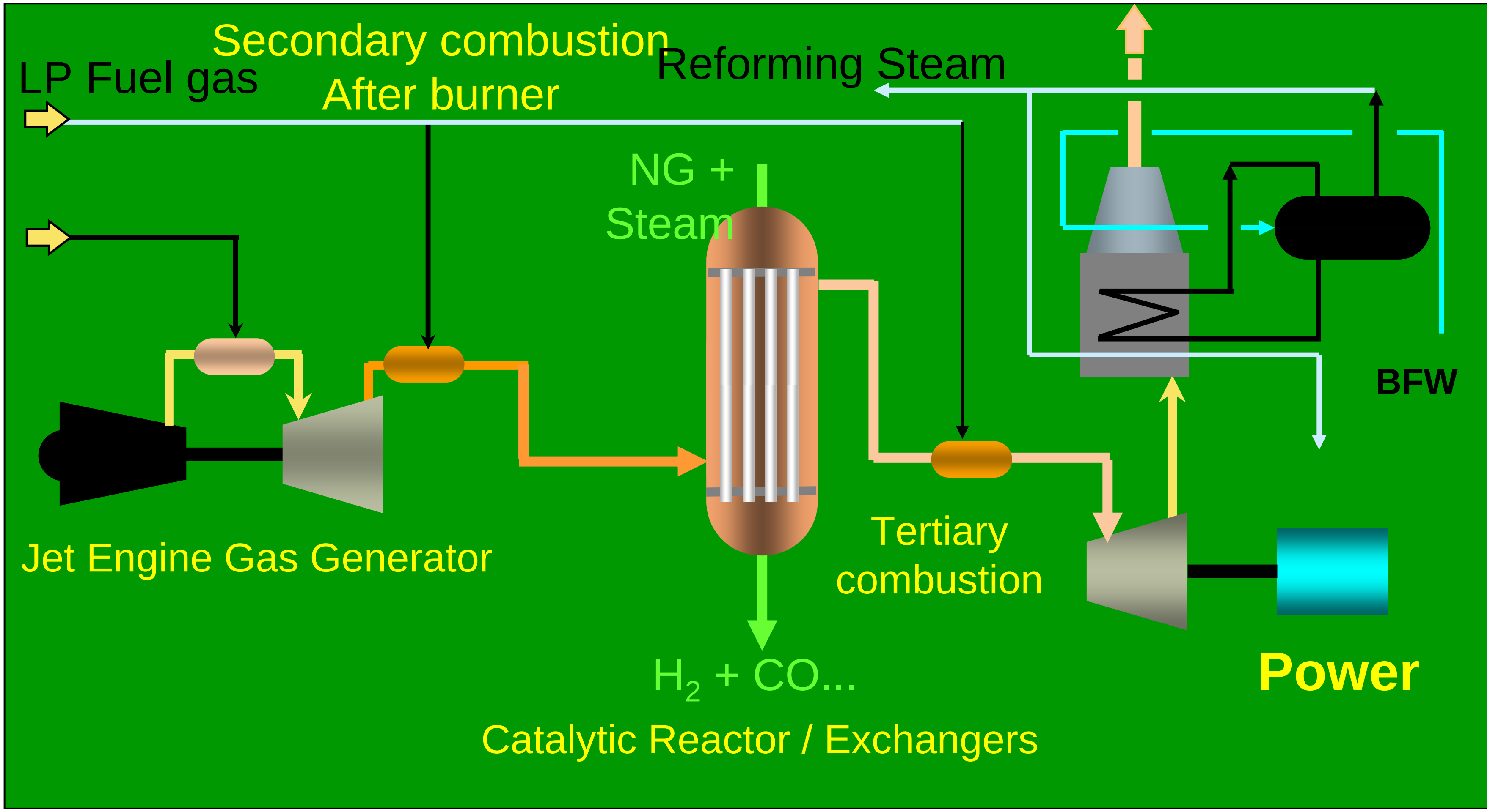
European Capture Projects: CACHET

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 1st April 2006

15 M euro, 50 % from EU, 20% from CCP

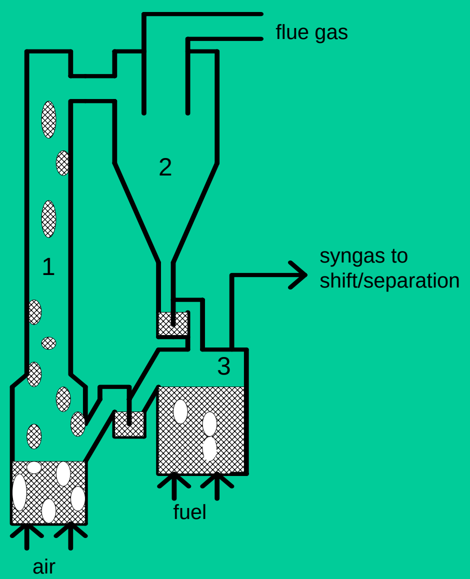
European Capture Projects: CACHET



European Capture Projects: CACHET

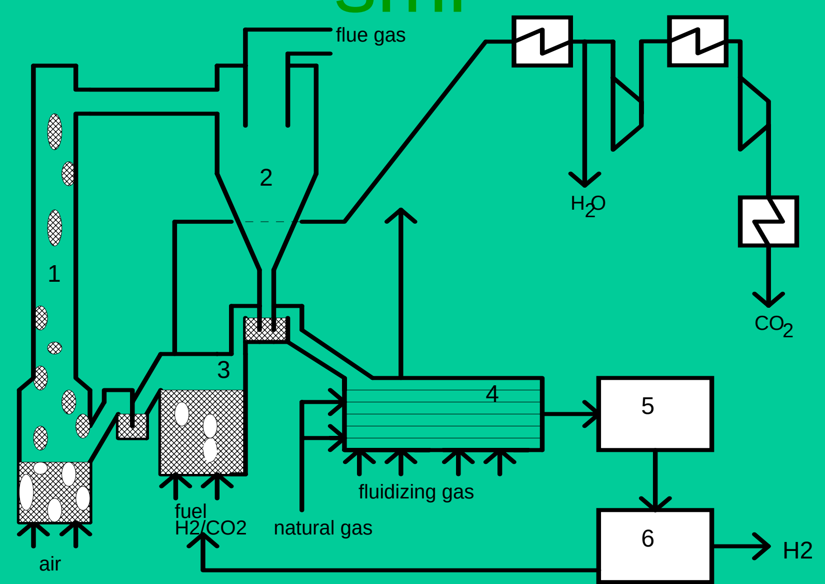
chemical looping reforming

autothermal



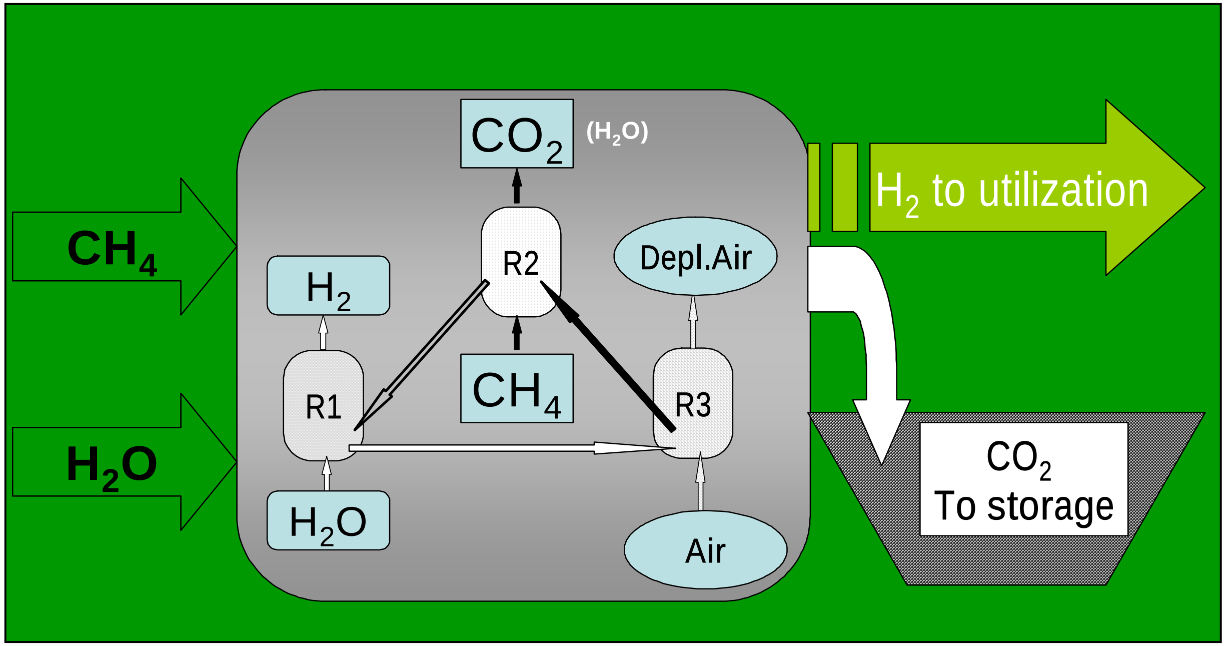
1 Air reactor/riser
2 Cyclone
3 Fuel reactor

smr



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 CO_2/H_2 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.

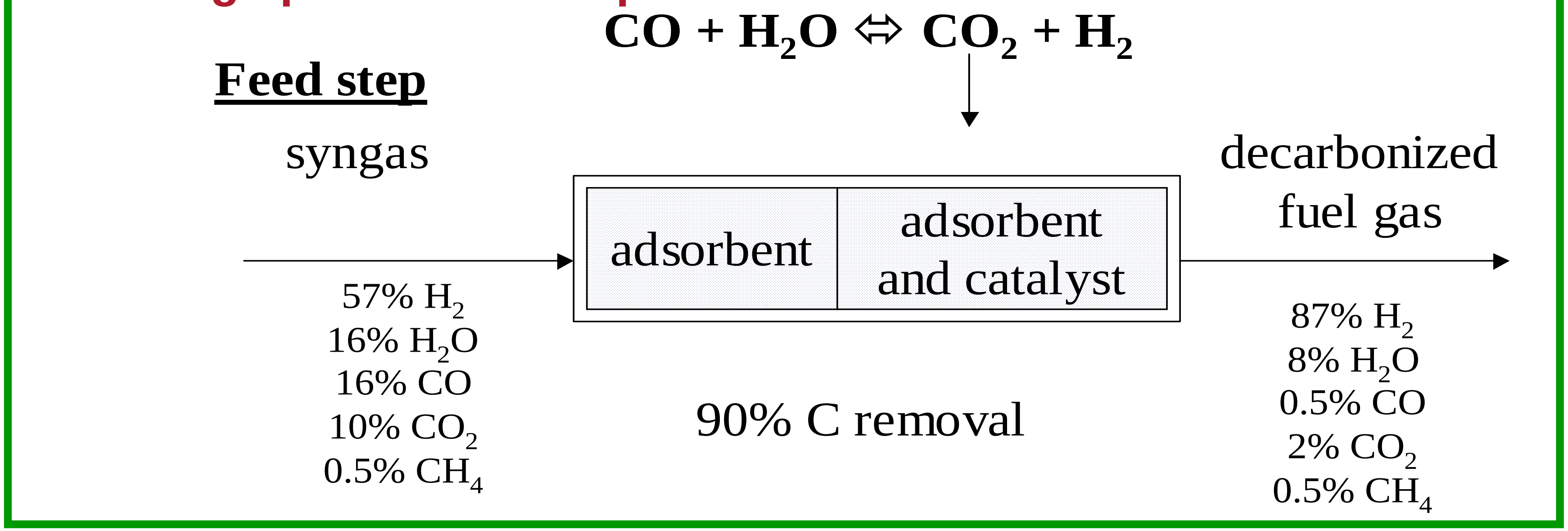
One-step decarbonisation



Circulating "redox" solid material that can be oxidized via water splitting thereby producing H_2, and reduced by a carbon-containing stream, typically hydrocarbons, producing CO_2

European Capture Projects: CACHET

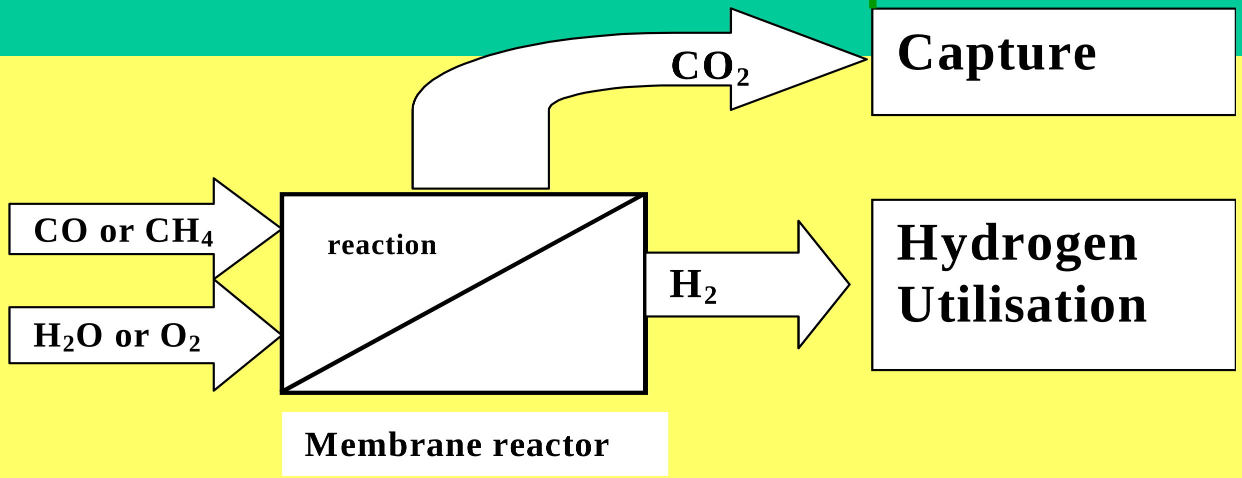
sewgs process concept



- Water gas shift catalyst + high temperature CO_2 adsorbent
- Removes CO_2 from hot syngas (400-500^{o}C), drives CO towards extinction
- Multiple beds undergo cyclic process steps (reaction/adsorption and regeneration

European Capture Projects: CACHET

combined reaction and separation

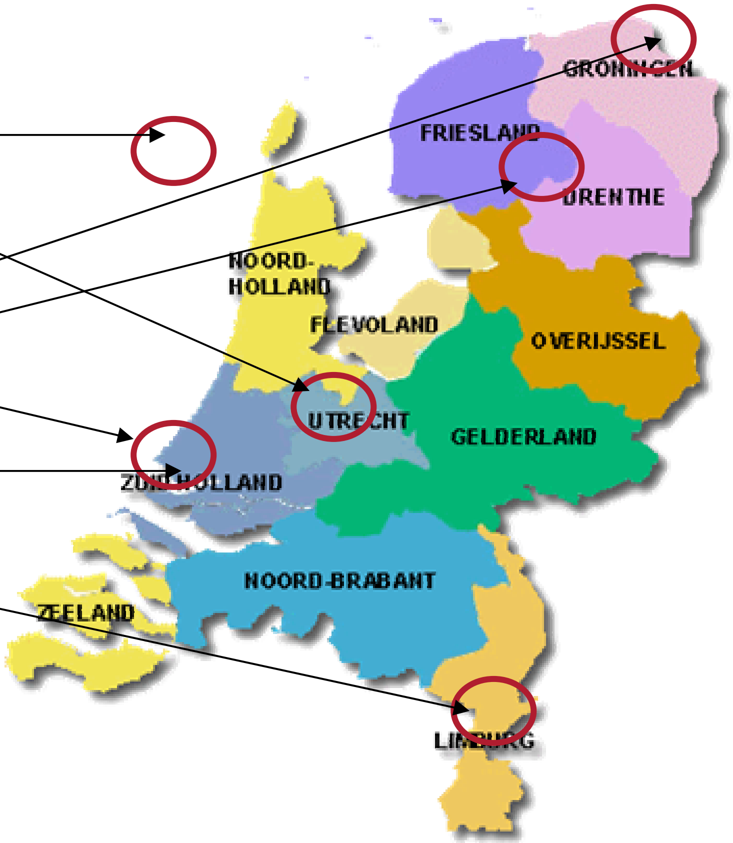


Operating temperature	Type of reaction	Active membrane
300-400°C	Water gas shift	Metal membrane
400-600°C	Low temperature reforming of methane	Metal membrane

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 CATO

Unique Dutch knowledge network in the area of CO_2 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)

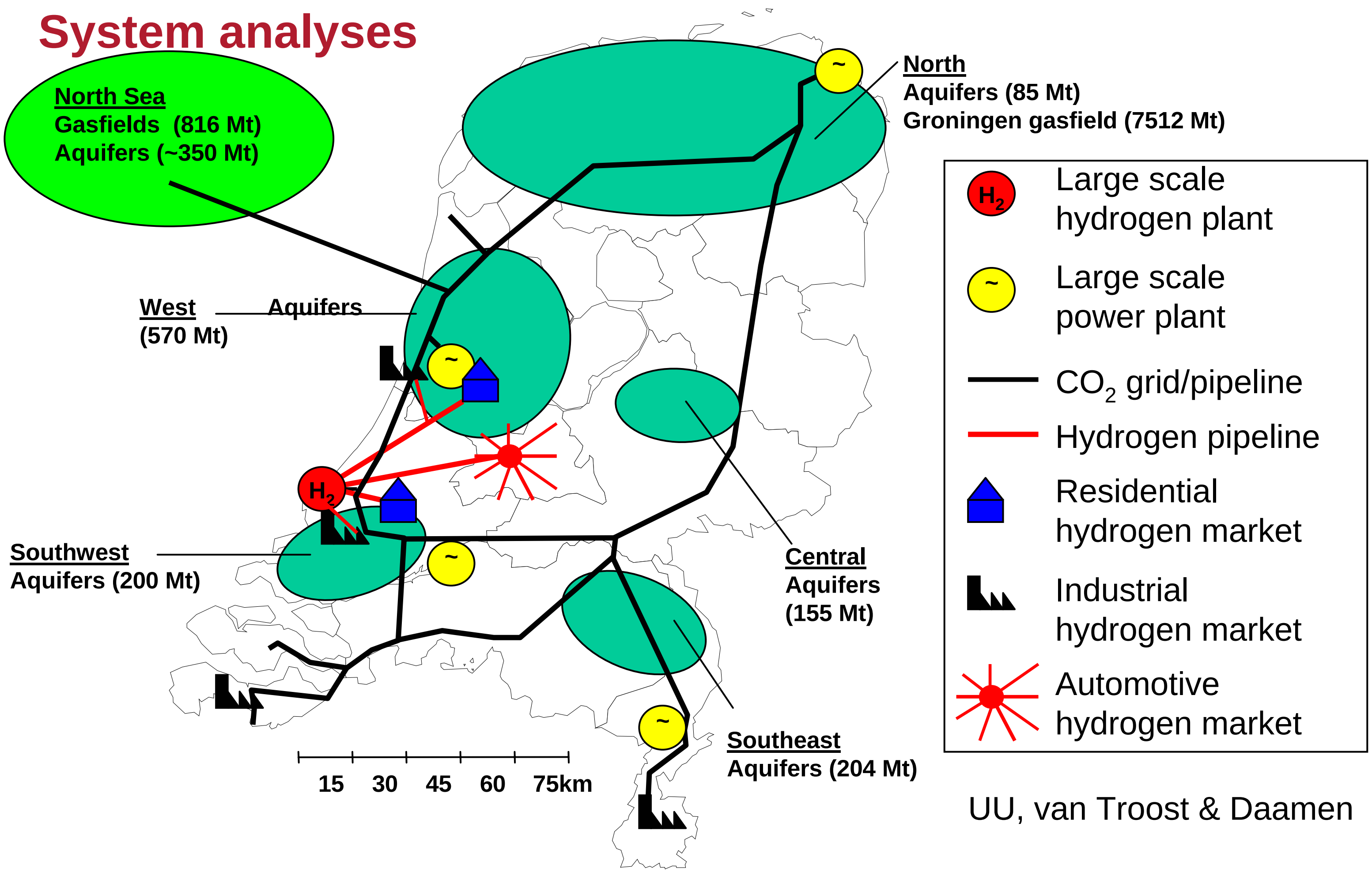
CCS projects in The Netherlands CATO

WP	Subject	WP Leaders
1	System analysis & Transition	UU-Copernicus Ecofys and ECN
2	Capture of CO_2 2.1 Post-combustion 2.2 Pre-combustion 2.3 Denitrogenated conversion	 TNO S&I ECN TNO S&I
3	Storage of CO_2 3.1 Storage gas fields 3.2 Storage coal fields (ECBM)	 TNO-NITG Shell (SIEP)
4	Mineralisation 4.1 Subsurface mineralisation 4.2 Surface mineralisation	 Shell (SIEP) ECN TNO S&I
5	Monitoring, safety and regulations	TNO-NITG
6	Communication	Leiden University
7	Management and knowledge transfer	UU-UCE

CCS projects in The Netherlands

CATO

System analyses



UU, van Troost & Daamen

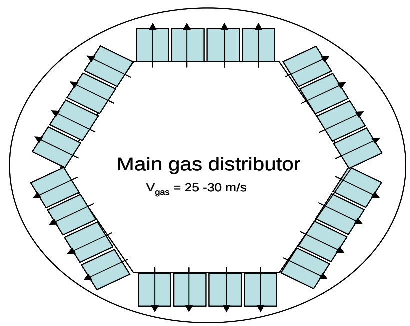
CCS projects in The Netherlands

CATO

Post combustion capture

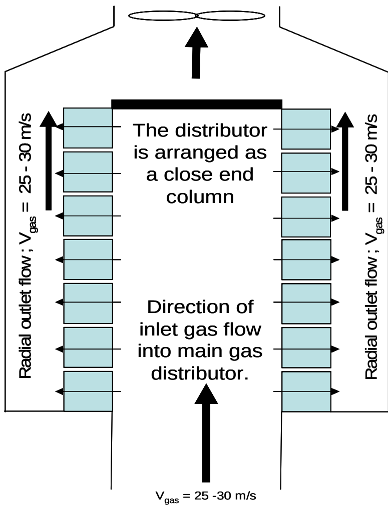
- CO_2 capture with solvent and membrane contactors
- CATO pilot plant in E.on PC boiler Maasvlakte in the Roterdam area
- 50% capture cost reduction
- Design for membrane aborber which is 4 times compactor the conventional absorbent

TOP VIEW



= Membrane module gas channel
Vgas = 2 m/s

SIDE VIEW



CCS projects in The Netherlands CATO

Pre combustion capture; Pd alloy membrane reactor

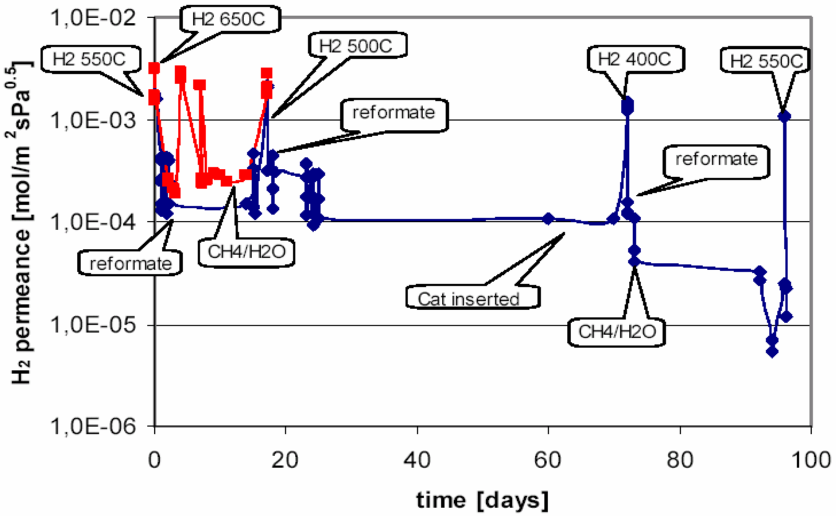
Steam reforming: $CH_4 + H_2O \rightleftarrows 3\,H_2 + CO$ (ΔH = 206 kJ/mol)

Water-gas shift: $CO + H_2O \rightleftarrows H_2 + CO_2$ (ΔH = - 41 kJ/mol)

$$CH_4 + 2\,H_2O \rightleftarrows 4\,H_2 + CO_2$$

Shifting the equilibrium to the product side

- **System analyse**
- **Membrane development**
- **Membrane reactor design**
- **Catalyst screening**
- **PDU tests**



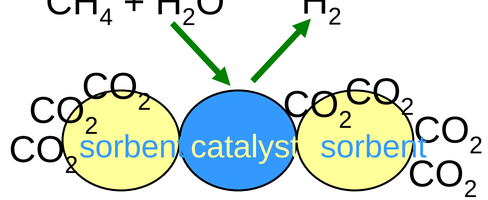
CCS projects in The Netherlands CATO

Pre combustion capture; Sorption Enhanced Reaction Process

Steam reforming: $CH_4 + H_2O \rightleftarrows 3\,H_2 + CO$ (ΔH = 206 kJ/mol)

Water-gas shift: $CO + H_2O \rightleftarrows H_2 + CO_2$ (ΔH = - 41 kJ/mol)

$CH_4 + 2\,H_2O \rightleftarrows 4\,H_2 + CO_2$

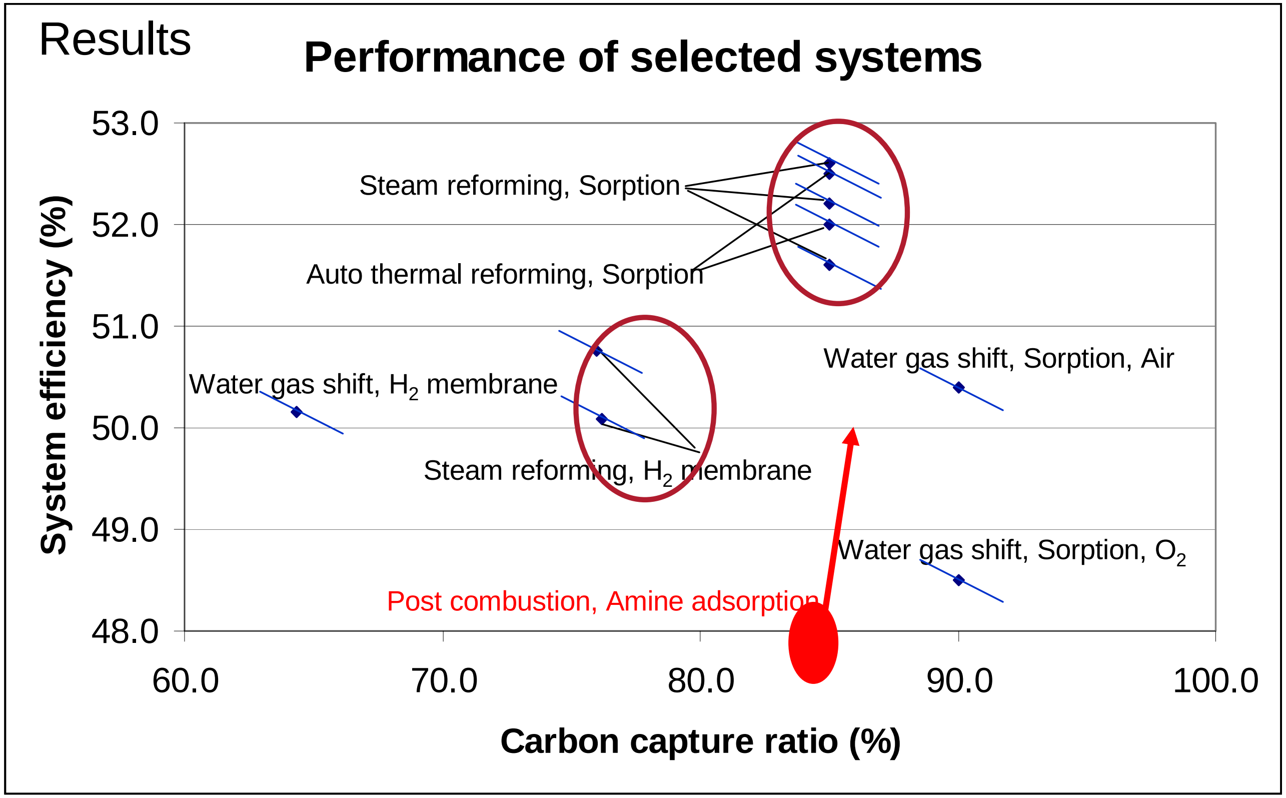


Sorption-enhanced Reforming

Shifting the equilibrium to the product side

- Hydrotalcite materials suitable for SE water gas shift reaction, not for SE reforming
- Hydrotalcites not stable > 450 ^{o}C
- Temperatures between 550 en 750 ^{o}C are needed for steam reforming
- New HT sorbents under development

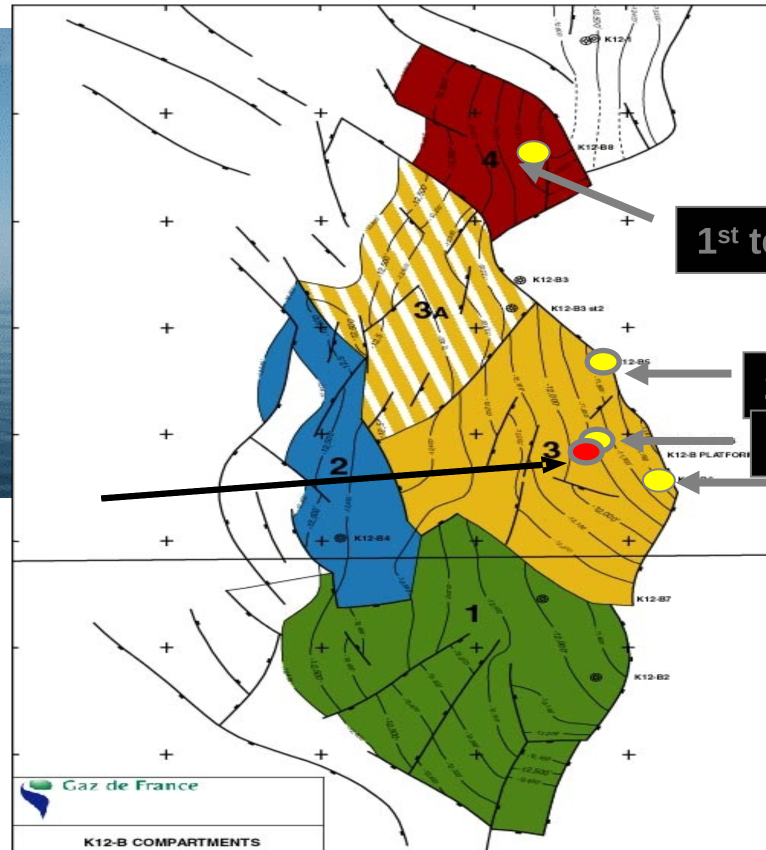
System evaluations : Pre combustion capture technologies



Reference power plant without CO_2 capture: 57.1% efficiency

CCS projects in The Netherlands CRUST

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

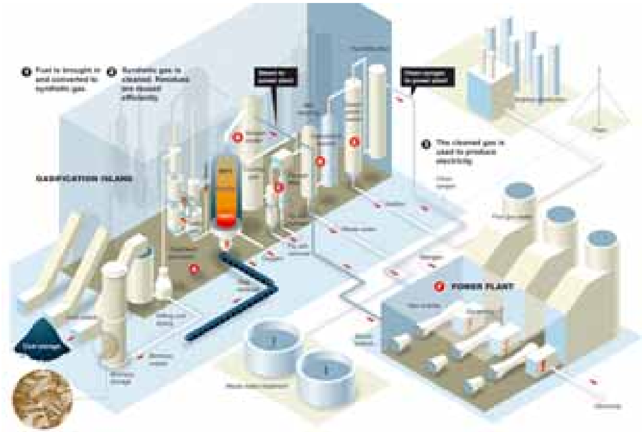
courtesy GdF Netherlands

CCS projects in The Netherlands OCAP

Industrial CO_2 re-use in greenhouses

- CO_2 from Shell Pernis,
- 170 kton CO_2 reduction

CCS Initiatives in The Netherlands



Nuon MAGNUM capture ready IGCC

SEQ oxy fuel ZEPP in Drachten

Nuon WAC Pre-combustion demo

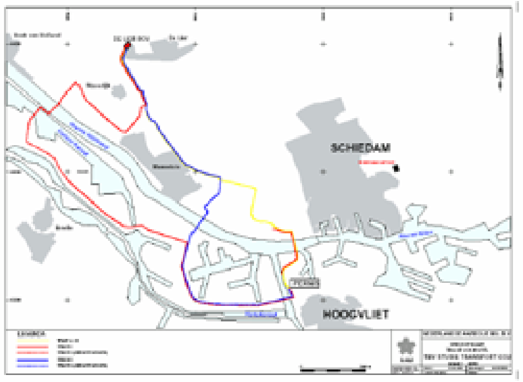


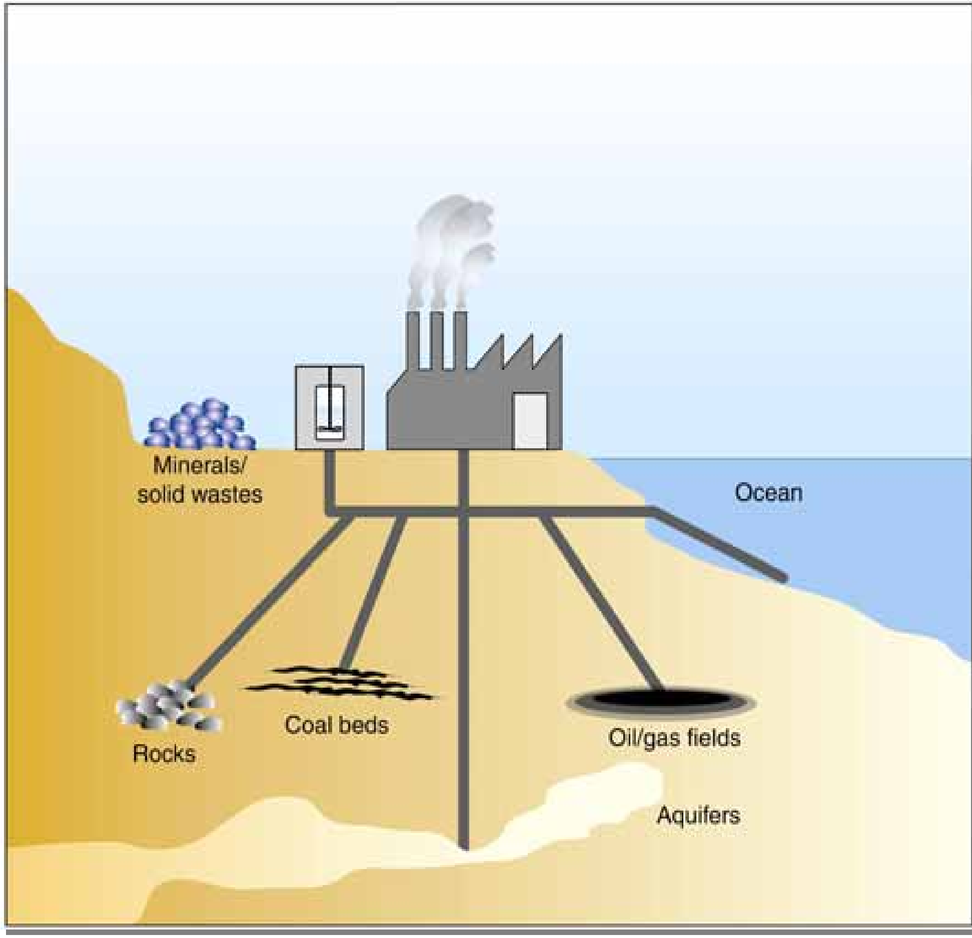
Figure 2 Map showing pipeline routes between Shell Pernis and De Lie r gas field

NAM CO_2 storage in de Lier

ECN CCS activities

DECAFF

- Pre-combustion decarbonisation
  - Sorption-enhanced reaction
  - Hydrogen-selective membrane reactors
  - CO_2 selective membrane reactors
- Oxyfuel combustion
  - SOFC + afterburner
  - Oxygen conducting membranes
- CO_2 re-use/storage
  - Mineralisation



Participation ECN in programs & projects

- **CATO:** Dutch national CO_2 program
  - Co-ordination Utrecht University
  - Running time 2004 – 2009
  - ECN co-ordinates the pre-combustion CO2 capture work package: hydrogen membranes and CO_2 sorbents

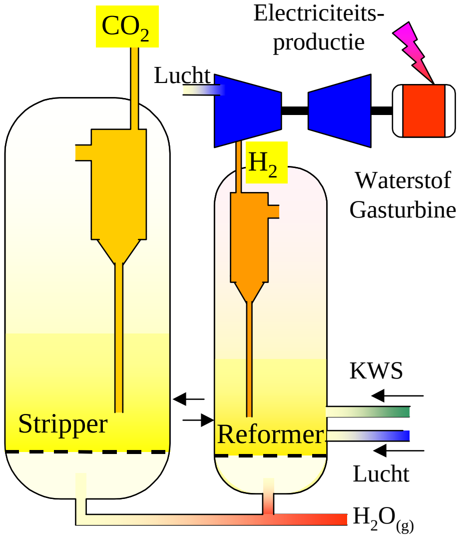
- **CACHET**: EU FP6 Integrated Project
  - Co-ordination BP
  - Running time 2006 until 2009
  - ECN co-ordinates membrane WP and participates in WP on sorption-enhanced Water Gas Shift coordinated by Air Products and is co-financed by CCP.

- **GCEP** (Global Climate and Energy Program)
  - Co-ordination: Stanford University
  - Running time 2005 -2008
  - Sponsors: ExxonMobil, Toyota, Schlumberger, GE
  - ECN carries out the project ‘Advanced membrane reactors for hydrogen production’ together with TU Delft. Development of a CO_2 separating membrane reactor.

Participation ECN in programs & projects

National EOS projects

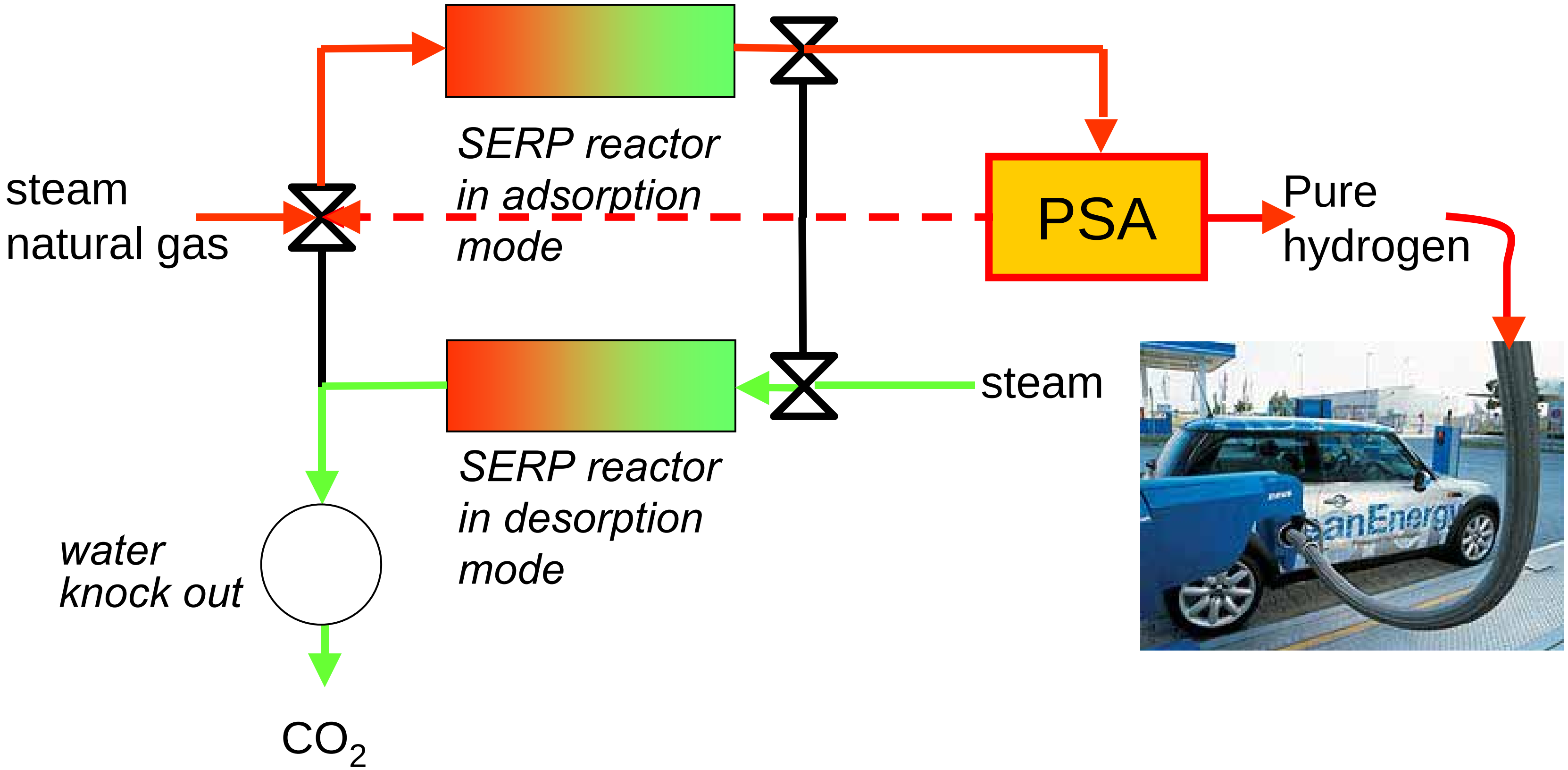
- **C- CLEAR**
  - Continuous SERP for “ZEPP”
  - Co-ordination: ECN
  - running time 2005-2008
- **CATHY**
  - Catalysts for Separation enhanced reformers
  - Co-ordination:ECN
  - running time 2006 –2009
- **CAPTECH:** extension to CATO
  - Capture technologies for IGCC and PC
  - Co-ordination: ECN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



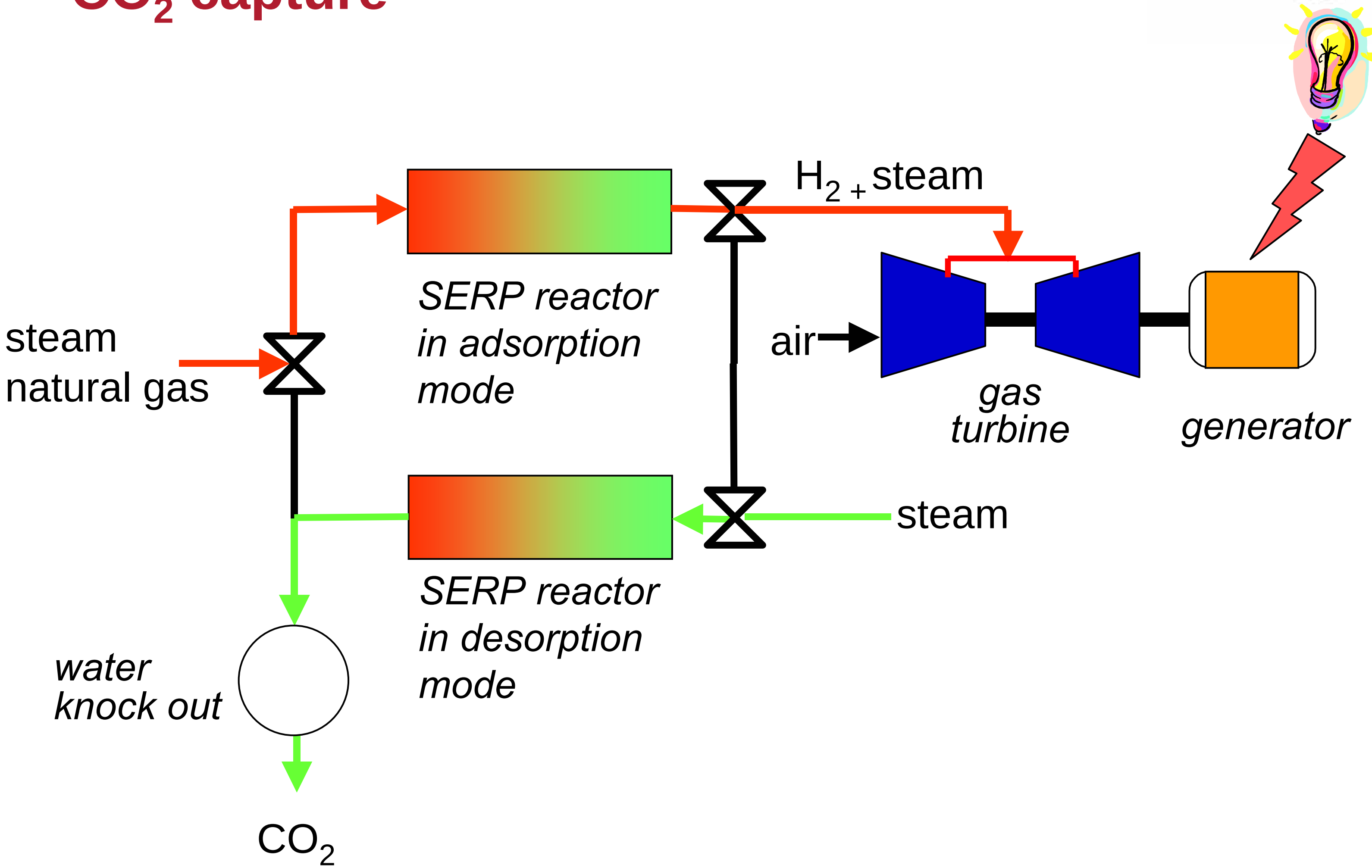
EU IP projects

- **CO2ReMOVE** (Policy studies, H_2&CFF)
  - CO_2 monitoring and verification
- **ACCEPT** (Policy studies)
  - Public Acceptance of CO_2 storage, economics, Policy and technology

SERP for hydrogen production with CO_2 capture



SERP for electricity production with CO_2 capture

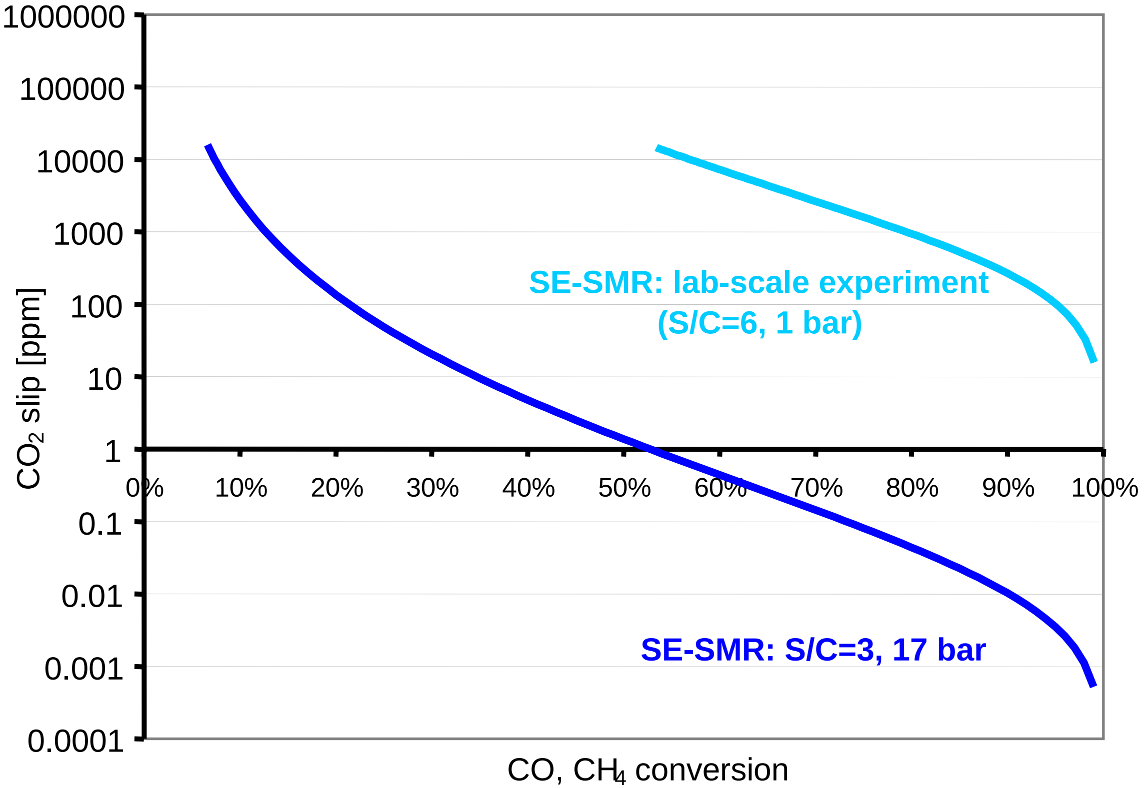


Shifting the equilibrium

Steam reforming

$$CH_4 + 2H_2O \rightleftharpoons 4H_2 + CO_2$$

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



SERP: Shifting the equilibrium

Steam reforming

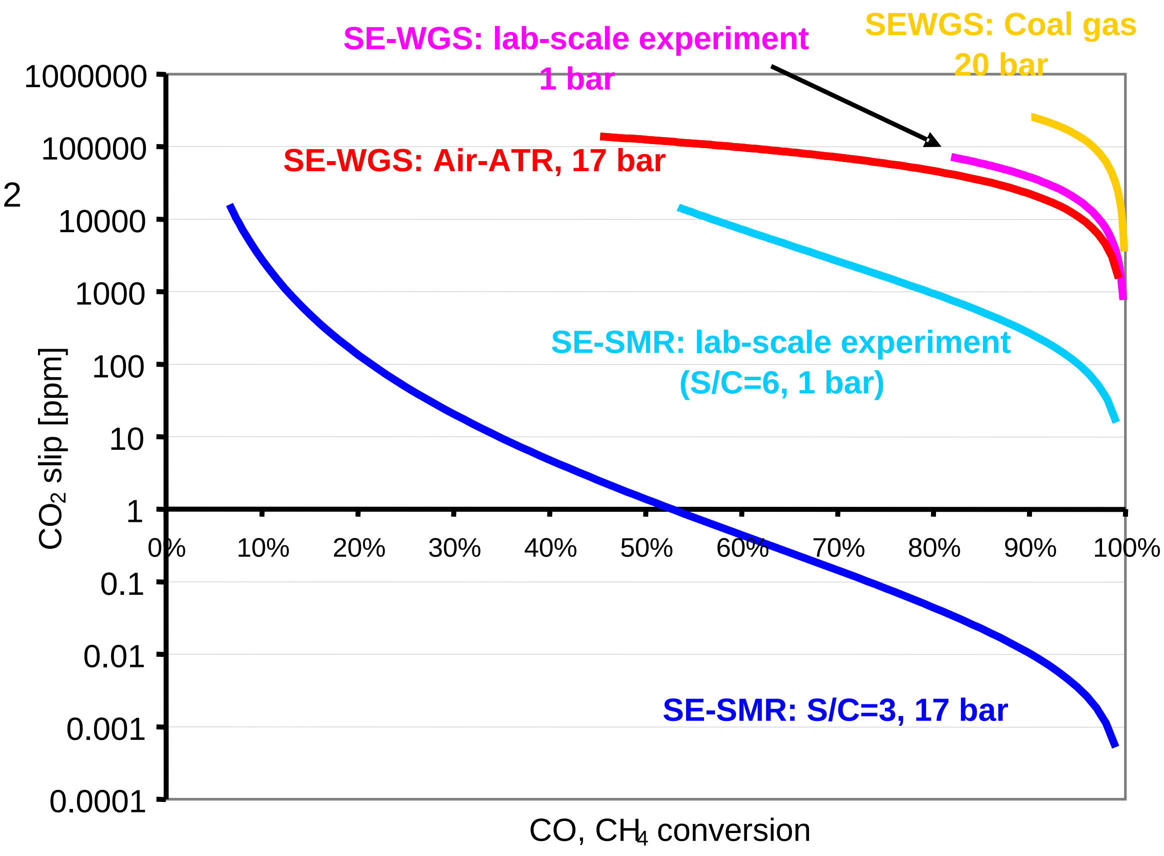
$$CH_4 + 2H_2O \rightleftharpoons 4H_2 + CO_2$$

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

Water gas shift

$$CO + H_2O \rightleftharpoons H_2 + CO_2$$

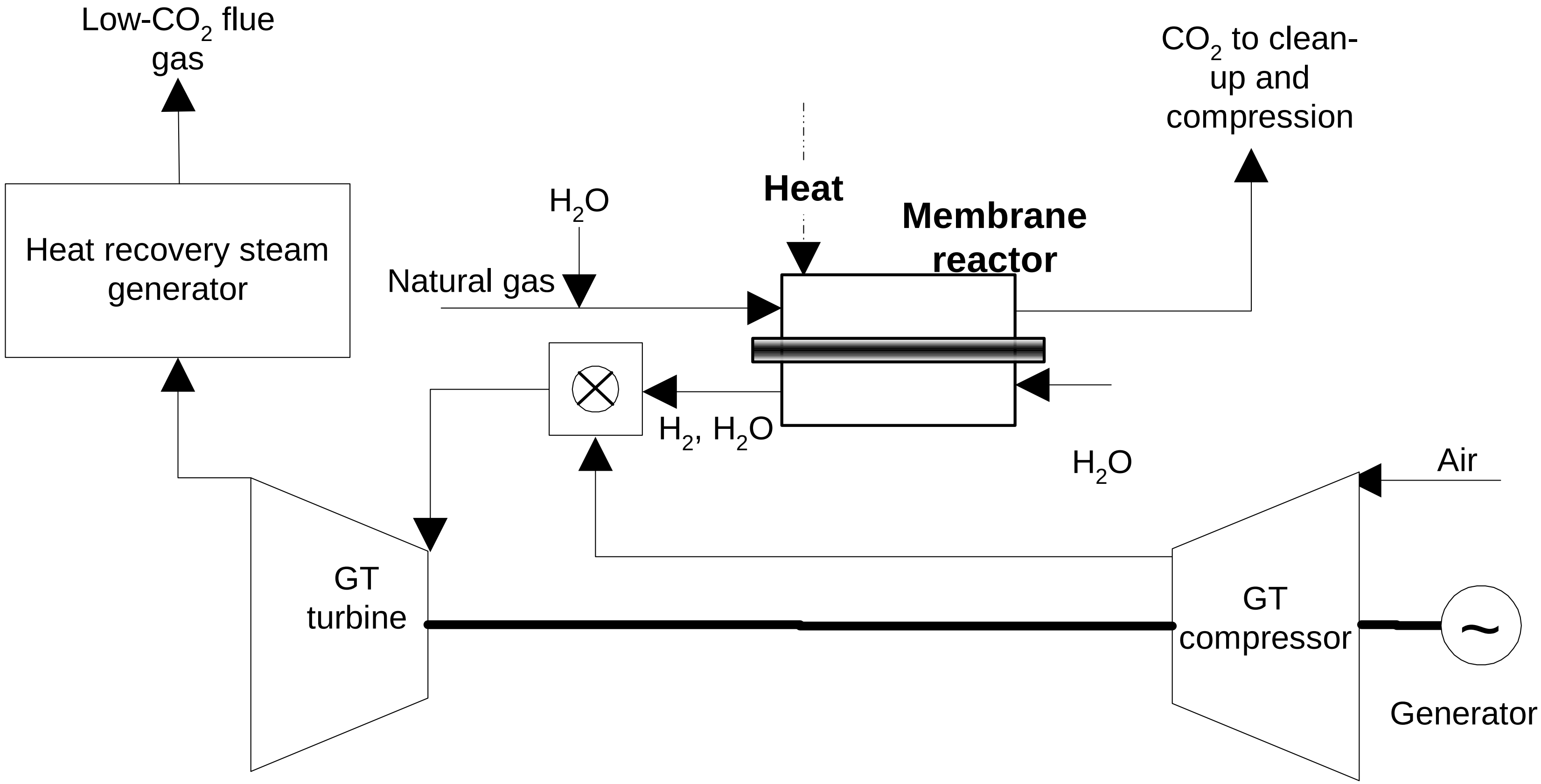
$$K_{eq} = \frac{[CO_2][H_2]}{[CO][H_2O]}$$



ECN CCS activities

DECAFF

Hydrogen-selective membrane reactors



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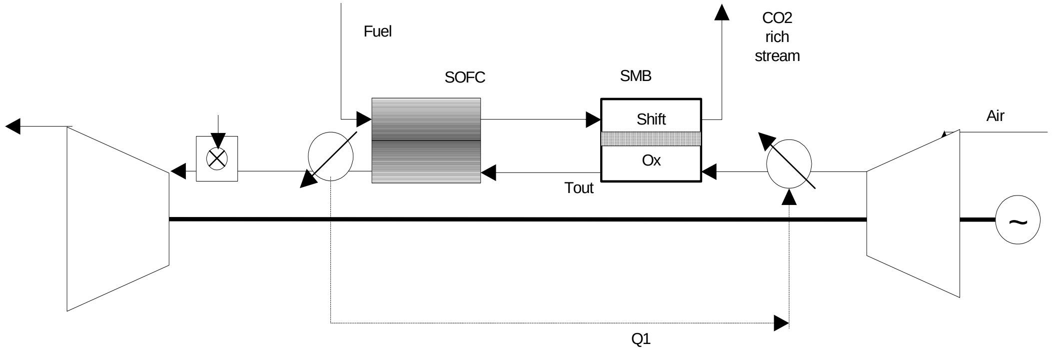
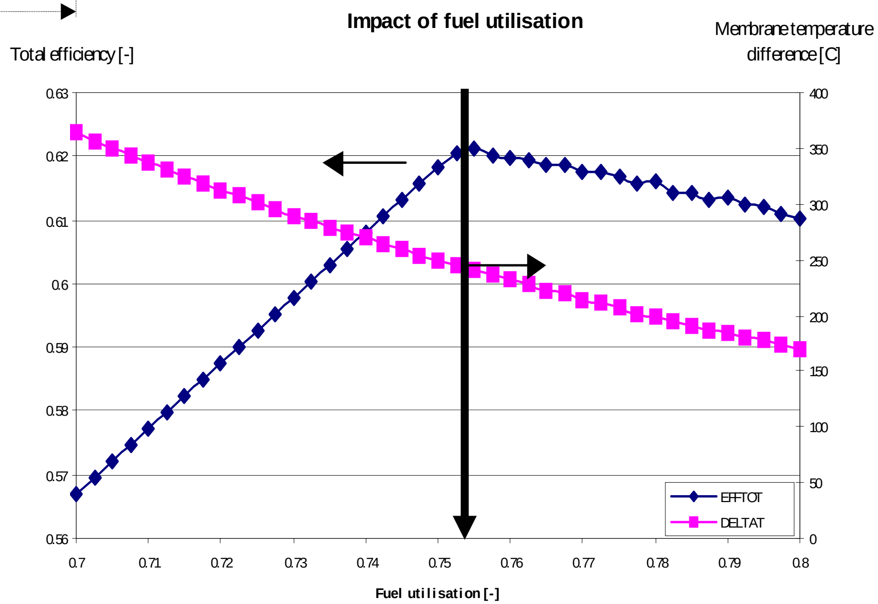
ECN CCS activities DECAFF

Power generation in SOFC with H2-MR



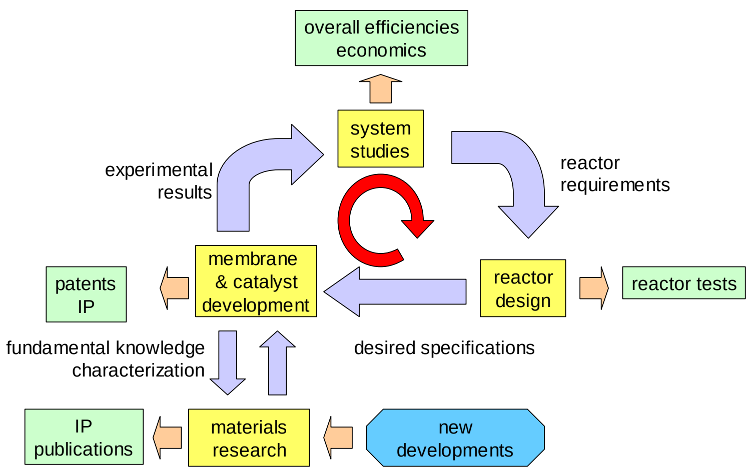
- Efficiency up to 62% LHV
- Fuel utilisation SOFC is key parameter



CCS projects at ECN GCEP

CO_2 separating membranes for advanced energy systems

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

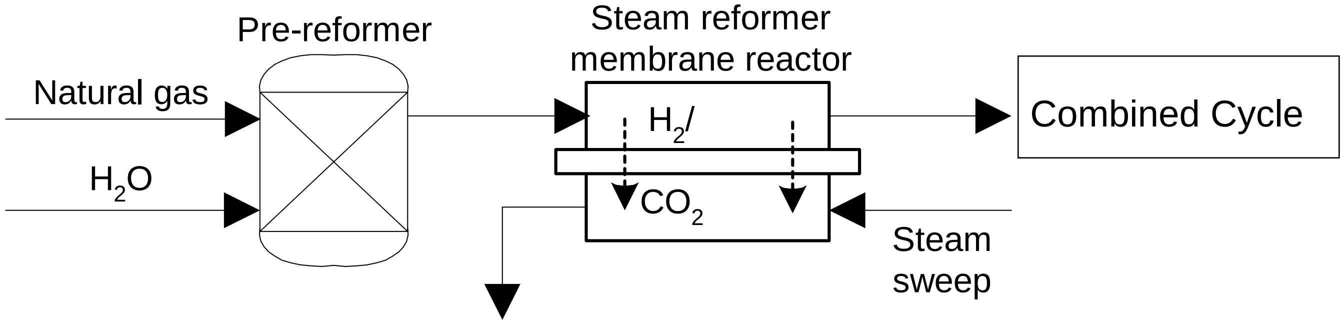


Task 1.	System analysis and thermodynamic evaluations	Executed by ECN
Task 2.	Hydrogen membrane research & development	Executed by TUD
Task 3.	CO_2 membranes research & development	Executed by ECN+TUD
Task 4.	Catalyst screening	Executed by ECN
Task 5.	Reactor modelling and design	Executed by ECN

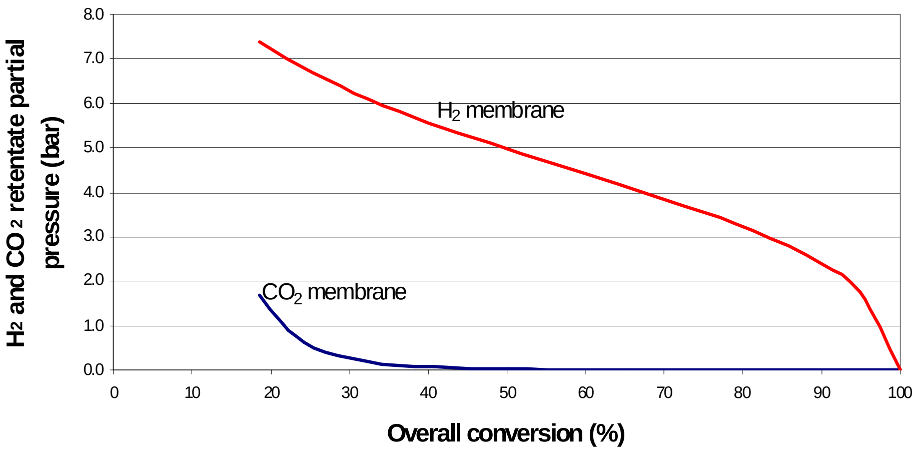
CCS projects at ECN

GCEP

Steam Reforming



Membrane reformer: Residual partial pressure of permeating compontent 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)

- *Conversion relatively easy enhanced by separation of H_2 → favourable kinetics*

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

ECN CCS activities DECAFF

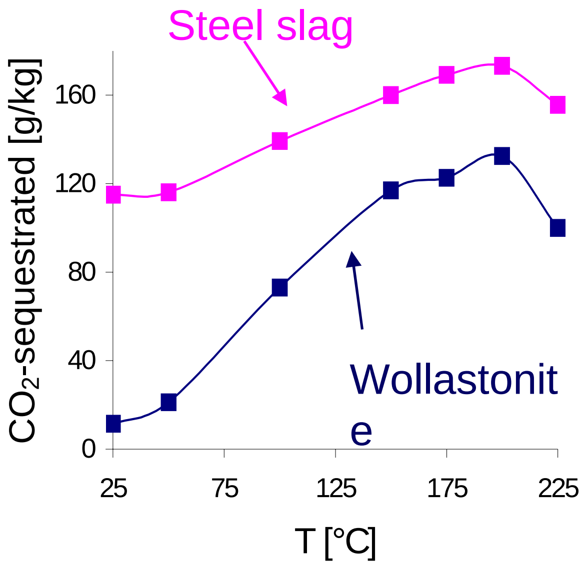
Mineral CO_2 sequestration in alkaline solid waste

Main route of natural CO_2 sequestration:

→ weathering of (Ca,Mg)-silicates

$$CaSiO_3\ (s) + CO_2\ (g) \rightarrow CaCO_3\ (s) + SiO_2\ (s)$$

$$\Delta H_r = -87\ kJ/mol\ \&\ \Delta G_r = -44\ kJ/mol$$

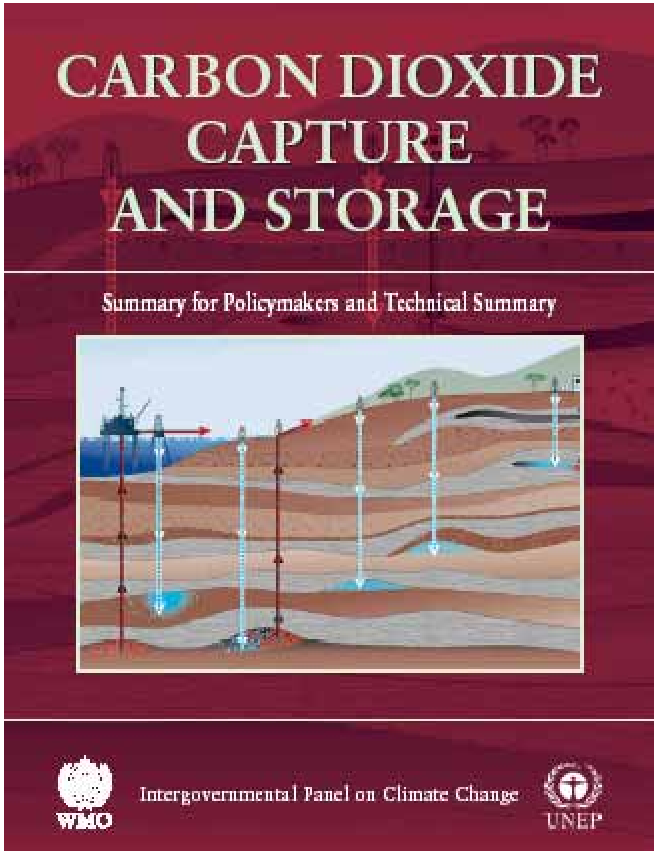


d < 106 μm, p_{CO2} = 20 bar

ECN CCS activities

DECAFF

IPCC special report CCS



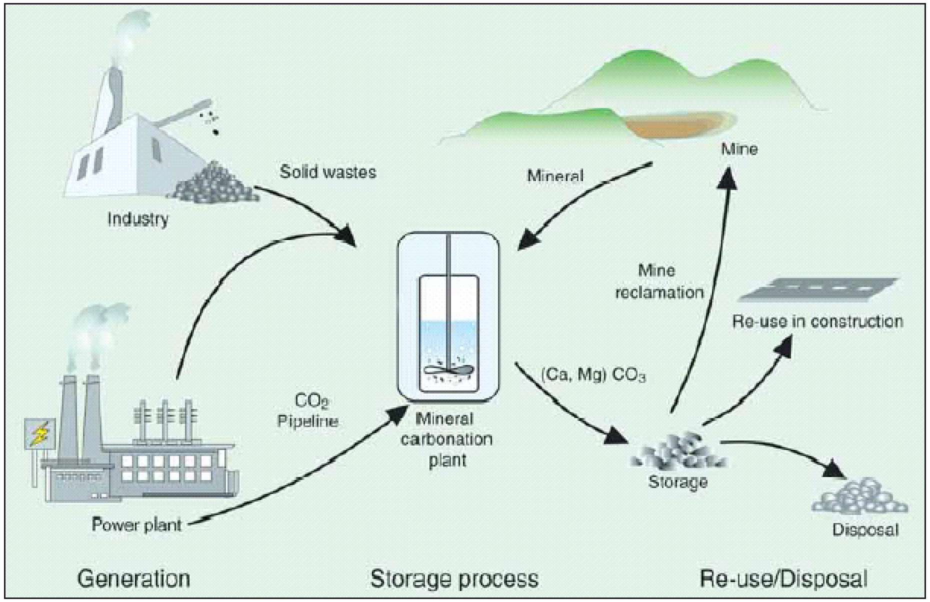


Figure TS.10. Material fluxes and process steps associated with the mineral carbonation of silicate rocks or industrial residues (Courtesy ECN).

Down load: WWW.IPCC.CH

Overview European CCS activities and R&D work at ECN

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