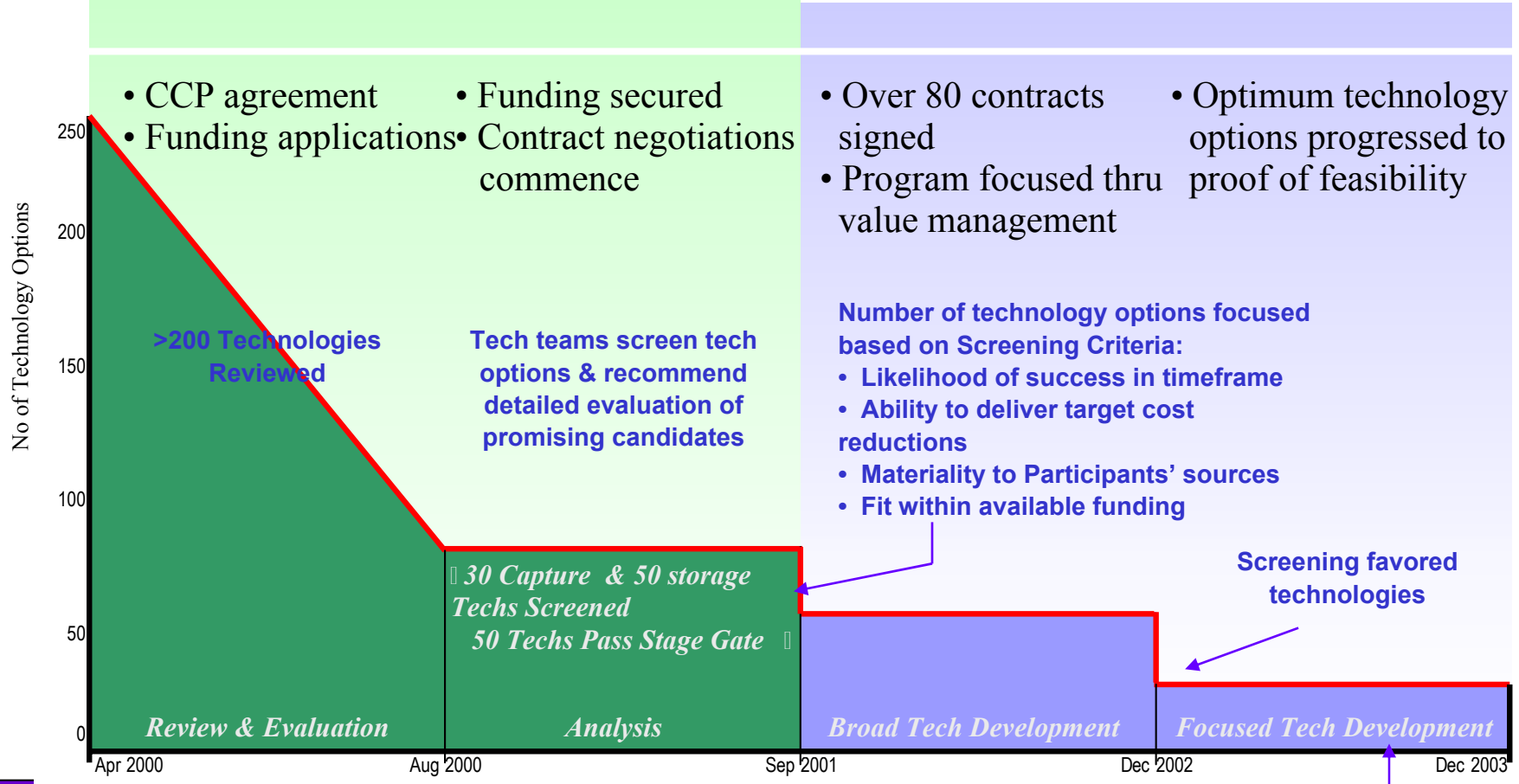
CCP2 CAPTURE PROGRAMME

Washington DC. November 2, 2005

CO_2 Capture Project

BUILDING ON CCP1 RESULTS



CO_2 Capture Project

- **CCP1 favored technologies achieved:**

  - ✓ **Proof-of-Feasibility**
    - **Concept successfully tested at the lab scale**
    - **Critical items for development identified.**
  - ✓ **Potential for consistent reduction in CO_2 Capture costs compared to currently available technology.**

CCP2 Technology Portfolio
Main Features

- **Technologies with different "time to market" in a sequenced approach:**
  - **Short Term (by 2010)**
  - **Mid-Term (2010-2012)**
  - **Long Term (by 2015)**
- **Emphasis on Pre-Combustion technology, but continuation of most promising Post-Combustion and Oxy-firing Projects.**

CCP2 Capture Program Targets

- **Achieve significant progress for each technology:**
  - **Scaling-up successfully operation by at least one order of magnitude.**
  - **Addressing and solving critical issues identified in CCP1**

- **At least one technology ready for field demonstration by the end of the Project.**

CCP2 Capture Program Timeline

- **2004**
  - **Selection of Technology Portfolio.**
  - **Preparation of Project Proposals.**
  - **Submission to Governmental funding entities (Oct-Dec).**

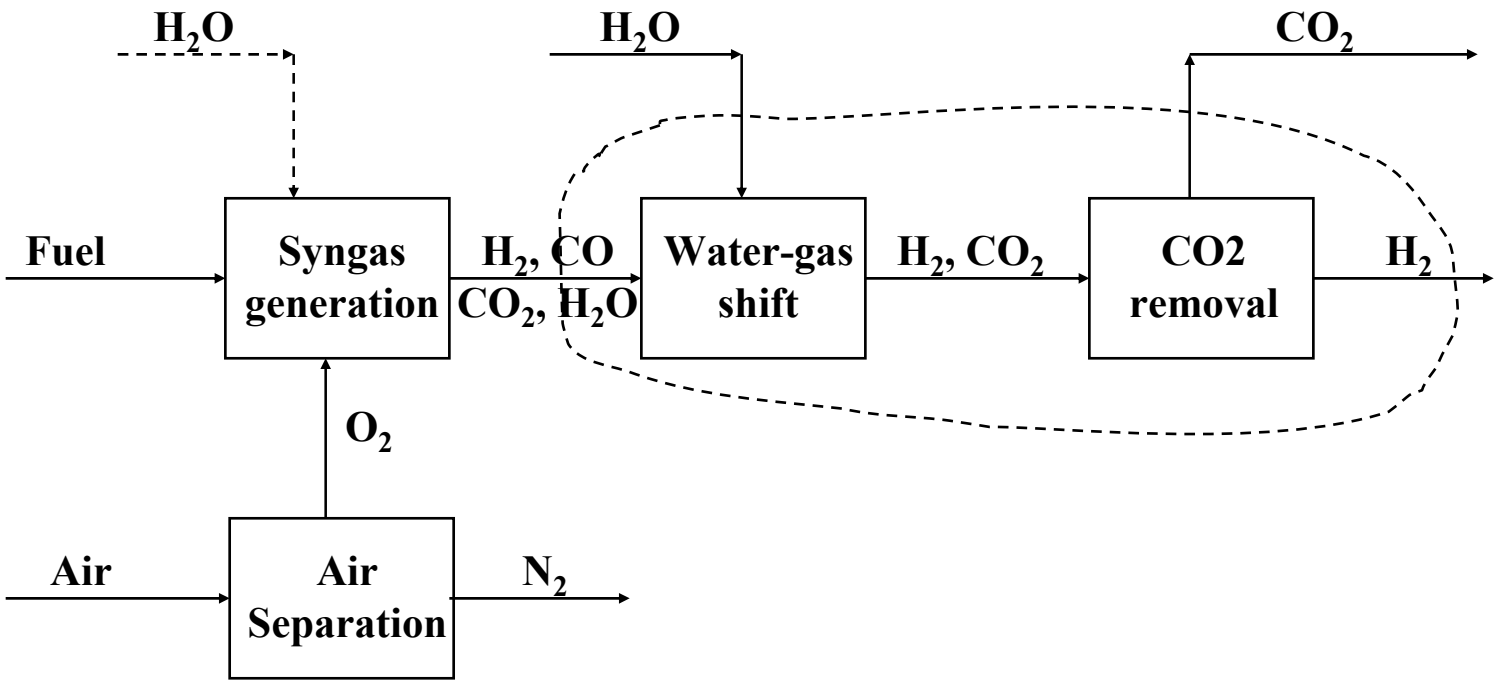
- **2005**
  - **Approval of Project Proposals (Mar-May).**
  - **Definition of further needs .**
  - **Start Technical Program (Sep-Dec).**
  - **Prepare additional proposal if necessary.**

- **2006-2008**
  - **Run technical Program to completion maintaining stage gate approach.**
  - **Update economical evaluations.**
  - **Continue monitoring of novel concepts and competing technologies.**

The CCP2 Portfolio (Aug. 2005)

- **Pre-Combustion**
  - **CO2 separation technologies**
    - **Membrane Water Gas Shift (MWGS)**
    - **Sorption Enhanced Water Gas Shift (SEWGS)**
  - **Novel Syngas/Hydrogen production technologies**
    - **Hydrogen Membrane Reforming (HMR)**
    - **Chemical Looping Reforming**
    - **One-Step Hydrogen**
    - **HyGenSys**
    - **Membrane Reforming**

CO_2 Capture Project



The CCP2 Portfolio (Aug. 2005)

- **Post-Combustion**
  - **BIT (Best Integrated Technology)**
- **Oxy-firing**
  - **Chemical Looping Combustion (CLC)**

The CCP2 Projects

- **Three major Projects approved:**
  - **CLIMIT (Co-Funder Norwegian Council for Research)**
  - **CACHET (Co-Funder European Union)**
  - **CLCGASPOWER (Co-funder European Union)**

CO_2 Capture Project

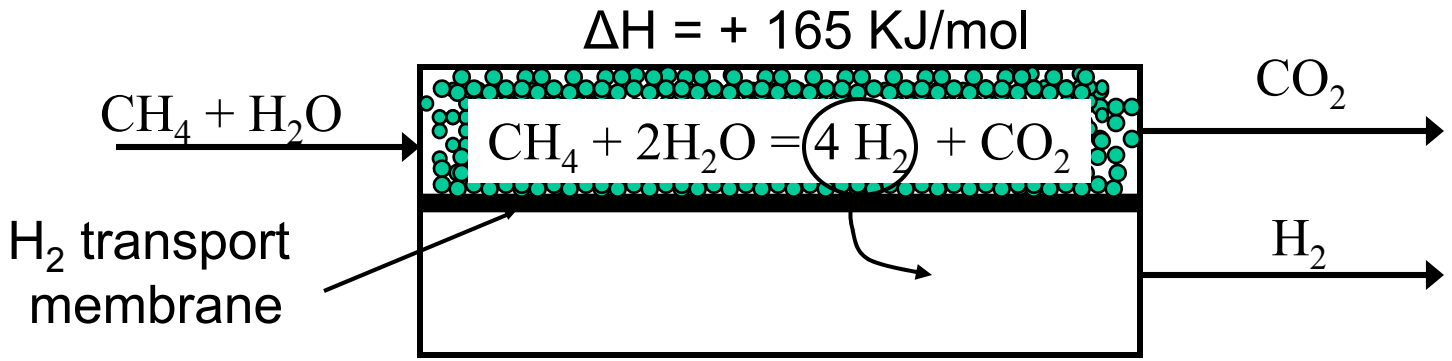
CLIMIT

- **Co-Funder: Norwegian Council for Research)**
- **Duration: 36 Months**
- **Total Budget: ~ 7 MM$ (subject to exchange rate)**
  ~ 90% Capture
- **Technologies Included:**
  - **HMR (Hydro): 36 Months**
  - **MWGS (Sintef) : 6 Months**
  - **BIT (GE) : 12 Months**

CO_2 Capture Project

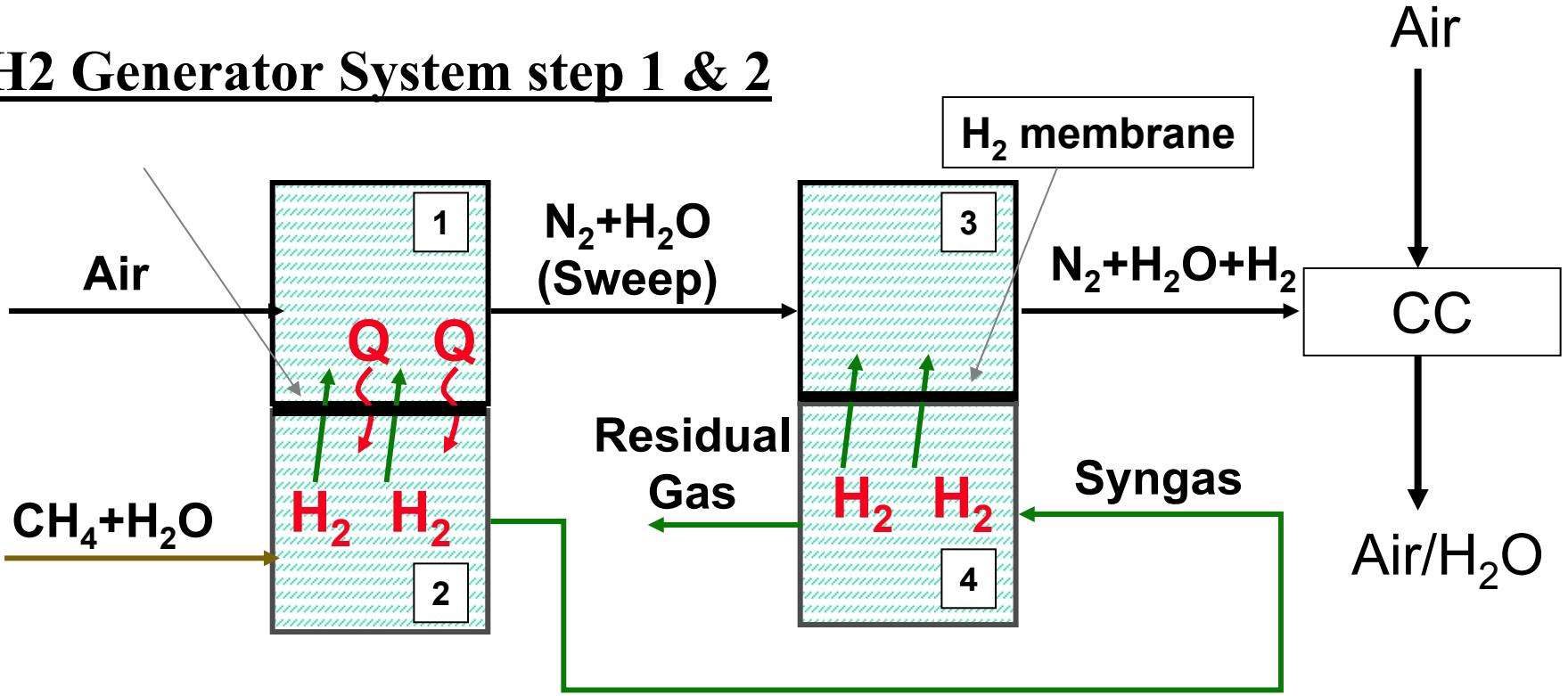
Hydrogen Membrane Reformer: The Concept

- **Combination of reforming reactor and separation**
- **Extract product gas (H_2) from reactor, no traditional CO_2 removal system required**
- **Drive equilibrium limited reactions towards completion**
- **Expand allowed range of temperatures and pressures**



CO_2 Capture Project

H2 Generator System step 1 & 2



1 $\frac{1}{2} O_2+H_2 = H_2O$

3 Sweep

2 $CH_4+H_2O = CO+3H_2$
$CO+H_2O = CO_2+H_2$

4 $CH_4+H_2O = CO+3H_2$
$CO+H_2O = CO_2+H_2$

Hydrogen Membrane Reforming

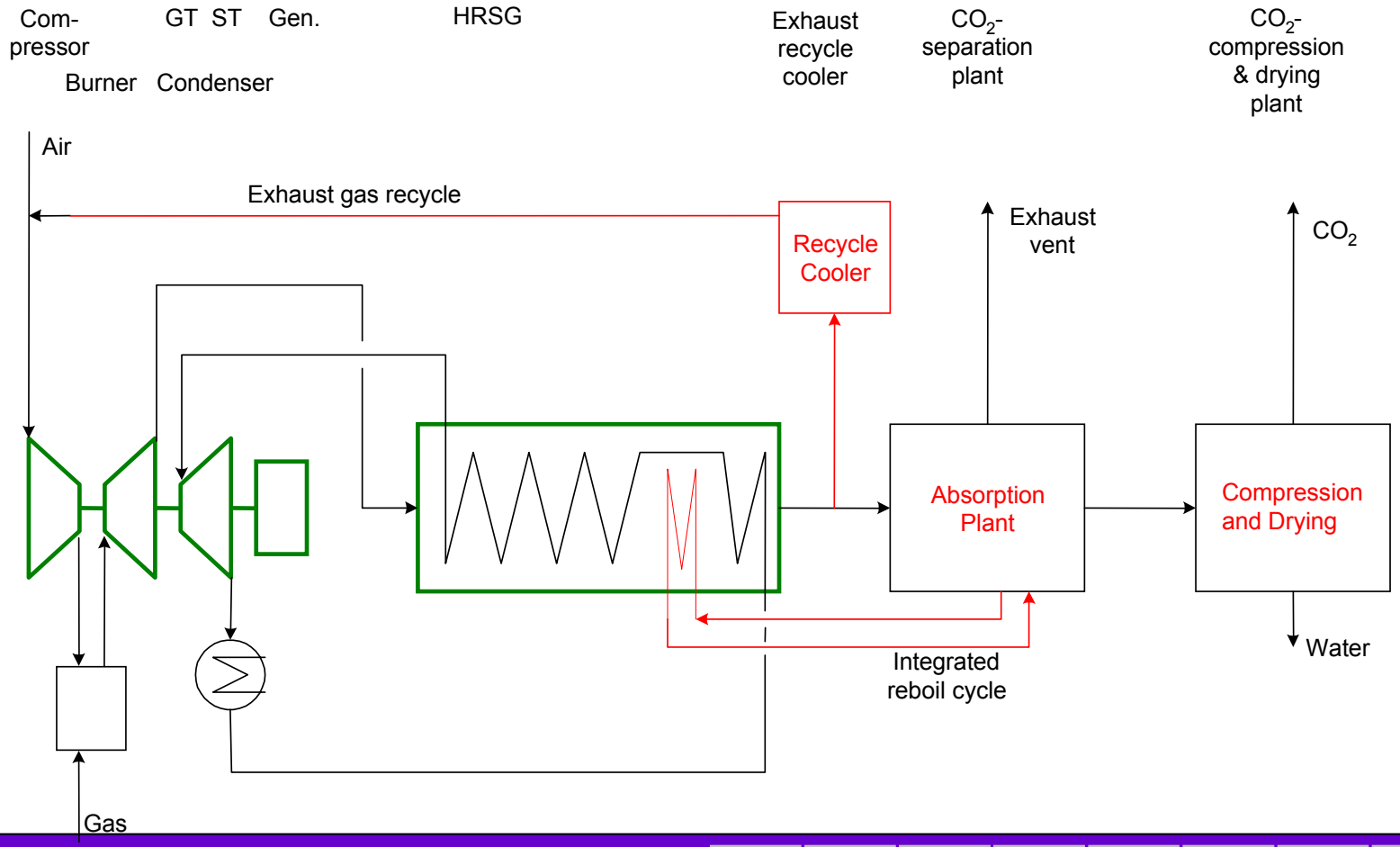
- **Strategic Features**
  - **Long Time to Market (2015)**
  - **High Potential for Cost Reduction**
  - **Application to Power Generation from Natural Gas**

- **CCP1 Achievements**
  - **Developed materials with good permeability and stability**
  - **Developed method for manufacturing supported membranes in the form of small tubes (10cm length, overall diameter 8mm).**

Hydrogen Membrane Reforming

- **CCP2 Expected Development**
  - **Develop membranes in the form of monoliths.**
  - **Successfully test at the laboratory level 2X2 cm monoliths.**
  - **Fabricate 7x7 cm monoliths that will form the base unit for pilot plant (25 kW).**
  - **Review and optimize process scheme including collaboration with turbine vendor.**

Best Integrated Post-Combustion Technology



Best Integrated Post-Combustion Technology

- **Strategic Features**
  - **Short Time to Market (2008-2010)**
  - **High Potential for Cost Reduction**
  - **Application to Power Generation from Natural Gas**

- **CCP1 Achievements**
  - **Developed low-cost integrated process scheme based on application of concepts developed in engineering study.**

Best Integrated Post-Combustion Technology

- **CCP2 Expected Development**
  - **Assess feasibility and constraints of flue gas recycle to combustor.**
  - **Contribute to development of novel solvents.**
  - **Review and further optimize the CCP1 process scheme.**
  - **Include novel concepts udner development.**

CO_2 Capture Project

CLCGASPOWER

- Co-Funder: European Union
- Type of Project: STREP
- Duration: 30 Months
- Total Budget: ~ 2.8 MM$ (subject to exchange rate)
- Single Technology Development of Chemical Looping Combustion by a Consortium formed by:

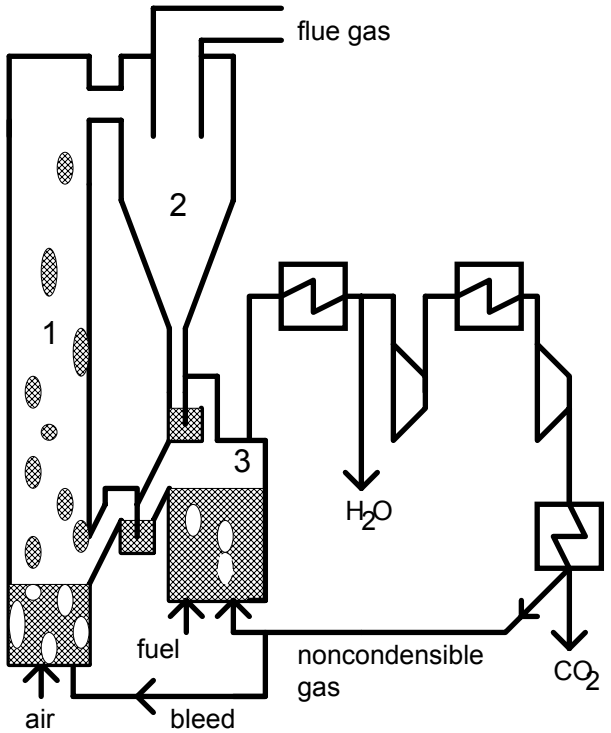
  - Chalmers University of Technology
  - Alstom Boilers
  - CSIC
  - Shell
  - Vienna University of Technology
  - Tallinn University of Technology

CO_2 Capture Project

Chemical Looping Combustion

- Chemical Looping is a new combustion technology based on oxygen transfer from combustion air to the fuel by means of a metal oxide acting as a solid carrier. Core of the technology is a two-reactors system with continuous circulation of solids:

- Fuel reactor: $4MeO + CH_4 \Rightarrow 4Me + 2H_2O + CO_2$
- Air reactor: $4Me + 2O_2 \Rightarrow 4MeO$



Chemical Looping Combustion

- **Strategic Features**
  - **Mid Time to Market (2010-2012)**
  - **High Potential for Cost Reduction**
  - **Application to gas fired boilers/ steam turbine power generation**
- **CCP1 Achievements**
  - **Developed materials with good activity by extensive screening and development.**
  - **Achieved proof-of feasibility in a 10kW bench scale unit with continuous solid circulation.**

Chemical Looping Combustion

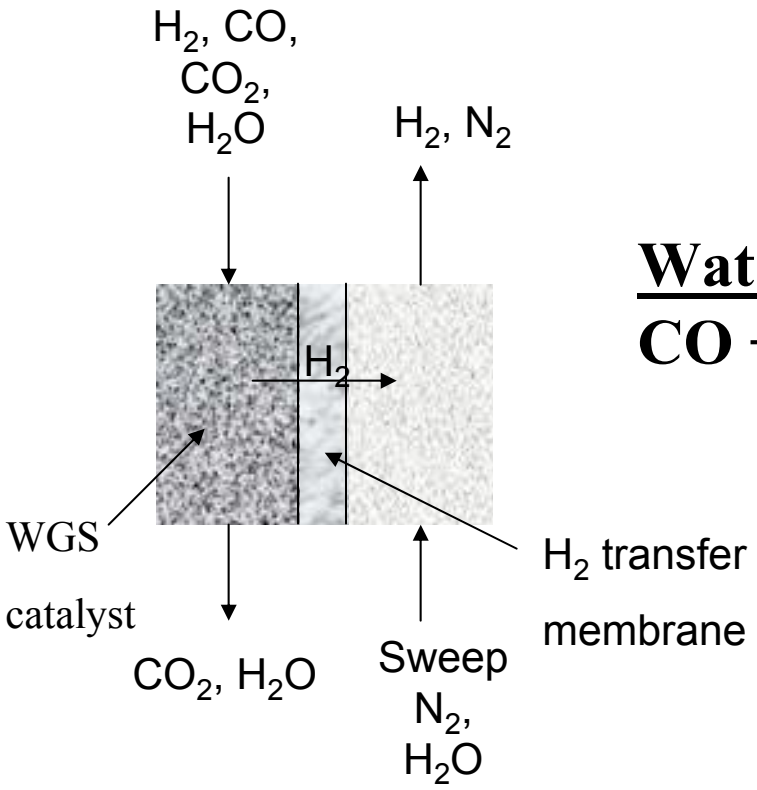
- **CCP2 Expected Development**
  - **Assess long time resistance (both chemical and mechanical) of developed materials**
  - **Scale-up to 200kW pilot unit c/o Vienna University of Technology.**
  - **Prepare concept design for demo unit (20-50 MW).**

CO_2 Capture Project

CACHET

- Co-Funder: European Union
- Type of Project: Integrated Project for Production of Hydrogen from Natural Gas with CO_2 Capture
- Duration: 36 Months
- Total Budget: ~ 16.5 MM$ (subject to exchange rate)
- Consortium of 29 Partners from 18 Countries.
- Targets:
  - Develop in parallel to "ready-for-pilot" several novel hydrogen production and pre-combustion CO_2 Capture Technologies.
  - Identify optimal process scheme through optimized integration of technologies driven by economic evaluation.

Membrane Water Gas Shift



Water gas shift

$CO + H2O \leftrightarrow CO2 + H2$

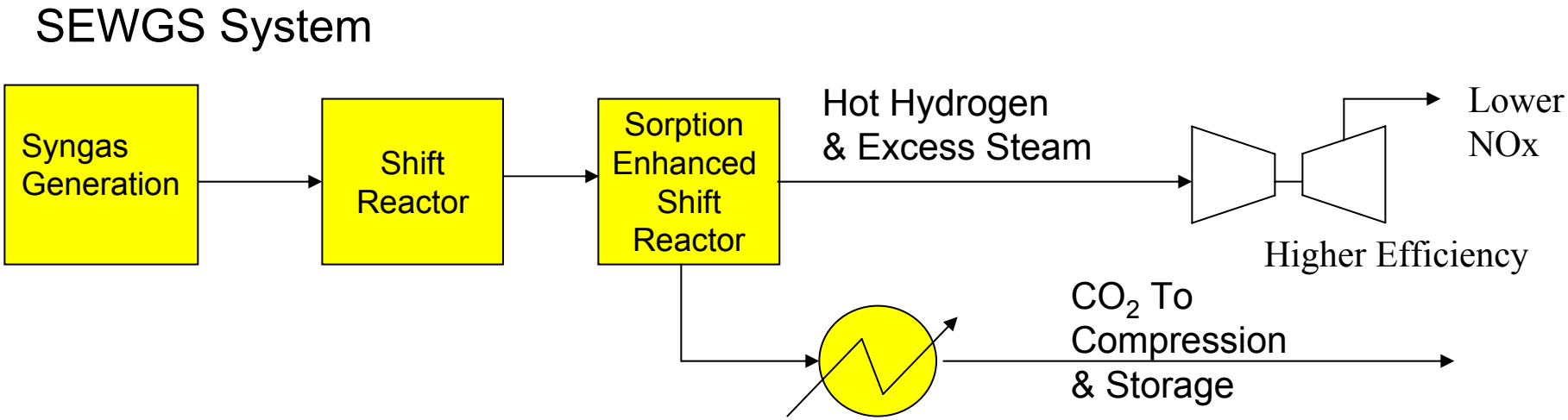
Membrane Water Gas Shift

- **Strategic Features**
  - **Mid Time to Market (2010-2012)**
  - **Mid Potential for Cost Reduction**
  - **Preferential application to heaters/boilers or steam turbine power generation from natural gas.**
- **CCP1 Achievements**
  - **Developed very thin palladium layers (< 5μ) supported on porous stainless steel (SINTEF)**
  - **Developed vanadium membranes in palladium layers sandwich to improve permeability (Eltron).**

Membrane Water Gas Shift

- **CCP2/CACHET Expected Development (SINTEF/ECN)**
  - **Develop and test supported palladium membranes in the form of 1 meter long tubes (I.D. 12.5 mm)**
  - **Build and operate a bench scale reactor module (12 tubes) with hydrogen production roughly equivalent to 15-30 kW.**
- **Further development of Eltron membranes**
  - **Option to include in CCP2 Portfolio development in a DOE co-funded Project under evaluation.**

Sorbent Enhanced Water Gas Shift



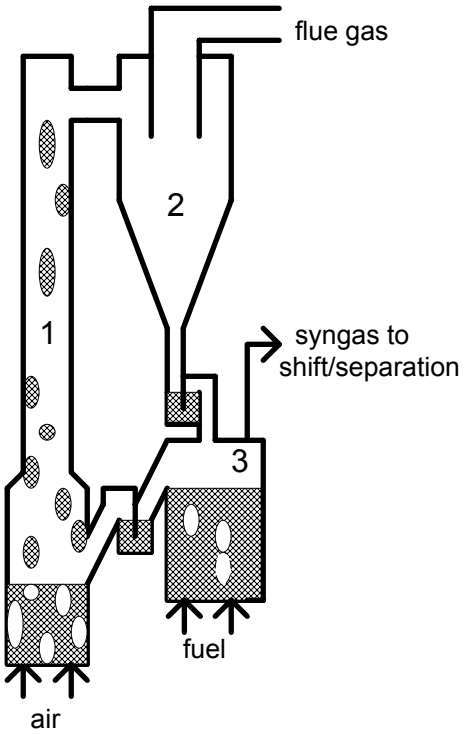
Sorbent Enhanced Water Gas Shift

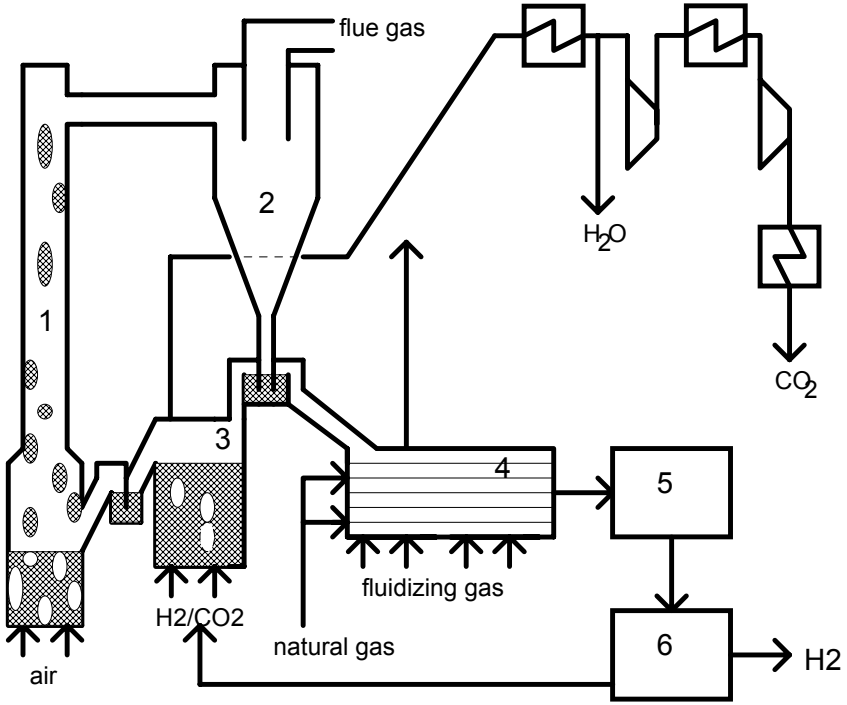
- **Strategic Features**
  - **Short Time to Market (by 2010)**
  - **Mid/High Potential for Cost Reduction**
  - **Preferential application to power generation from natural gas in combined cycle.**
- **CCP1 Achievements (Air Products)**
  - **Develop modified hydrotalcites with good adsorption properties.**
  - **Successfully tested in a single lab reactor with alternate adsorption/desorption.**

Sorbent Enhanced Water Gas Shift

- **CCP2 Expected Development (Air Products/ECN)**
  - **Further optimization of adsorbent materials.**
  - **Build and operate a lab unit with 7 reactors in parallel to simulate the commercial operating cycle. Reactors with full commercial length and small diameter.**

Chemical Looping Reforming



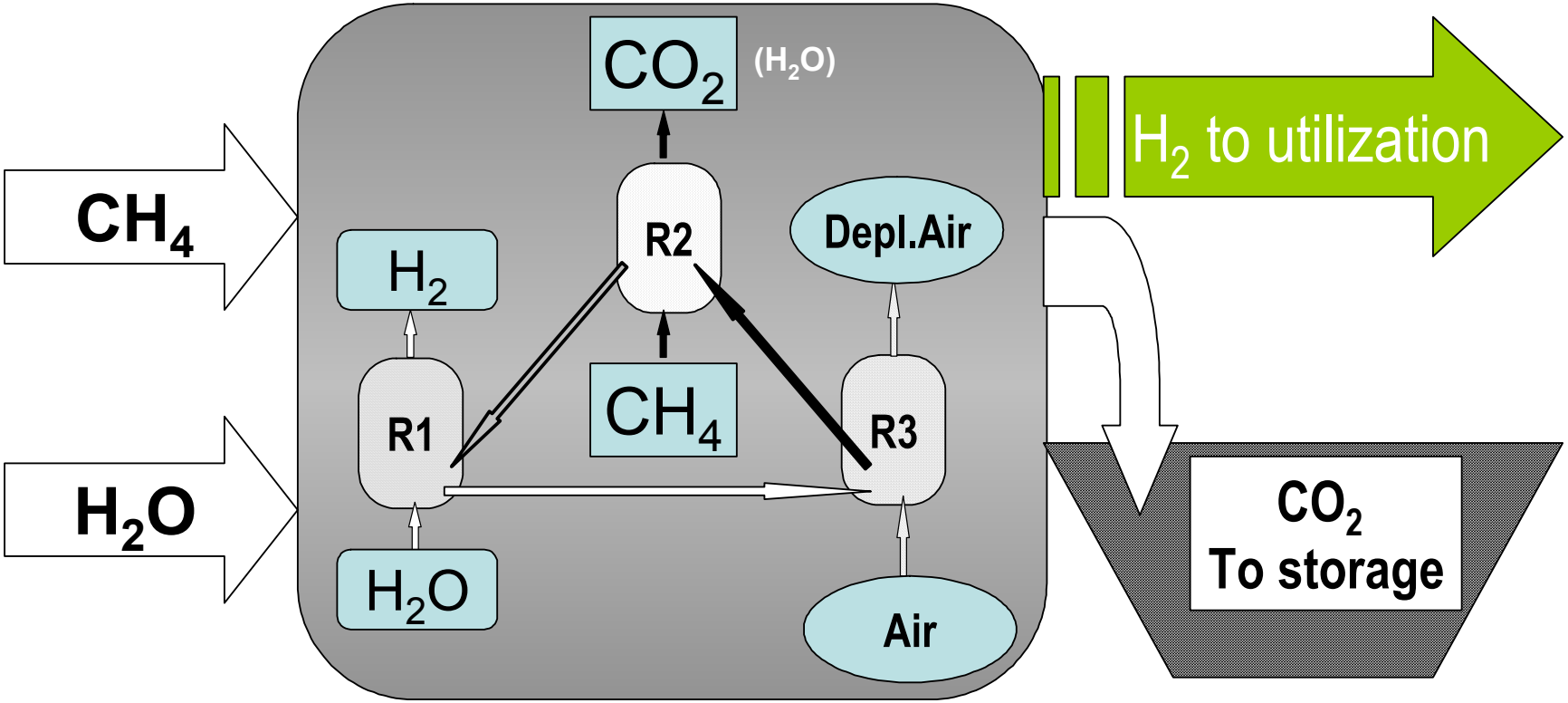


Chemical Looping Reforming

- **Mid/Long Term time to market (2012/2015)**
- **CCP2 Expected Development (CLC Consortium)**
  - **Screening and optimization of solid carrier materials at the lab scale.**
  - **Engineering development will benefit from parallel CLC development.**

CO_2 Capture Project

One-Step Hydrogen



One Step Hydrogen

- **Mid/Long Term time to market (2012/2015)**
- **CCP2 Expected Development (EniTecnologie)**
  - **Optimization of solid carrier materials at the lab scale, and scale-up of production with commercial manufacturer.**
  - **Reactor and Process scheme optimization**
  - **Hydrodynamic optimization through "mock-up" with continuous solid circulation.**

HyGenSys

- HyGenSys is a novel reforming technology based on the Gas Heating concept (avoidance of furnace emissions) and strict integration with a gas turbine. In the power generation mode, hydrogen burning in the turbine is needed for zero emission.

HyGenSys

- **Short Term time to market (by 2010)**
- **CCP2 Expected Development (IFP)**
  - **Process Optimization with turbine vendor.**
  - **Reactor mechanical design.**
  - **Hydrodynamic optimization through large “mock-up”**

Low Temperature Membrane Reforming

- **Novel reforming technology based on the development of dense Pd alloy membranes to separate hydrogen as it is formed, able to operate at a temperature of about 600°C.**

Low Temperature Membrane Reforming

- **Long Term time to market (by 2015)**
- **CCP2 Expected Development (ECN, SINTEF)**
  - **Development of suitable membranes at laboratory level.**
  - **Test in base module reactor (the same designed for MWGS).**

Completion of CCP2 Portfolio
Coal Gasification

- CCP1 showed that, once the coal gasification route is selected, additional cost for CO_2 Capture is very low.
- Cryogenic technology seems to be favoured due to potential poisoning of any catalyst, solvent or sorbent.
- A task force is finalising CCP2 work program in this field.

The CCP2 Time Sequenced Portfolio

- **Short Term (2008-2010)**
  - SEWGS
  - BIT
  - HyGenSys
- **Mid-Term (2010-2012)**
  - Chemical Looping Technologies
  - MWGS
- **Long Term (2013-2015)**
  - HMR
  - One-Step Hydrogen
  - Low Temperature Membrane Reforming.