GHGT-10

The EU FP6 CACHET Project - Final Results

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Abstract

After 3 years and over one thousand person-months of effort, the FP6 CACHET project was successfully concluded in the first half of 2009. CACHET focussed on pre-combustion capture of carbon dioxide (CO₂) from natural gas fuelled power generation and hydrogen (H₂) production. Through a combination of experimental and paper studies, CACHET developed, optimised and evaluated four promising capture technologies: Advanced steam methane reforming (HyGenSys), Redox technologies (chemical looping), Metal membranes and Sorption enhanced water gas shift (SEWGS).

This paper reports the technical and economic conclusions of the project and provides a look ahead to the future for each of the technologies and the challenges for full scale deployment. All technologies showed the potential to reduce CO₂ emissions by more than 90% and the opportunity to improve the energy efficiency compared to the state-of-the-art technology.

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Introduction

After 3 years and over one thousand person-months of effort, the FP6 CACHET (www.cachetCO2.eu) project was successfully concluded in the first half of 2009. This paper reports the technical and economic conclusions of the project and provides a look ahead to the future for each of the technologies and the remaining challenges for full scale deployment. CACHET consisted of a diverse consortium of research institutes, universities, energy businesses, engineering and manufacturing companies. Co-ordinated by BP with 28 participants from EU Member states and EU Acceding and Associated countries, USA, Canada, China and Brazil. CACHET was co-supported by the joint industry/government CO₂ Capture Project (CCP). The partners included:

- Oil & Gas Companies – BP, Chevron, ConocoPhillips, ENI, Petrobras, Shell, StatoilHydro and Suncor
- Electricity Utility Companies – Endesa, E.ON, Electricity Authority of Cyprus
- Engineering, Plant and Equipment and Contractors – Siemens, Process Design Centre (PDC), Air Products, Technip, Alstom, Meggitt
- R&D Institutes – Energy Centre of the Netherlands (ECN), IFP Energies Nouvelles (IFP), Fraunhofer Umsicht, Institute for Ecology of Industrial Areas (IETU), Dalian Institute of Chemical Physics (DICP), SINTEF, Consejo Superior de Investigaciones Científicas (CSIC)
- Universities – Technical University of Vienna, Technical University of Sofia, National Technical University of Athens, Chalmers University

Following a 4 year period of extensive assessment, the CO₂ Capture Project1 (CCP) project selected (in 2005) four innovative technologies as having high potential for efficient H₂ production with CO₂ capture and which could meet the EU cost targets. The CACHET project developed these four technologies, targeting a 50% reduction in the cost of CO₂ capture from natural gas with hydrogen production. CACHET researched four promising enabling technologies: Advanced steam methane reforming, Redox technologies, Metal membranes and Sorption enhanced water gas shift. During the 3 years of the CACHET project, the team has taken significant steps towards scaling up these technologies, activities ranged from process simulation to large scale experimental equipment.

HyGenSys

The advanced steam methane reforming technology incorporates a convectively heated reformer, integrated with a gas turbine. This process configuration, known as the Hydrogen-Generation-System, (HyGenSys) with high energy integration leads to a co-generation of hydrogen and electric power that can be readily combined with carbon dioxide capture. The steam methane reforming reaction may be described as follows:

\[
\text{CH}_4 + \text{H}_2\text{O} \leftrightarrow \text{CO} + 3\text{H}_2
\]

The reforming reaction is strongly endothermic and typically these reformers have a furnace where fuel is burnt with air and the heat produced radiates through the wall of tubes which contain a mixture of natural gas and steam together with a suitable catalyst. An equilibrium mixture of hydrogen, carbon monoxide, carbon dioxide and steam is produced known as synthesis gas (or syngas), at a temperature of approximately 800 to 900°C and a pressure of 10 to 30 barg. The products of combustion also leave the furnace at high temperature and this heat can then be recovered in a convective heat exchange section. The large amount of heat available can be used to pre-heat the natural gas and steam prior to entering the radiant tubes, and also produce large amounts of steam. Viewed on its own the energy efficiency of the radiant section of the reformer is low (about 50%) and the overall energy efficiency of the process can only be enhanced by utilising the large amount of steam produced in the convective section.

Evaluation of the HyGenSys concept shows the energy efficiency of power production using steam methane reforming can be improved by up to 3% points, due to the recovery of heat from the exhaust gas of a gas turbine. This reduces the amount of by-product steam produced by the reformer. The reformer is operated at elevated pressure on the exhaust gas side (shell side), which will result in a higher heat exchange rate and the process may incorporate catalytic supplementary firing to increase the exhaust gas temperature and improve heat transfer.

IFP with support from the HyGenSys work pack partners, notably Technip, made significant strides in the detailed design of the HyGenSys reactor [1]. The reactor design is complex and critical to the success of the technology; IFP have selected a double pipe / bayonet tube concept (figure 1). These will be mounted in a refractory walled and pressurised shell with the heat input from an external combustion chamber. The three train system will comprise of 8m diameter reactors, each containing an estimated 300 tubes. A ‘cold mock-up’ unit has been built to replicate the
fluid dynamics in a single HyGenSys reactor tube; this has proved that a standard reformer catalyst can be loaded and unloaded consistently into the bayonet reformer tubes.

To form part of an electric power generation plant with carbon dioxide capture the syngas produced by the HyGenSys process must be further processed to undergo the water gas shift reaction in which the carbon monoxide content is converted into further hydrogen and carbon dioxide. The water gas shift reaction maybe described as follows:

\[ \text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2 \]  

(2)

After the water gas shift reaction the carbon dioxide is separated before the residual syngas, which is now mainly hydrogen, is used as the fuel in a Combined Cycle Gas Turbine (CCGT) power plant. To deliver high overall carbon dioxide capture rates, the gas turbine forming part of the HyGenSys process and the supplementary fuel used to fire the reformer would also operate on the same high-proportion hydrogen fuel gas as the CCGT power plant.

The initial three train HyGenSys concept showed a potential 78% CO$_2$ Capture ratio, and 44.5% efficiency, the relatively low capture rate can be attributed to high methane slip. The team has since developed an alternative configuration which increases the capture rate to over the 90% CACHET target. This has been achieved by replacing one of the HyGenSys reactors with an air-blown Autothermal reformer, downstream of the other two HyGenSys reactors.

The Autothermal reformer performs the reforming steam methane reaction at a higher temperature, thereby increasing the conversion of methane and producing additional H$_2$.

**RedOx technologies**

Chemical looping uses metal oxide particles for oxygen transfer, which undergo alternating reduction and oxidation as they are moved through a series of reactors and gives rise to the “RedOx” name.

CACHET has explored the application of RedOx technologies (Chemical Looping) to hydrogen production and power generation. Three distinct concepts have been developed; these include Chemical Looping Steam Reforming (CLR$_{\text{steam}}$), Chemical Looping Autothermal Reforming (CLR$_{\text{aut}}$) and One Step Decarbonisation (OSD).

Chemical looping reforming is a development of Chemical Looping Combustion (CLC). Both of these processes use metal oxide particles to transfer oxygen from an air reactor, in which the metal particles are oxidised, to a fuel reactor, where the hydrocarbon fuel is either fully oxidised (CLC) or partially oxidised (chemical looping reforming). The metal particles are then circulated back to the air reactor to form a continuous process.

**Figure 2: Chemical Looping Combustion and Chemical Looping Reforming**

In the chemical looping steam reforming concept CLR$_{\text{aut}}$ heat is provided from the circulating metal oxide particles to tubes containing natural gas, steam and a suitable catalyst in a fluidised bed heat exchanger. The reforming reaction (1) takes place within the tubes to produce syngas. The fluidised bed heat exchanger is fed with metal oxide particles from the fuel reactor in a CLC circuit. The syngas is further processed in a water gas shift reactor to produce a mixture of largely hydrogen and carbon dioxide. This is then fed through a Pressure Swing Adsorber (PSA) which separates pure hydrogen from a tail gas stream containing hydrogen and carbon dioxide. In an electric...
power generation plant with carbon dioxide capture the CCGT power plant would be fuelled with the hydrogen stream and the tail gas stream would be used as the fuel in the CLC fuel reactor. The subsequent exhaust stream from the fuel reactor would contain the majority of the carbon in the natural gas originally fed to the reformer in the form of carbon dioxide mixed with steam, which could be separated by condensing out as water.

CACHET partners have tested particles based on iron, nickel, copper and manganese oxides, as well as perovskites. During continuous operation in 300 W and 500 W chemical-looping combustors, several materials have shown excellent results as several hundred hours of continuous operation have shown no degradation of particles, making them strong candidates for CLR$_{(o)}$.

The Technical University of Vienna has recently successfully operated the 120kW Chemical Looping test rig (see figure 3). This unit, constructed within the CLCGASPOWER EU project, is one of the world’s largest and will provide essential data on the scale up of the chemical looping process. The unit has successfully operated with both nickel oxide and the cheap, natural mineral ilmenite with some additional nickel oxide added to promote the rate limiting splitting of the methane.

In conventional auto-thermal reforming a mixture of steam and hydrocarbon fuel is fed into a reactor containing a suitable catalyst with an oxidant (either air or oxygen) and the heat produced by oxidation of part of the hydrocarbon fuel allows the reforming reaction (1) to proceed. Syngas is produced containing hydrogen, carbon monoxide, carbon dioxide, steam and (if air is used as the oxidant) nitrogen. In chemical looping reforming the metal oxide particles carry oxygen into the reactor and the syngas produced is comparable to that produced by conventional auto-thermal reforming. The chief advantage foreseen for chemical looping auto-thermal reforming is that oxygen is provided to the reactor without the need for a conventional cryogenic air separation unit and as a consequence significant cost savings are expected.

Tests undertaken by CACHET partners at 300W to 150kW scale have proven particles are capable of producing syngas containing no methane and with low stoichiometric oxygen to fuel ratios suitable for CLR$_{(o)}$. However economic evaluation of atmospheric pressure CLR$_{(o)}$ show the economics of the process are challenged and substantial economic benefits can be foreseen if the syngas can be produced at elevated pressure. To understand the potential for this, testing in a pressurized semi-batch and semi-continuous units has begun. This has shown the kinetics to be enhanced and importantly there has been no apparent increase in carbon formation, providing some positive evidence that CLR$_{(o)}$ at pressure may be feasible if the engineering challenges can be overcome.

The One-Step Decarbonisation (OSD) process is a novel and innovative carbon dioxide capture and hydrogen production technology. It is based on the use of a circulating “RedOx” solid material that can be oxidised via water splitting thereby producing hydrogen, and reduced by a carbon-containing stream, typically a hydrocarbon, producing carbon dioxide. The process comprises a three-bed continuous circulating fluid bed reactor. The solid material is first partially oxidised with steam producing hydrogen, then fully oxidised with air in a second reactor before being reduced in the third reactor by reaction with hydrocarbon fuel. The exhaust gas from the first reactor is hydrogen which is supplied as fuel to a CCGT power plant and the exhaust gas from the third reactor is carbon dioxide and steam which can be separated by condensation of water.

ENI have tested the three OSD redox steps in batch-wise experimental work investigating optimum operating conditions. Economic analysis has focused the project towards testing the iron based material at higher pressures, to make the process economics more competitive. The results produced are better than expected. Perovskite based materials have been produced and the initial screening process is completed. Several of the materials tested show a better performance than the reference material currently used in the One-Step hydrogen reactor.

Analysis of the technical and economic performance of the three chemical looping concepts show all three concepts are capable of reducing CO$_2$ emissions by 90% and that CLR(s) offers the greatest opportunity to improve the energy efficiency over the state-of-the-art technology (+5.4% points) due to the technology’s ability to produce pressurised syngas. Overall analysis suggests CLR(s) can deliver a 13% reduction in capture cost; the challenge is to reduce the capital cost to enable the full efficiency improvements to be reflected in the CO$_2$ capture cost and COE.
Metal membranes
In CACHET the metal membranes work package has developed, tested and evaluated the potential of membrane reactors using palladium (Pd) and palladium alloy (Pd-ally) membrane technology to capture carbon dioxide either from syngas in a water gas shift (WGS) reactor or directly from an integrated natural gas membrane reformer. The delivered hydrogen-rich gas stream can be used directly in a CCGT power plant. In CACHET the choice has been made to focus on asymmetric Pd or Pd-ally membranes featuring a very thin Pd membrane layer (ensuring high flux and low cost) applied to a porous support structure which will provide mechanical strength to the membrane.

Using a dense metal membrane on a porous support ensures that the carbon dioxide cannot pass through the membrane and comes out of the reactor in the retentate stream at close to the feed pressure whereas the hydrogen emerges in the permeate stream. The hydrogen stream may be fed to a CCGT power plant for electric power generation and the carbon dioxide can be dried and compressed for storage.

![Diagram](image)

Figure 4: Membrane Reactor Concept for Reforming or Water Gas Shift [2]

By incorporating the hydrogen-selective membrane in the reactor hydrogen is removed from the feed-side to the permeate side by selective transport through the membrane. The combination of reaction and separation in membrane steam reforming and/or membrane water gas shift offers higher conversion of the reforming (1) and/or shift (2) reactions. The reforming reaction is strongly endothermic and with this technique can be forced to completion at lower temperature than normal (typically 500 to 600°C), while the exothermic WGS reaction can be operated at a higher temperature.

Two different membrane manufacturing techniques have been developed to produce and evaluate Pd-ally membranes. SINTEF have built upon the work undertaken in the FP5 ‘GRACE’ project scaling up their Pd membranes on porous stainless steel support technology from 2.5cm to 50cm long. Long-term stability tests over 150 days at a temperatures from 325 - 400°C concludes the membrane lifetime would be between 2-3 years (<400 °C) [3]. SINTEF’s work has also shown that permeance is reduced by a factor of five for a synthesis gas mixture compared to a H₂/N₂ mixture. The decrease is due to hydrogen dilution, depletion and competitive adsorption of other components on the membrane surface [4].

SINTEF testing has shown some promising results:

- Hydrogen flux up to 2477mL/cm²/min @25bar dP, 400°C
- High pressure H₂/N₂ permeselectivity 3000 (@25bar dP, 400°C)
- Hydrogen permeance up to 8x10⁻⁷ mol/m²/s/Pa (WGS conditions @20bar dP, 400°C)
- Stable performance during operation in H₂/N₂ and WGS for a total period of more then a year

DICP has scaled up technology for preparation of Pd membranes to 50cm in length by electroless plating on ceramic supports. The pure H₂ permeance through 3-5μm membranes has been measured at >2x10⁻⁶ mol/m²/s/Pa (2.0MPa dP H₂) with a nonlinear pressure dependence of H₂ permeance (n=0.64) indicating external mass transfer/surface process limitations. 200 hour stability tests have produced constant 99.9% H₂ at 88.7% recovery rates at 400°C.

ECN have designed, built and operated the membrane Process Development Unit (PDU), which has been used to test multiple 50cm long tubes, which were prepared by DICP for both reforming and WGS: the detailed experimental results have been reported [5].

The Integrated Membrane Water Gas Shift reactor appears to be economically advantaged over the Integrated Reformer Membrane. The membrane temperature limits are a larger constraint for the reforming reactor, where the hydrogen partial pressure driving force is significantly lower than for the WGS membrane application. This observation may be reversed if the hydrogen product is required at lower pressures. Future research for membrane reforming should focus on materials with higher temperature stability.


Sorption Enhanced Water Gas Shift

The fourth technology area of CACHET features a Sorption Enhanced Water Gas Shift (SEWGS) process for the simultaneous production of hot, high pressure hydrogen from a catalytic water gas shift reactor, with simultaneous adsorption of carbon dioxide on a high temperature adsorbent. The system operates in a cyclic manner with steam for adsorbent regeneration.

Current state-of-the-art processes for separation of hydrogen from hydrogen/carbon dioxide mixtures include ambient temperature PSA or liquid absorbents, both chemical and physical. These processes require electric power or heat for regeneration and produce hydrogen at ambient temperature. They also result in condensing excess water associated with the hydrogen, some of which is required for blending with hydrogen to control flame temperatures in the gas turbine. The SEWGS process has the advantage of increasing the conversion of carbon monoxide and steam to carbon dioxide and hydrogen in the equilibrium limited water gas shift reaction (2) by removing the carbon dioxide in the reactor. The separation of carbon dioxide at high temperature minimises heat exchange equipment and the hydrogen leaves the reactor at high pressure and with surplus steam which is anyway required as a diluent when burning the hydrogen in a gas turbine. The SEWGS process involves a cyclic flow through the reactor. Syngas is shifted and the carbon dioxide is adsorbed producing a forward flow of hydrogen and steam. The syngas flow is then shut-off and the reactor is depressurised and a reverse steam purge is used to desorb the carbon dioxide. By arranging a number of reactors in parallel which are suitably sequenced a continuous forward flow of hydrogen/steam can be maintained to the CCGT power plant and a steady flow of carbon dioxide/steam can also be maintained which goes to drying and compression.

During the CACHET project ECN has constructed and operated both a single column and multiple column unit (see figure 5). The single column unit contains a single reactor (2 m tall, 44 mm diameter) which is able to simulate key stages of the cycle. The multi-column unit: six columns, each three times as tall as that in the single column and is able to continuously simulate all stages of the complete cycle.

The results from the single column unit have shown the steam requirements for rinse and purge are lower than expected. A model has been built to help understand the experimental data and optimise the cycle. The model is capable of matching the single column data accurately. The multicoloumn data has been much more complex to analyse and calibrate a model to fit. While the multicoloumn unit has proven the enhancement of the WGS reaction by separation of the carbon dioxide, some experimental observations are difficult to understand. The chemical stability of the sorbent has presented an opportunity for improvement as the current Mg70 degraded after several thousands of cycles, an improved sorbent has been developed in the CAESAR follow on project [6]. New cycles have been developed including a countercurrent steam rinse cycle, which appears to outperform the co-current CO2 rinse cycle [7].

Evaluation of the technical and economic performance conducted within the project conclude that the SEWGS technology can improve the energy efficiency, compared to state-of-the-art by 3.4%pts, with a 16% reduction in the cost of avoiding CO2 [8].

There is clearly an opportunity for more experimental work and study to allow the high prospects of this technology to be realised. Some of the earlier experimental work suggested there may be some challenges with the lifetime of the hydrotalcite material as dusting became evident. A modified material showed some improvements and these can be expected to continue in the FP7 CAESAR follow-on project.
Integration and Optimisation

The Optimisation and Integration team has evaluated the benefits of combining a CACHET synthesis gas production technology with a CACHET CO₂ separation technology, to achieve mutually enhanced synergetic performance. Initially fifty five combinations where identified and screened, eight combinations were deemed to have sufficient potential and selected for more detailed investigation:

- HyGenSys – Sorption Enhanced Water Gas Shift (SEWGS)
- Chemical Looping Steam Reforming (CLR(α)) – Membrane Water Gas Shift (MWGS)
- One Step Decarbonisation (OSD) –MWGS
- CLR(α) – SEWGS
- Integrated Membrane Reformer (MREF) – Chemical Looping Combustion (CLC)
- MWGS – CLC
- CLR(α) – MWGS

The integration, performance and economics of each technology combination have been evaluated. Figure 6 shows the results of the combination study, which suggest that the best combinations can improve the efficiency by up to 2.6% pts (compared to the stand along technology). Although estimation of capital costs suggests the energy efficiency benefits are outweighed by the total capital cost increase (see figure 6).

<table>
<thead>
<tr>
<th>Combined Process</th>
<th>Process 1</th>
<th>Process 2</th>
<th>ΔEfficiency relative to (%pts)</th>
<th>ΔCOE relative to (€/MWh)</th>
<th>ΔCapital Cost relative to (€m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HyGenSys - SEWGS</td>
<td>HyGenSys</td>
<td>SEWGS</td>
<td>0.26</td>
<td>2.66</td>
<td>n.a.</td>
</tr>
<tr>
<td>CLR(α) - MWGS</td>
<td>CLR(α)</td>
<td>MWGS</td>
<td>0.00</td>
<td>-0.02</td>
<td>1.4</td>
</tr>
<tr>
<td>CLR(α) - OSD</td>
<td>CLR(α)</td>
<td>OSD</td>
<td>0.04</td>
<td>0.03</td>
<td>-4.6</td>
</tr>
<tr>
<td>OSD - MWGS</td>
<td>OSD-Mem</td>
<td>MWGS</td>
<td>0.00</td>
<td>-0.01</td>
<td>1.2</td>
</tr>
<tr>
<td>CLR(α) - SEWGS</td>
<td>CLR(α)</td>
<td>SEWGS</td>
<td>-5.00</td>
<td>-3.60</td>
<td>16.7</td>
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<tr>
<td>MREF - CLC</td>
<td>MREF</td>
<td>CLC</td>
<td>0.10</td>
<td>n.a.</td>
<td>6.0</td>
</tr>
<tr>
<td>MWGS - CLC</td>
<td>MWGS</td>
<td>CLC</td>
<td>-0.90</td>
<td>n.a.</td>
<td>10.8</td>
</tr>
<tr>
<td>CLR(α) - MWGS</td>
<td>CLR(α)</td>
<td>MWGS</td>
<td>No detailed investigation - parameter studies reveal no obvious economic advantage</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6: Results of integrating two or more CACHET technologies

Economic & Performance Analysis

Figure 7 shows the final performance and economic analysis from the CACHET project for all seven variants of the four technology areas being developed within the project. All technologies have shown that they meet the CACHET targeting of reducing the CO₂ emissions by 90% or more. Simulation results, supported by experimental results, show that all the CACHET technologies have the potential to increase the energy efficiency beyond the of the state-of-the-art base case for pre-combustion CO₂ capture, with membrane water gas shift showing the highest energy efficiency of 47.1% (LHV).

Achieving the CACHET objective of reducing the cost of CO₂ capture by 50% has proven extremely challenging. The technology with the lowest CO₂ avoidance cost, Membrane WGS, has shown a 31% projected cost reduction, although this is less than the objective, it still represents a significant benefit which should provide the industry with sufficient incentive to continue to develop and scale up the technology. Both the HyGenSys and SEWGS technology project smaller, but still significant capture costs savings. Analysis of the three chemical looping technologies suggest that the CLR(α) technology will lower the cost of capture, although the high capital costs present a significant barrier to delivering a step change in capture cost reduction compared to the state-of-the-art.
<table>
<thead>
<tr>
<th>Reference Case (no CCS)</th>
<th>Base Case</th>
<th>HyGenSys</th>
<th>CLR(a)</th>
<th>CLR(s)</th>
<th>OSD</th>
<th>MemRef</th>
<th>MemWGS</th>
<th>SEWGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power output (MWe)</td>
<td>389.8</td>
<td>366</td>
<td>480</td>
<td>363</td>
<td>330</td>
<td>356</td>
<td>352</td>
<td>392</td>
</tr>
<tr>
<td>Efficiency (% LHV)</td>
<td>57.2</td>
<td>40.9</td>
<td>41.9</td>
<td>46.3</td>
<td>42.1</td>
<td>46.2</td>
<td>46.2</td>
<td>47.1</td>
</tr>
<tr>
<td>Total fixed investment (€m)</td>
<td>195</td>
<td>462</td>
<td>587</td>
<td>562</td>
<td>586</td>
<td>534</td>
<td>530</td>
<td>476</td>
</tr>
<tr>
<td>Cost of electricity (€/MWh)</td>
<td>55.9</td>
<td>86.6</td>
<td>82.7</td>
<td>81.3</td>
<td>94.0</td>
<td>84.2</td>
<td>87.4</td>
<td>74.4</td>
</tr>
<tr>
<td>CO2 Captured (%)</td>
<td>-</td>
<td>94.8</td>
<td>93.4</td>
<td>93.5</td>
<td>94.3</td>
<td>93.8</td>
<td>93.5</td>
<td>93.5</td>
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<tr>
<td>CO2 Avoided (%)</td>
<td>-</td>
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<td>91</td>
<td>92</td>
<td>92.2</td>
<td>92.3</td>
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<tr>
<td>Cost of CO2 capture (€/t)</td>
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<td>77.1</td>
<td>81.5</td>
<td>101.2</td>
<td>88.1</td>
<td>96.1</td>
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<tr>
<td>Cost of CO2 avoided (€/t)</td>
<td>-</td>
<td>117.5</td>
<td>107.9</td>
<td>102.4</td>
<td>140.6</td>
<td>110.8</td>
<td>121.1</td>
<td>81.2</td>
</tr>
</tbody>
</table>

Figure 7: Summary of CACHET performance and economic analysis (costs on 2006 basis)

Conclusions

After three years of intensive studies the CACHET project has developed seven technologies, each has shown the ability to achieve higher energy efficiency than the current state-of-the-art for pre-combustion CO2 capture. Analysis has shown that all the technologies are capable of avoiding 90% or more of the CO2 emissions. The technology with the lowest CO2 capture cost is the Integrated Membrane Water Gas Shift process which is projected to reduce the cost of avoidance by >30%, although none of the developed technologies have achieved the ambitious 50% cost reduction. Reducing the capital cost of the technology has been the largest barrier to success in the project. Each technology has taken substantial steps to lowering the cost of CCS across Europe and the rest of the world, and the CACHET project has led to the initiation of several follow on projects, including CAESAR (SEWGS) and CACHET-2 (membranes), which will continue to build upon the achievements of the CACHET project as the technologies continue towards widespread commercial deployment.

Acknowledgment

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