WHAT HAVE WE LEARNT FROM IEAGHG CO_2 CAPTURE AND CCS GENERIC TECHNICAL STUDIES

Report: 2010/TR1

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Executive Summary

This report is considered the 3rd in a series of reports summarizing the learning points from the different IEAGHG activities. This series of reports started by summarizing the learning points from the storage activities (report 2009/TR1, February 2009) and the CCS demonstration projects (report 2009/TR6, November 2009). This 3rd report summarises key learning points on CO_2 capture and generic CCS studies from Operating Phase 5 of the IEAGHG, which commenced in 2005 and effectively coincided with the publication of the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC SRCCS). IEAGHG activities revolve mainly around contracted studies and organisation of the international research networks.

IEAGHG studies are chosen by programme members and sponsors from a wide list of proposals, ensuring those selected are focussed on topical technical issues. Study reports issued from 2005 onwards have contributed significant knowledge to major capture topics, including: post combustion; pre combustion; oxy-fuel combustion; economics; environmental impact; retrofit; capture readiness; biomass; low rank coal; CCS safety; CCS and CDM; CCS projects finance; and medium sources of emissions.

The evaluated studies resulted in major conclusions on the different CO_2 capture topics and recommended future activities and areas of focus. Current and future IEAGHG studies will continue to seek to address these recommended areas, in conjunction with the work of the international research networks. The major conclusions in CO_2 capture and generic CCS highlighted by IEAGHG activities since 2004 include, among others:

- For post combustion capture, solvent scrubbing is considered the state of the art and the solid adsorbents and membranes based processes are considered to be 2nd or even 3rd generation technologies.
- The changeable economic climate makes the economic evaluation and costs estimates uncertain and that requires special caution while assessing these results.
- The extra cost of electricity, efficiency losses and costs of CO_2 avoided are quite similar for the three major capture technologies (post, pre and oxy-fuel combustion).
- Retrofitted CO_2 post combustion capture showed lower capture cost and smaller efficiency reduction compared to CO_2 pre combustion capture for natural gas combined cycle plants.
- It was found that unless capture is retrofitted relatively soon after plant start up, it is not worthwhile building a plant which has a substantially higher cost of before capture to make it capture ready.
- From an economic point of view it would be better to invest in more power plants with optimum capture rather than fewer of near zero emission performance.
- Oxy fuel combustion coal processes are best suited to being adapted to high capture ratios; post combustion processes can be modified to approach near zero emissions but only at excessive cost and pre-combustion capture cannot reach very high capture ratios.
- Comparing the physical absorption processes for pre-combustion capture,, the Rectisol process resulted in lower operating costs but higher capital costs compared with the Selexol process.
- The standalone biomass power plants showed a higher loss in net efficiency, larger increase in the capital costs and higher cost of electricity (COE) compared to co-fired power plants.

- CO_2 capture has a net environmental benefit, due to the avoidance of CO_2 emissions. However, there is a valid concern regarding solvent losses and other wastes produced from the capture plants. The environmental impacts of chemical emissions required detailed evaluation.
- Capturing CO_2 from medium scale installations will depend on the carbon price, the possibility of CO_2 collections and the availability of storage sites.
- In the cement industry, both post combustion and oxy-fuel combustion capture options can be considered. Although, oxy-fuel offered the lowest cost, post combustion could be easier retrofitted to existing plants.
- While there are numerous hazards associated with CCS, the hazard analysis did not find any fundamental safety issues which could not be fully managed.
- For CO_2 capture and transport existing regulations are largely adequate. However, the main underground elements of CCS require significant development of the permitting process.
- In order to move forward with CCS, governments need to provide financial support to the first CCS projects and to have robust CCS policies that provide certainty to investors.
- The inclusion of CCS in the CDM may not have any significant ramifications for the global carbon market or other CDM technologies in the near or medium terms.

IEAGHG studies recommended further research and activities on different areas of interest, which include: small and medium stationary sources of CO_2, the preparation of guidelines for capture ready, industries where biomass is used as fuel, a full life cycle emissions analysis, environmental impacts of solvent scrubbing, safety and incident database for the CCS industry. In addition, after evaluating the IEAGHG studies, different areas were defined as missing or were not covered through IEAGHG CCS studies in the period 2005-2009. These areas of interest include:

- A guideline for capture processes techno-economic benchmarking, comparison and evaluation.
- CO_2 capture risk assessment.
- CO_2 capture scale-up challenges and strategy.
- Overviews of the CO_2 capture global R&D and commercial activities.
- A detailed technical study on the IGGC development and new technologies.
- More involvement in the EU and the international CCS projects and R&D programmes.
- More detailed technical and engineering studies (process and heat integration, process design and development).

IEAGHG will continue to focus on these knowledge gaps, through selected studies and the continued activities of the international research networks.

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What Have We Learned From IEAGHG CO_2 Capture and CCS Generic Technical Studies (2005-2009)?

1 Introduction

This report is intended to provide a summary of key learning points from recent IEAGHG technical studies related to CO_2 capture and generic CCS topics. This makes it the 3rd in a series of reports summarizing the learning points from the different IEAGHG activities. This series of reports started by summarizing the learning points from the storage activities (report 2009/TR1, February 2009) and the CCS demonstration projects (report 2009/TR6, November 2009).These studies were selected by programme members and sponsors from proposals drawn up by IEAGHG staff and from other sources.

IEAGHG studies are typically undertaken by contractors, selected through a competitive tendering process. IEAGHG studies typically involve desk-based reviews undertaken over a six month period, followed by an independent expert review process. The fact that these studies are selected from a wider list of proposals by IEAGHG members ensures that the studies focus on topical themes and address or identify knowledge gaps.

2 CO_2 Capture Studies

2.1 Introduction

This section summarises key learning points from IEAGHG studies on CO_2 capture completed between January 2005 and September 2009. A list of these reports is presented at the end of the report. Findings and key learning points are considered mainly in the context of broad capture associated technical topics: CO_2 capture from power stations (post combustion, pre combustion and oxy-fuel capture), CO_2 capture from power plants with different types of fuel (low rank coal and biomass), the concepts of CO_2 capture retrofit and capture ready, environmental impact of CO_2 capture, novel approaches to improve the capture technologies, CO_2 capture economics and CO_2 capture from other sources of emissions (residential and industrial medium scale sources).

2.2 CO_2 Post combustion capture

Carbon dioxide post combustion capture using amine-based solvent scrubbing systems is considered the-state-of-the-art. This technology has the advantages of:

- The possibility to be retrofitted to existing power plants
- The technology is proven on a small scale
- Has a strong research base, which should lead to better solvent and cheaper process

On the other hand, this technology still facing major challenges, include among others:

- High efficiency penalty
- High cost

- The lack of experience with large scale capture from power plants
- Solvent degradation and corrosiveness problems
- Side effect environmental impact

IEAGHG has conducted two major studies on CO_2 post combustion capture. The first study (2007/15) summarised most of the activities related to post combustion capture solvents and contractors developments. It was concluded that while major efforts are focusing on the development of new solvent with lower regeneration energy and improving the design of the scrubbing contractor; the pilot plants and demonstration projects are important to build a real condition experience. In addition, the major challenge to reduce the costs of CO_2 capture still exists.

The second IEAGHG study (2009/02) focused on what so called the 2nd and 3rd generation post combustion capture technologies. This study considered the use of solid sorbents and membranes for CO_2 post combustion capture as potential alternatives of solvent scrubbing systems. Simple porous solid sorbents such as activated carbons are not well suited to post combustion capture because of their relatively low CO_2 capacities and CO_2/N_2 selectivities. Metal organic frameworks (MOFs) look promising but are at early stage of development. Much of the research activities connected with functionalised solid sorbents were not encouraging. Finally, the dry regenerable solid solvents have the advantage of being cheap but the requirements of huge quantities of fresh feed could be a major showstopper.

Membrane systems for post combustion capture also appear to be at an early stage of development and possibly better suited to pre-combustion applications. Membrane behaviour could be improved by introducing the membrane gas absorption concept (membrane contactor with chemical solvent). The potential success of solid sorbents and membranes will depend on the evolution in the development of solvent absorption systems. In general, solid sorbents and membranes based processes are considered to be 2nd or 3rd generation post combustion capture technologies (see Figure 1).

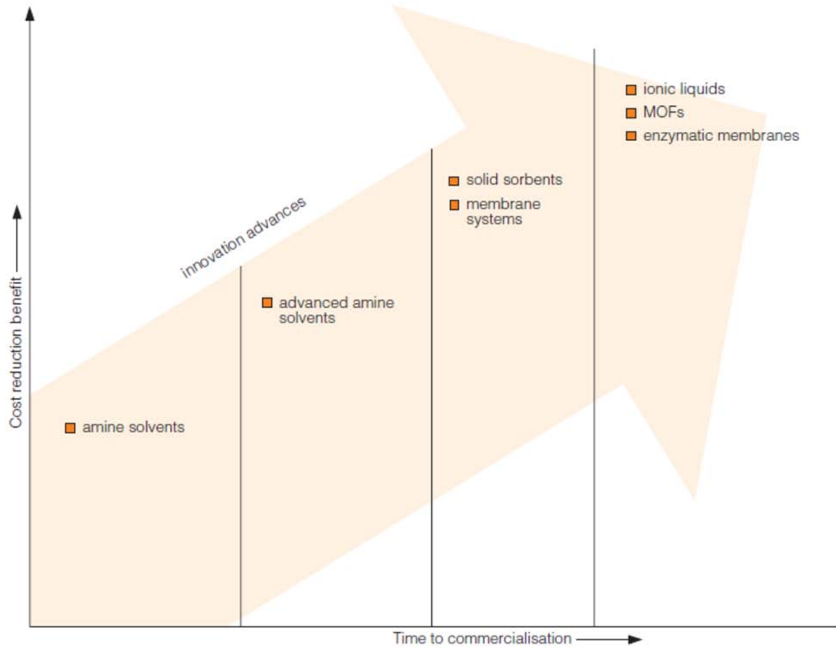

Figure 1: Innovative CO_2 capture technologies - cost reduction benefits versus time to commercialisation (Figueroa et al., 2008)

2.3 CO_2 Pre combustion capture and hydrogen production

The production of hydrogen and electricity by high rank coal gasification with CO_2 capture and the advantages of flexible co-production were evaluated (report 2007/13). The techno-economic performance was evaluated based on three coal gasifiers: Shell, GE Energy and Siemens, and two acid gas removal processes (Selexol and Rectisol).

The costs of electricity were found very similar for the three gasification processes. However, the plant based on Shell gasification has the highest thermal efficiency and the lowest production of CO_2. For acid removal processes, the Rectisol plants have lower variable operating costs than the Selexol plants, mainly due to lower overall energy consumptions. On the other hand, the capital costs of the Rectisol plants are higher.

Different scenarios of producing electricity or hydrogen only, co-productions of hydrogen with fixed or variable ratio, and with and without hydrogen storage were assessed. The best scenario with the lowest costs was the one based on flexible co-production and hydrogen storage.

Two major concerns of gaseous underground storage are the possible contamination of hydrogen with other gases such as H_2S and CH_4. For this reason a cost allowance for a hydrogen purification unit has been considered in the scenarios including storage. The second concern is the possibility of leakage of hydrogen through the storage walls, which strongly dependent on the type of storage environment. However, hydrogen storage has been safely carried out on an industrial scale. Other types of hydrogen storage have been evaluated (liquefied storage and aboveground storage) but they have been excluded because of their huge cost and storage in metal hydride is not suitable for large quantities.

The economic analysis of the IGCC with co-production of hydrogen was updated in 2008 (2008/09) to include the effect of the higher coal price and the increase in the capital investment due to the general inflation in costs of process plants. In the updated calculations of 2008, the capital costs were increase by 25% and the costs of electricity, hydrogen production and CO_2 abatement were increase by 50-60% compared to the costs in 2007 (see Table 1). In the current changeable economic climate it is uncertain and difficult to judge whether costs in future will continue to increase, stabilise or fall.

Table 1: The IGCC investment and CO_2 avoided costs of 2007 and 2008

	2007		2008	
	Without capture	With capture	Without capture	With capture
Specific investment [€/kWe]	1661	2379	2070	2970
Cost of CO_2 avoided [€/tonne CO_2]	-	31.3	-	48

2.4 CO_2 Oxy fuel combustion capture

The evaluation of the CO_2 oxy-fuel combustion capture was done with limitation to the available knowledge at the time of the study (2005) rather than to expected future development on oxy-fuel combustion. It was concluded that a pulverised fuel power station converted to oxy-fuel firing was the best proven technology basis. The amount of CO_2 recycled has a considerable effect on conditions in the plant. The further the recycle is reduced the more the design deviates from conventional practice. To allow the use of the same conventional boiler design, a recycle with net effect of feeding about 30% oxygen in the CO_2 was used. The recycled CO_2 stream, which will replace air used in milling coal and transporting it, has to be cooled and dried with no addition of oxygen to minimize risk of fire and explosions.

The extra costs of electricity, efficiency losses and costs of CO_2 avoided in CO_2 capture oxy fuel combustion processes are similar to those for coal fired pre and post combustion options, but higher for gas fired plant (all cost calculations are based on the year 2005). Table 2 summarises the major techno-economic evaluation results of both coal and gas oxy-fired power plant.

The need for a completely new gas turbine is a major hurdle for application of this technology to a gas fired combined cycle gas turbine process. The oxy fuel combustion technology needs further development in certain key areas including: plant start up, control systems, burner and flame characterization and material issues. However, none of these development areas are likely to represent a technical show-stopper.

Table 2: Performance and costs of oxy-fired power plants

	Coal Fired PF		Gas fired NGCC	
	Base Case	Oxy-fired	Base Case	Oxy-fired
Cost of electricity [¢t/kWh]	4.9	7.28	3.35	6.13

Cost of CO_2 avoided [$/ton]	-	37	-	77
Net power [MWe]	677	532	388	440
Capital cost [$million]	1024	1246	217	658
Specific capital [$/kWe net]	1513	2342	559	1495
Efficiency [% LHV (net)]	44.2	35.4	56	44.7

2.5 Oxygen production technologies

Large quantities of oxygen are required by some power generation and industrial processes with CO_2 capture, for example about 40,000 tonnes/day for a 2,000 MWe coal fired oxy-combustion power plant and about 15,000 tonnes/day for the same size of IGCC plant. Oxygen production plants account for about 10% of the cost of an IGCC with CO_2 capture and 20% of the cost of a coal based oxy-fuel combustion plant.

The IEAGHG study (2007/14) described the cryogenic and membrane oxygen production processes, and recent and potential future improvements in these oxygen production processes. Cryogenic is considered the conventional mature technology for oxygen production. It is demonstrated in plants with capacities up to 4,000 tonnes/day. However, the cryogenic oxygen production process is considered an energy intensive process. For example, it will be responsible of almost 6 percentage point of efficiency for a coal-fired oxy-combustion power plant.

Alternative technologies known as Ion Transport Membrane (ITM) or Oxygen Transport Membrane (OTM) are currently being developed. These transport membranes have very large flux rates and infinite selectivity of oxygen. They offer up to 50% oxygen cost reduction potential, compared to the conventional cryogenic process. Studies indicated that ITM's could significantly reduce the net capital power costs for oxygen production, for example by about 35% in IGCC. However, ITM's have not yet been demonstrated in large scale plants, so these savings are subject to uncertainties.

The current development in improved oxygen production techniques are encouraging and are expected to result in significant reductions in oxygen production costs for CO_2 capture. Cryogenic oxygen will still have a potential in the future for specific applications particularly coal-fired oxy-fuel power stations.

2.6 Retrofit of CO_2 capture to power plants

Considering the fact that the power plants have long lives, 40 years of more in many cases, it may be cheaper to retrofit capture process to an existing power plant rather than prematurely retire it and build a new power plant with capture. The feasibility and costs of retrofitting CO_2 capture to power plants were assessed using natural gas combined cycle power plant and post and pre combustion capture technologies (IEAGHG study 2005/01).

Based on the cost information and assumptions used in this study, retrofitting CO_2 capture to natural gas combined cycle plants increased the cost of electricity by about 2-3 c/kWh, corresponding to about 70-90 $/tonne CO_2 avoided (2005 as reference year). In addition, retrofitted CO_2 post combustion capture showed the lowest capture cost and the smallest efficiency reduction compared to CO_2 pre combustion capture. However, remote capture installation was not an option with post combustion capture due to the large flue gas flow. In addition, retrofitting a coal gasification plant with CO_2 capture could be attractive option if gas costs are high and coal costs are low.

Major barriers to retrofit can be: the space requirement for the capture plant, space availability for process integration (e.g. steam and flue gas pipes), utilities requirement, plant operability and flexibility, such as the ability to operate efficiently at part load. Many of the potential barriers to retrofit CO_2 capture to existing power plant could be overcome in the design phase of the power plant.

2.7 CO_2 Capture ready plants

There is no agreed definition of "capture ready" power plant. For the purposes of this work, a CO_2 capture ready power plant is defined as: a plant which can include CO_2 capture when the necessary regulatory or economic drivers are in place. The aim of building plants that are capture-ready is to avoid the risk of stranded assets of carbon lock-in. An IEAGHG study (2007/04) assessed the main options for making power plants capture ready and their advantages and disadvantages. In addition, this study identified the necessary and potentially economically attractive options for pre-investment in the power plants to make retrofit economically feasible.

For the power plant to be capture ready, space would need to be provided for the CO_2 capture equipment (CO_2 scrubber, CO_2 compressors, ASU, ...), additional infrastructure including cooling water and electrical system, safety and barrier zones, pipelines and space would be needed for construction of additional power generation plant.

For CO_2 transport, it is important to identify distances from the capture plant, and how CO_2 could be transported to the storage sites. For pipeline transportation, issues concerning routes and public acceptance should be addressed. For ships, the feasibility, safety and acceptability of on shore CO_2 buffer storage and ship loading and unloading facilities should be assessed. The potential stores and their capacities should be evaluated. The requirement for qualifying a storage reservoir for a capture ready plant will have to be defined by policy makers.

In general, the main areas of the power plant which will be affected by CO_2 capture retrofit are flue gas treatment and the steam turbine and its ancillaries. The flue gas desulphurization (FGD) plant should be designed so that it could be adapted to the different efficiencies, gas flows and composition. Modifications of the steam cycle to allow flexible steam extraction and to utilise additional low grade heat.

There are two major reasons for not making major capture ready pre-investment: economic discounting, which means that economic resources in the future are worth less than at present and uncertainty. These uncertainties are connected to future regulations, values of carbon credits and capture technologies development. It was found clear that unless capture is retrofitted relatively soon after plant start-up, it is not worthwhile building a plant which has a substantially higher cost of before capture. This conclusion was drawn by comparing IGCC plant and supercritical PC plants with and without capture.

A spreadsheet tool was developed to allow an assessment of the trade-off between pre-investment and subsequent savings for a range of different techno-economic factors. This tool was made available to the IEAGHG members.

2.8 Near zero emission technology for CO_2 capture

The capabilities of the various CO_2 capture technologies of delivering near zero emissions, the cost of doing so and how close to zero emission the most promising systems can come were assessed. It was found that the notion “near zero emission power plants” is more appropriate than “zero emission power plants” when life cycle aspects of the entire fuel chain are taken into account. In addition, the definitions and the evaluation method used for “zero emission” or “near zero emission” power plants need to be reviewed and evaluated.

From a purely economic point of view it would be far better to invest in more power plants with optimum capture rather than fewer of near zero emission performance. However, Oxy-fuel combustion coal processes were found best suited to being adapted to high capture ratios with little extra cost. Post-combustion processes can be modified to approach the near zero emissions performance but only at excessive cost and through installation of large pieces of additional equipment. Pre-combustion processes cannot reach very high capture ratios. Even though, the advanced processes (water cycle, AZEP, SOFT-GT and chemical looping) offer the prospects of near 100% CO_2 emission reduction, their costs of electricity are subject to a large uncertainty.

Life cycle considerations limit the overall reduction of emissions in the full fossil fuel to electricity energy chain because of emissions caused by transport and production. These are sufficient to question the wisdom of increasing capture of CO_2 emissions at power plants beyond the economic optimum even for oxy-fuel combustion.

Capture processes already eliminate many of the toxic emissions and further increases in CO_2 capture percentages to the levels of near zero emissions would yield little or no further advantage with respect to SOx, NOx, particulate or mercury emissions.

2.9 CO_2 Capture in low rank coal power plant

The low rank coal (sub-bituminous coal, lignite and brown coal) are important fuels for power generation in several countries. An IEAGHG study was therefore carried out to estimate the performance and costs of low rank coal fired power plants with CO_2 capture based on various technologies (post-combustion, pre-combustion and oxy-fuel combustion).

By assessing the performance and costs of power plants with CO_2 capture, it was found that there are little differences between the costs and thermal efficiencies of low rank coal power plants with CO_2 capture based on post-combustion capture, oxy-fuel and IGCC. The optimum technology will depend on the technology maturity, the coal analysis, and other local circumstances.

The differences between the costs of the different technologies (with capture) are within the limits of uncertainty of the assessment, with a maximum difference between the alternatives of 10%. However, the Circulating Fluidized Bed (CFB) with post-combustion capture has shown a slightly lower cost (see Table 3).

Table 3: Cost and performance summary for different capture technologies with low rank coal

	Net power [MWe]	Efficiency [LHV %]	CO_2 capture [%]	Capital cost [€/kW]	Electricity cost [€c/kWh]
Post combustion capture					
Pulverised coal	761.0	35.5	85.0	1645	5.39
CFB	614.4	35.5	85.0	1552	5.34
PCFB	688.4	32.5	85.0	1788	5.55
Oxy-combustion					
Pulverised coal	741.3	37.5	93.0	1882	5.46
Pre-combustion capture					
Future Energy gasifier	665.2	34.7	85.8	1706	5.41
Shell gasifier	628.8	34.5	85.2	1917	5.94
Foster Wheeler gasifier	686.6	34.1	82.9	1795	5.64

On a LHV basis, the efficiencies of the brown coal power plants with capture are similar to the efficiencies of bituminous coal plants using the same technology, as reported in other IEAGHG studies, but on a HHV basis the brown coal plants are less efficient. This is related to the partial drying of the lignite, which is advantageous to increase LHV efficiency, utilizing low temperature heat sources available in the plant at various locations. The efficiency penalty for post combustion CO_2 capture is slightly higher for low rank coal CFB plants than for the pulverised bituminous coal plants reported in PH4/33. This could be related to the higher quantities of CO_2 which need to be captured per kWh of electricity in a low rank coal power plant compared to bituminous coal.

2.10 Biomass fired and co-fired power plant with CO_2 capture

The use of biomass in power generation is one of the important ways in reducing greenhouse gas emissions. Specially, the co-firing of biomass with coal could be regarded as a common feature to any new build power plant if a sustainable supply of biomass fuel is readily accessible. IEAGHG carried out a study (2009/09) to estimate the performance and costs of standalone biomass fired power plants or coal co-fired with biomass power plants with CO_2 capture based on current state of the art boiler and steam generation equipment and standard MEA post combustion capture technologies.

In addition, the potential impacts of any incentives from the green certificate or the ETS mechanism were evaluated. For simplicity reasons, the revenues from the green certificate and ETS mechanism were assumed to be constant over the whole 25 years economic life of the power plant. This means that if the prices go below the assumed values, then the NPV will be negative.

A higher loss in net efficiency and larger increase in the capital costs and cost of electricity (COE) were observed for cases using a standalone biomass fired power plants compared to co-fired power plants, which could be related to the following factors:

- The higher cost of the biomass fuel compared to coal
- Installation of additional flue gas clean up equipment (i.e. external FGD)
- The installation of the direct contact cooler
- The lower LHV of biomass with respect to coal
- The larger volume of flue gas from a standalone biomass fired power plant to be handled compared to a similar size of coal fired boiler.

The increase in the capital cost due to the installation of CO_2 capture process was larger in the CFB case compared to the PC case, which could be attributed to the additional cost associated to the installation of the external flue gas desulphurisation which was not required for the CFB power plant without CO_2 capture.

It was concluded that the 250 MWe biomass fired CFB power plant could only be competitive as compared to their co-fired biomass counterpart when the cost of biomass fuel would drop down to around 50 €/t dry basis. On the other hand, 75 MWe biomass fired BFB power plant without CO_2 capture would need a biomass price down to 30 €/t day basis to make it comparable to their co-fired biomass cases. The COE from the 250 MWe biomass fired CFB power plant with CO_2 capture would only be competitive if both incentives (green certificate and ETS certificate) are included in addition to a low price of biomass fuel (50 €/t dry basis).

2.11 Future costs and investment decisions of CO_2 capture technologies

Predicting possible future trends in the costs of power plants with CO_2 capture is an important factor for investment and R&D decisions. This prediction could be done by analysing the cost reductions those were achieved for a range of process technologies. An IEAGHG study (2006/06) assessed the historical cost trends and reductions of different related technologies (i.e. FGD, SCR, GTCC, LNG and SMR) and employed these assessment findings to estimate the cost reductions those might be achieved at power plants with CO_2 capture technologies (post-combustion, pre-combustion and oxy-fuel combustion) in the future.

Major factors contribute to process technology cost reductions include, but are not limited to: improvements in technology design, materials, product standardisation, system integration or optimisation, economies of scale and reductions in input prices.

Analysis of various process technologies indicated that in most cases capital costs were reduced by 10-15% for each doubling of installed capacity. The corresponding reduction in operating and maintenance costs was 5-30%.

Based on learning rate data from analogous process technologies, the cost of electricity from power plants with CO_2 capture was predicted to be reduced by 10-18% after 100 GWe of capacity is installed. Reductions in the incremental costs of CO_2 capture were predicted to be 13-40%. IGCC with CO_2 capture was estimated to have a higher overall costs reduction from learning than other coal based power technologies because of greater cost reductions in the core power generation sections of the plant. However, the reduction in the incremental cost of capture in IGCC was estimated to be lower than for plants with post combustion capture.

In another IEAGHG activity (2006/08), the results from previous IEAGHG studies were pulled together with the intention to provide a guideline for power plants investors and to evaluate the contribution of CO_2 capture as a factor in power station investment decisions.

The analysis showed a high level of interest in CO_2 capture with a clear idea that abatement of greenhouse gas emissions did factor in their choice of power generation. However, the most popular alternatives to CO_2 capture technologies were: efficiency improvement on existing power plants, renewable energy and switch to CO_2 neutral fuels like biomass. The least popular options were: reducing power output to control emissions and new build nuclear plants.

GTCC plant incorporating pre-combustion capture best matched investors' preferences. Of the coal fired plant options, IGCC ranked best for new plants in the multi criteria analysis but post-combustion capture was seen as the most needed technology, both for new and retrofit plants.

There was a wide range in the investors' awareness of the capture technologies, with the evidence suggesting that post-combustion capture plant is most widely understood, followed by IGCC, pre-combustion capture through reformation of natural gas and oxy-fuel combustion least widely understood.

2.12 Novel approaches to improve the performance of CO_2 capture

The idea of the IEAGHG study 2008/10 was to search for innovative CO_2 capture process concepts outside traditional fields of enquiry and break away from a classical chemical engineering process based approach.

The following 8 areas were identified as of interest for further exploration in attempts to improve the overall value of CO_2 capture technology:

1. Bundling of CCS as part of a low carbon energy offer to end users
2. Better use of oxygen and nitrogen in oxy-combustion processes
3. Site selection of CCS capture plant
4. Partial mineralisation to lock-up some of the capture CO_2
5. Bio-systems to create solid carbonates
6. Better use of bio-mass co-fired in CCS plant
7. Pre-combustion capture catalyst improvement
8. Greater use of information flows to improve CO_2 capture processes

Out of the above mentioned eight options; systems integration in its widest sense seems to offer the greatest potential for improving the CCS. In fact apart from area 7 (pre-combustion capture catalyst improvement) all other involve an increase in the complexity of the CCS system. The easiest area on which to start is area 2 (better use of oxygen and nitrogen in ox-combustion), a second area is area 6 (better use of biomass co-firing in CCS plant) and the third area where it might be worthwhile making a start is on biological methods for CO_2 mineralisation.

2.13 Environmental impact of solvent scrubbing of CO_2

Solvent scrubbing is currently the leading technology for pre and post combustion capture of CO_2. Therefore it is important to study and understand the environmental impact of these solvent systems before full scale deployment of the technologies. The IEAGHG 2006/14 study provided a preliminary analysis of the environmental impacts of large scale use of solvent scrubbing processes for CO_2 capture in power plants, using a Life Cycle Assessment (LCA) methodology. This analysis included the direct impact (e.g. avoidance of CO_2 emission, solvent emissions and degradation) and indirect impact (e.g. higher fuel use and solvent disposal) excluding the CO_2 transport and storage.

This study focused on MEA solvent for post-combustion and MDEA solvent for pre-combustion. The environmental impacts of other solvents may be substantially different, so it is not possible to draw conclusions about the impacts of solvent based CO_2 capture processes in general.

The method of weighing with shadow prices leaded to the conclusion that per MWh the natural gas reformer plant with MDEA CO_2 pre-combustion capture will cause the least environmental impact, closely followed by the natural gas combined cycle plant with MEA CO_2 post-combustion capture. On the other hand, this method showed that the highest environmental impacts of all capture plants was caused by the post-combustion coal fired power plant, although the difference with pre-combustion coal firing is small.

Based on this study, which did not include a detailed chemical emissions evaluation, CO_2 capture showed a net environmental benefit, due to the avoidance of CO_2 emissions to the atmosphere. The development of new CO_2 capture solvents should be focussed on those which have reduced environmental impacts.

2.14 CO_2 capture from medium and small sources of emissions

Large CO_2 sources such as power stations and large industrial plants are expected to provide the main opportunities for CO_2 capture and storage. Small and medium scale fixed sources account for a smaller but nevertheless substantial proportion of total global emissions of CO_2 (15-20%). In order to achieve the large reductions in CO_2 emissions that are expected to be necessary to avoid major climate change, major reductions in emissions from these sources will be required. Two studies have so far been carried out by IEAGHG to assess capture and storage of CO_2 from medium scale, which will be discussed in this section.

2.14.1 CO_2 capture from medium scale combustion installation

The study assessed the costs and performance of CO_2 capture technologies installed in medium combustion installations (1-100 MWth fuel input) in the industrial and commercial sectors (reciprocating engines, gas turbines, boilers and furnaces and , possibly in the long term, fuel cells). CO_2 emissions from chemical processes and cement kilns were outside the scope of the study.

The most suitable capture technology for medium scale combustion installation will depend on site-specific conditions, including the size and efficiency of the installation, its operating load factor and opportunities to utilise low grade heat. The highest costs were estimated for post-combustion capture in the relatively small reciprocating engine case. The costs per tonne of CO_2 avoided, was approximately twice as high as for a large scale (670 MWe) power plant.

The estimated cost for the membrane oxy-combustion with oxygen conducting membranes (OCMs) cases were substantially lower than that for post-combustion capture case, because of a lower energy penalty and lower capital and operating costs. However, there are greater uncertainties regarding the performance and costs of the membrane cases. Significant technical issues need to be addressed, in particular the design of the membrane air separation unit and its sensitivity to impurities and fouling, and integration of the equipment.

An important issue for medium scale installations is the transportation of the capture CO_2 to a storage site. The cost of CO_2 transport will depend on the proximity to other CO_2 sources, because there are large economics of scale in CO_2 pipeline systems. In addition, the economic feasibility of capturing CO_2 from medium scale installations will depend on the carbon price, which depends on the extent of which global emissions of CO_2 need to be reduced and the costs of alternative ways of reducing emissions.

2.14.2 CO_2 capture in the Cement industry

The cement industry is one of the world's largest industrial sources of CO_2 emissions, accounting for more than 6% of global emissions from the use of fossil fuels in 2005. IEAGHG carried out a study (2008/03) to assess the technologies that could be used to capture CO_2 in cement plants and their performances and costs.

The addition of CO_2 capture to new build cement plants to significantly reduce CO_2 emissions was found feasible. Both post-combustion and oxy-combustion options can be considered. Pre-combustion capture would be less suitable for cement plants because it would not capture the CO_2 from carbonate mineral decompositions, which account for about two thirds of the CO_2 from a modern cement plant.

Oxy-combustion capture offered the lowest cost solution for CO_2 capture at new build cement plants but further research and development is needed to address a number of technical issues to enable this technique to be deployed. Costs were estimated to be 23-40 Euro/tonne CO_2 avoided, which will increase the cost of cement production by almost 17 Euro/tonne cement product. The estimated costs of post-combustion capture at new build cements plants were 59-107 Euro/tonne CO_2 avoided, which is equivalent to 63.7 Euro/tonne cement product.

Even the estimated cost of CO_2 avoided for post-combustion capture was higher than oxy-combustion capture, post-combustion will remain the more mature and lowest technical risk capture solution. In addition, Post-combustion capture could be readily retrofitted to existing cement plants provided sufficient space is available. Substantial rebuilding would be necessary to accommodate an oxy-combustion retrofit but this may nevertheless be the least cost option.

The cost of CO_2 capture at a cement plant using oxy-combustion is expected to be similar to the cost of capture at a typical coal-fired power plant. The quantity of oxygen required per tonne of CO_2 capture of about three times lowers at a cement plant but the economics of scale are less favourable. On the other hand, the cost of post-combustion capture at a cement plant is expected to be substantially higher than at a power plant, mainly because of lower economics of scale and the need to install FGD, DeNOx and a boiler to provide steam for the solvent regeneration.

3 CCS Generic Studies

3.1 Distributed collection of CO_2

Carbon dioxide emitted from small and medium sources account for a small but nevertheless substantial proportion of the total global emissions of CO_2. The IEAGHG study (2007/12) assessed the economic and practical viability of a distributed carbon dioxide collection and transmission network using a network of pipelines and compressor. The economic evaluation revealed that having a central suction station serving several small sources appeared cheaper than equipping each source with its own compressor or blower.

In this study, high pressure CO_2 lines are constructed of carbon steel and the CO_2 is dried to avoid corrosion. For intermediate and low pressure lines HDPE could be used and this would be resistant to wet CO_2 corrosion. However, drying units were specified at every location to avoid any problems related to water build up in the system.

The costs of collecting CO_2 from moderate sized industries were found not excessive and should be considered when planning CO_2 pipelines and storage infrastructure. The cost of CO_2 collection and transmission for the whole network was calculated to be $9.7/tonne. Removing all sources below about 600 000 tonnes per year reduced the total cost to $8.5/tonne.

When taking marginal costs into consideration it became apparent that in this instance distributed CO_2 collection is not viable for very small sites, even using low cost suction networks. The alternative to carbon capture and storage for these distributed sources would be to provide them with green electricity or hydrogen. Overall there are many obstacles to hydrogen distribution, however if subscription to such a network was high, the costs could be reduced significantly. Although green electricity is becoming more competitive, the cost of production is still substantially higher than electricity from traditional fossil fuel routes.

3.2 Safety in CCS

The safety issues in a generic CCS system consisting of power plant with CO_2 capture, transport by trunk line to an on or offshore injection site were examined. The safety of all surface facilities was considered but not the risks associated with underground reservoirs or the below ground sections of wells. The most established forms of the three leading processes (pre, post and oxy combustion) for CO_2 capture at power stations were all considered.

A set of bow tie diagrams, which effectively describe all of the factors those could contribute to causing incidents in CCS systems, were constructed. It is anticipated that they can be used in the first phase of safety management in future CCS projects.

A list of 23 areas of potential hazards was formulated, which could be used as part of a safety check list at various stages of a CCS project. Examples of the identified potential hazards are: HP CO_2 leaks, cold burns from CO_2 release, toxic hazards due to mercury accumulation, fires in oxygen enriched atmosphere, brittle failure during depressurisation of CO_2, fires involving new solvents, corrosion problems, new solvents used for CCS to contain toxic materials and incomplete coverage when advanced CO_2 pipeline leak detection systems are deployed.

A few areas where further research and development are needed were noted:

- Consequence modelling of CO_2 releases
- Pipeline failure criteria
- Understanding the propensity of dense phase CO_2
- Design and operational standards for CO_2 pipelines and other equipments are still in development
- Aspects of emergency response planning

The extensive hazard analysis performed during this study did not find any fundamental safety issues which could not be fully managed. Nevertheless there are numerous hazards associated with CCS surface operations which will have to be addressed.

3.3 Permitting issues for CCS

To ensure that CCS can be deployed successfully in the required timescales any issues that may arise during permitting of CCS projects need to be identified and permitting procedures to be developed and agreed. An IEAGHG study (2006/03) was commissioned to provide an overview of permitting issues in CCS projects and provide some guidance to operators and regulators who are concerned with the technology. The permitting requirements were subdivided into those required for each of the three main temporal phases: planning and construction, operation and closure and decommissioning.

For CO_2 capture and transport existing regulations in all the jurisdictions studied are largely adequate but there are a few minor gaps and areas only partially covered. The areas include among others: energy penalty, storage of amine solutions, equipment safety, waste product discharges, population density, removal of water and risk. On the other hand, there are significant issues for both the injection/storage and the long term reservoir stewardship phase which are not covered by existing permitting systems. Considerable development of legislation and permitting procedures for these activities are thus required.

The study suggested that uncertainties about reservoir performance may result in use of time limited permits for the injection phase, requiring operators to renew permission as reservoir pressure and CO_2 content increases. In addition, performing environmental impact assessment (EIA) is identified as a key process which will be central to the successful permitting of CO_2 storage activities.

It is not clear at this stage to what extent regulations or standards should prescribe the information which should be provided and methods which should be used. If prescribed in great detail the result might be too prescriptive and innovation will be stifled. On the other hand operators might prefer to know in advance exactly what information they need to collect and generate.

Even when regulations cover all aspects of CCS activities well, when CCS applied it may raise a few issues for which minor adaptations and interpretations will be required. It was suggested in the study that regulators will require emergency and remediation plans to be in place before permits are granted.

3.4 Financing CCS projects

Two expert meetings on financing CCS were organised in 2007 and 2008. These meetings provided an opportunity to discuss the issues that are restricting the development of CCS from a financial prospective. These meetings also enabled a discussion of the options to overcome these issues as well as ways to facilitate and encourage more CCS projects.

There is a lack of CCS project history and risk profiles, so new novel ways to mitigate and mange any new risks that CCS presents are needed. In addition, it was noted that while there is considerable work and interest in CCS, policy and regulatory regimes are also very uncertain and CCS is largely unknown to policy analysts, planners, politicians.

An important outcome is that many speakers thought the difficulties and issues surrounding CCS can be resolved. However, in order to move forward, governments need to provide financial support to the first CCS projects. In addition, governments need to have robust CCS policies that provide certainty to investors and allow for the deployment of CCS projects.

The workshops discussion provided the following points of note:

- CCS is not supported by a policy framework except in Norway and Netherlands.
- There is a perception that climate change and energy security supply issues will be drivers in the development and commercialization of CCS.
- If the required rapid large scale commercial deployment of CCS is going to happen, then the installation of significant GW capacity of CCS is needed as building demonstration plants alone is unlikely to bring costs down quickly enough.
- The financial sector is interested in CCS but needs to have more information on CCS and also the mechanisms available for financing the projects and what rate or return each generates.
- Lunching IEA CCS International Regulatory Network may enhance the speed of CCS regulatory development.
- There is a perception that an emissions trading scheme will not be enough to accelerate deployment of commercial CCS projects and other financial incentives are needed to make CCS projects viable.
- Legal and environmental liability is seen as an issue. Insurance companies have the business models to insure CCS projects during the operational phase but there is a lack of data to provide coverage for the long term liability.

3.5 CCS evaluation tools

The development of techno-economic evaluation tool will help in evaluating and screening the newly developed novel process concepts. In additions, these tools could be used to design and estimate the behaviour of the CCS chain or a smaller component in this chain (i.e. CO_2 pipelines). In the last five years, IEAGHG developed and upgraded two tools that could be used for CCS evaluation: the power plant assessments program (PPAP) and the CO_2 pipeline systems calculator.

The PPAP program, which is excel spreadsheet based, presents results in two output worksheets as well as a worksheet with a complete vector of all inputs and outputs which is useful for detailed comparisons and cross checking. In addition, it accepts input heat and material balance information produced by external process simulators as an alternative to relying on the rather simple routines in PPAP.

PPAP performs overall heat and material balance reconciliation, capital cost estimate, thermodynamic calculations of simple steam and gas turbine cycles, multi-criteria assessments of the proposed process and performance and unit cost calculations for the complete power plant.

The program assesses the overall commercial performance on a multi-criteria scoring basis taking into account, CO_2 emissions, fuel consumption, capital and operating costs as well as the process complexity and severity, construction material and natural resources requirements, development requirements, safety and environmental impacts. The units cost of electricity, total capital cost, operating costs, efficiency, fuel consumption and CO_2 emissions are all calculated and presented by the program.

In 2009, the calculator for CO_2 pipeline systems was updated and upgraded. A new pressure drop calculation procedure for CO_2 trunk lines was developed. The tables of the physical properties of pure CO_2 (density and viscosity) are now used as the basis for the calculations with extended ranges of the valid temperatures and pressures.

New routines to allow costs to be escalated using any of the four main published industrial construction costs indices and the possibility to calculate costs in different currencies were introduced. The ability to adjust costs for different world regions using regional cost factors was retained and extended to the other parts of the model. The revised cost and sizing calculator now allows more accurate high level sizing and costing of CO_2 pipelines and collection systems.

3.6 Global CO_2 emissions database

The IEAGHG global CO_2 emissions database, which was first published in 2002, was improved and updated in 2006. The most significant area of attention in the original database was quickly identified as the gas processing sector. Total emissions from this sector, which were estimated of 2859 Mt CO_2/yr in the original data base, were brought down to 66 Mt CO_2/yr.

Another source of error and problem was the lack of geographical locations (i.e. the Canadian entries), spelling errors in the names or because a town or city could not be identified many sites were not allocated co-ordinates (i.e. Asian emission sites).

Improving the database was done by the using updated emissions information and integrating other databases into the IEAGHG database. For example, the AEUB Canadian gas processing plant database, the published UK environmental agency pollution inventory, the European power sector data base developed by Chalmers University in co-operation with the European power generators, IPCC special report new entries and CO2CRC data for the Asia Pacific Region.

The latest version of the database contains around 8000 entries; reduce from the original 14000 entries. There are 13 sectors included in the data base (i.e. Ammonia, Cement, ethanol, Iron & Steel, power, refineries …). In addition, the latest version is more in line with the emissions figures published in the IPCC special report on CCS.

3.7 CCS and CDM

A concern raised about the inclusion of CCS in the clean development mechanism (CDM) is the negative effect that it may have on the global carbon market due to the increased supply of carbon credit. An IEAGHG study (2008/13) was carried out to assess the effect that coal power plants with CCS could have on the global carbon market.

On the basis of certified emission reduction (CER) price estimation CCS could potentially contribute of 0-16 percent of total CER supply at the estimated level of demand by 2012. This compares to 27 percent of CDM market share occupied by industrial gases and 18 percent from CH_4 based projects. The analysis suggested that CCS projects would only compete with other CDM candidate options at the margin if demand exceeds about 520 M CERs per year 2012.

The study adopted a figure from demand of 2100 million CERs per year in 2020, based on published research on potential CER supply in 2020. At this level of demand, CCS would be deployed at levels in the range 117-314 $MtCO_2$ per year, which will represent between 6-9 percent of total CER supply.

The marginal price effect on CERs in 2020 from CCS inferred by the analysis is a cost reduction per tCO_2 abated of between $24-30 at demand level of 2100 million CERs per year, equal to about a 47-60 percent reduction, but these estimates must be treated with care.

This study showed that even with high level uptake of coal fired power plants with CCS (4 plants by 2020 and 288 by 2032), with 20 $MtCO_2$ by 2020, the impact on the global carbon price remains minimal (not exceeding 2 €/tCO_2). It was concluded that the inclusion of CCS in the CDM may not have any significant ramifications for the global carbon market or other CDM technologies in the near or medium term.

3.8 CCS and transport fuels

The IEAGHG 2005/10 study aimed to assess the impact of CO_2 capture and storage on low emission pathways for road transport fuels. This study covered the impact of full fuel pathway (known as Well-to-Wheels analysis) and used the European JEC WTW study as a base case.

With CCS, the electricity and hydrogen pathways showed substantial emissions reductions over the gasoline reference case. Fossil fuel routes provided reductions of 60-80 % in greenhouse gas emissions compared with the reference case.

The costs of CO_2 avoidance were estimated in all cases hundreds of Euros. These costs are an order of magnitude greater than those for stationary applications of CCS (e.g. power generation).

Hydrogen from natural gas provided the lowest avoidance cost of the fossil fuel options for deep reductions in CO_2 emissions. For more modest reductions in CO_2 emissions, CNG offered the lowest avoidance costs of the various routes. While considering the potential of Biomass, the cost of PEM fuel cell and compressed hydrogen tank pressure values used in this study should be treated with great caution.

The costs in the WTW analysis are dominated by the cost of the vehicle because it is only driven for some small percentage of the time available. However, at a higher level of utilization (e.g. taxis) the fuel cost becomes a more significant factor.

3.9 Reduction of residential CO_2 emissions through the use of small cogeneration fuel cell systems

The potential of fuel cell based CHP systems in domestic and small commercial applications to reduce greenhouse gas emissions was investigated. Fuel cells in this application have advantages of very low emissions and potentially higher power to heat ratios than other CHP systems.

The ratio between electricity and power consumption is a key parameter when considering the potential of CHP systems in the EU. Also of importance in assessing the contribution of emission reductions is the baseline emission characteristics with the technology compete.

The heat and power demands were analysed for two types of dwelling, single family houses and multi family housing units in which a heating system is shared. This was done using a bottom up approach and later compared with the top down approach. Comparison of the results from the two approaches showed agreement to within roughly 13-16%, the bottom up estimates being consistently higher. The net result of the analysis was a slight increase of expected heat demand per house over time.

The results of the avoidance costs showed that economics of scale play a significant role so that the abatement costs for multi-family houses were estimated much lower than for single family houses. Also the relatively high cost of very small fuel cell systems makes for rather high avoidance costs. It was evident that unless there can be major cost breakthroughs the fuel cell systems are at a serious cost disadvantage compared to competing CHP systems based on Sterling engines.

The potential of CO_2 emission reduction from domestic fuel cell CHP systems were estimated to be between 1% and 4% of the emissions in the residential sector of the OECD. However, there were concerns about this small calculated potential of emission reductions and a feeling that the assumption of a purely heat lead system was too restrictive and that better results might result if better use was made of the electrical capacity.

4 IEAGHG Studies Conclusions and Recommendations

IEAGHG study reports represent a considerable body of knowledge on CCS, and recent (post 2004) studies have provided reports that serve as reference documents for key aspects of CO_2 capture and CCS including post combustion, pre combustion, oxy-fuel combustion, capture economics, environmental impact, capture ready, retrofit of CO_2 capture, biomass fired power plants, CO_2 capture from medium scale combustion installations, safety of CCS, CCS permitting and financing issues, and CCS in CDM.

The studies resulted in major conclusions and recommendations, listed below. However, it is important to consider the timing when these studies were conducted while analysing and evaluating these conclusions and recommendations. Current and future IEAGHG studies will continue to seek to address these recommended areas, in conjunction with the work of the international research networks and global CCS projects.

4.1 Conclusions

The conclusions listed in this section were extracted directly from the different IEAGHG studies in the period 2005-2009. This makes these conclusions time dependent, which means that some of these conclusions could not be completely correct now and might change in the future.

1. Efforts to improve the solvent scrubbing capture systems need to carry on because the main challenge of reducing the capture cost still exists.
2. For post combustion capture, solvent scrubbing is considered the state of the art and the solid adsorbents and membranes based processes are considered to be 2nd or even 3rd generation technologies.
3. The changeable economic climate makes the economic evaluation and costs estimates uncertain and that requires special caution while assessing these results.
4. The increase in the cost of electricity, efficiency losses and costs of CO_2 avoided are quite similar for the three major capture technologies (post, pre and oxy-fuel combustion).
5. The oxy-fuel combustion needs further development in key areas including: plant start up, control systems, burner and flame characterisation. However, none of these development areas are likely to represent technical show stopper.
6. Retrofitted CO_2 post combustion capture showed lower capture cost and smaller efficiency reduction compared to CO_2 pre combustion capture for natural gas combined cycle plants.
7. From an economic point of view it would be better to invest in more power plants with optimum capture rather than fewer of near zero emission performance.
8. Oxy fuel combustion coal processes are best suited to being adapted to high capture ratios; post combustion processes can be modified to approach near zero emissions but only at excessive cost and pre-combustion capture cannot reach very high capture ratios.
9. From the overall costs and efficiencies, it was found that post combustion and oxy fuel combustion capture processes are more competitive compared to IGCC for lower rank coals.
10. Comparing the physical absorption processes, the Rectisol process resulted in lower operating costs but higher capital costs compared with the Selexol process.

11. The standalone biomass power plants showed a higher loss in net efficiency, larger increase in the capital costs and higher cost of electricity (COE) compared to co-fired power plants.
12. IGCC with CO_2 capture was estimated to have a higher overall costs reduction from learning than other coal based technologies. However, post combustion capture is expected to have larger reduction in the incremental cost of capture.
13. The abatement of greenhouse gas emissions is one of the factors in the investment decision in the choice of power generation.
14. CO_2 capture has a net environmental benefit, due to the avoidance of CO_2 emissions. However, there is a valid concern regarding solvent losses and other wastes produced from the capture plants.
15. Capturing CO_2 from medium scale installations will depend on the carbon price, the possibility of CO_2 collections and the availability of storage sites.
16. In the cement industry, both post combustion and oxy-fuel combustion capture options can be considered. Although, oxy-fuel offered the lowest cost, post combustion could be easier retrofitted to existing plants.
17. Fuel cell CHP systems can only be expected to make a small contribution to emissions reductions in the domestic housing energy market in the future.
18. While there are numerous hazards associated with CCS, the hazard analysis did not find any fundamental safety issues which could not be fully managed.
19. For CO_2 capture and transport existing regulations are largely adequate. However, the main underground elements of CCS require significant development of the permitting process.
20. In order to move forward with CCS, governments need to provide financial support to the first CCS projects and to have robust CCS policies that provide certainty to investors.
21. The inclusion of CCS in the CDM may not have any significant ramifications for the global carbon market or other CDM technologies in the near or medium terms.

4.2 Recommendations

The recommendations in this section were extracted directly from the different IEAGHG studies in the period 2005-2009. This makes it time dependent and changeable in the future depending on the expected progress in the CCS field.

1. Compare the costs of abating CO_2 emissions from small stationary sources by CCS with the costs of using low-CO_2 energy carriers produced by large plants with CCS; this could include the use of biomass.
2. Monitor the development in oxygen production technologies and provide a short updated review at an appropriate time.
3. Help permitting authorities to prepare guidelines for capture ready plants by summarising the various candidate technologies, costs and the legal issues.
4. Review and assess the definition and the evaluation method used for “zero emission” or “near zero emission” power plants.
5. Include oxy-fuel CFB case and IGCC in any future assessments of low rank coal power plants.

6. Investigate the possible applications of CO_2 capture in some niche industries where biomass is normally used as fuel. In addition, continue to monitor the development of the use of biomass for power and heat generation.
7. Analyse the impacts of cost or revenue from CCS including EOR on the power station investment decisions.
8. Carry out a full life cycle emissions analysis of GHGs including the fuel supply and CCS.
9. Perform a detailed assessment of the environmental impacts of solvent scrubbing process of CO_2 capture.
10. Study alternative ways of reducing CO_2 emissions from medium scale energy users, including energy efficiency improvements, renewable energy and large scale fossil fuel with CCS.
11. Prepare a road map to assist zones with a high concentration of industry to collaborate, exchange information and develop plant infrastructure with a view to effectively cutting greenhouse gas emissions.
12. Assess the benefits of integrating (co-locating) cement plants with CO_2 capture (post or oxy-fuel combustion) and other large industrial plants, especially power plants.
13. While evaluating the reduction of residential CO_2 emissions through the use of small cogeneration fuel cell systems in 2008; it was recommended not to carry further work on the potential of fuel cell systems to reduce emissions in the short term future.
14. IEAGHG to make generic safety bow-tie diagrams available as an additional tool through its website and support setting a centralised incident database for the CCS industry.
15. Examine the state of the art for fuel cell production and usage and the production of biomass fuels both in the areas of transport and power generation.
16. Focus in future transport fuel work on the commercial vehicles sector.

5 What have we missed in the IEAGHG activities (2005-2009)?

After examining and evaluating the IEAGHG activities in the period 2005-2009, the following list summarises missing ideas and issues which are considered crucial for the CCS communities:

- A guideline for CO_2 capture processes techno-economic benchmarking, comparison and evaluation. This could include a standardised evaluation parameters and criteria. This work could be done in cooperation with ongoing R&D activities.
- CO_2 capture risk assessment.
- CO_2 capture scale-up challenges and strategy.
- Overviews of the CO_2 capture global R&D and commercial activities to define who is doing what with major focus on process development and large scale pilot plants and demonstrations projects.
- The IGGC development and new process concepts evaluation.
- More involvement in the EU and the international CCS projects and R&D programmes.
- Evaluate the expected future capture process improvement and cost reduction within a specific timeframe.
- The following topics are important but considered outside the scope of IEAGHG technical studies, which are provided for the members consideration:
    - Capture technologies heat recovery, integration and possibilities for energy requirement reduction by process engineering concepts.
    - Capture processes operability and control (dynamic behaviour and modelling).
    - First generation capture technologies front end engineering design (FEED).
    - Evaluate process engineering concepts to improve the capture process efficiency and costs.

6 List of IEAGHG Reports on CO_2 Capture and International Research Networks (2005 – 2009)

1. Retrofit of CO_2 capture to natural gas combined cycle power plants. 2005/01, JACOBS.
2. The IEAGHG power plant assessment program (PPAP). 2005/07, GasConsult, IEAGHG.
3. Oxy combustion processes for CO_2 capture from power plant. 2005/09, Mitsui Babcock.
4. Low greenhouse gas emission transport fuels: the impact of CO_2 capture and storage on selected pathways. 2005/10, C. J. Clark.
5. CO_2 capture in low rank coal power plant. 2006/01, Foster Wheeler Italiana.
6. Permitting issues for CO_2 capture and geological storage. 2006/03, Environmental resources management-Oxford.
7. Estimating the future trends in the cost of CO_2 capture technologies. 2006/06, Carnegie Mellon University.
8. Updating the IEAGHG global CO_2 emissions database: developments since 2002. 2006/07, IEAGHG.
9. CO_2 capture as a factor in power station investment decisions. 2006/08, Mott MacDonald.
10. Near zero emission technology for CO_2 capture from power plants. 2006/13, ECN.
11. Environmental impact of solvent scrubbing of CO_2. 2006/14, TNO.
12. CO_2 capture ready plants. 2007/04, E.ON-UK, Doosan Babcock and Imperial College.
13. CO_2 capture from medium scale combustion installations. 2007/07, ECN.
14. Expert workshop on financing carbon capture and storage: barriers and solutions. 2007/09, IEAGHG.
15. Distributed collection of CO_2. 2007/12, Gastec at CRE, AMEC.
16. Co-production of hydrogen and electricity by coal gasification with CO_2 capture. 2007/13, Foster Wheeler Italiana.
17. Improved oxygen production technologies. 2007/14, Rodney John Allam.
18. Post combustion capture from coal fired plants-solvent scrubbing. 2007/15, IEA Clean Coal Centre.
19. CO_2 capture in the cement industry. 2008/03, Mott MacDonald.
20. 2nd expert meeting on financing CCS projects. 2008/04, IEAGHG.
21. Co-production of hydrogen and electricity by coal gasification with CO_2 capture-updated economic analysis. 2008/09, Foster Wheeler Italiana.
22. Novel approaches to improve the performance of carbon dioxide capture. 2008/10, Innovaro.
23. Reduction of residential carbon dioxide emissions through the use of small cogeneration fuel cell systems. 2008/11, Forschungszentrum Julich.
24. Carbon dioxide capture and storage in the clean development mechanism: assessing market effect of inclusions. 2008/13, Environmental resource management.
25. Post combustion carbon capture from coal fired plants-solid sorbents and membranes. 2009/02, IEA Clean Coal Centre.
26. Upgraded calculator for CO_2 pipeline systems. 2009/03, Gastec, AMEC.
27. Safety in carbon dioxide capture, transport and storage. 2009/06, UK health and safety laboratory.

28. Techno-economic evaluation of biomass fired or co-fired power plant with post-combustion CO_2 capture. 2009/09, Foster Wheeler.