NOVEL APPROACHES TO IMPROVING THE PERFORMANCE OF CARBON DIOXIDE CAPTURE

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This report describes the preparation and outcome of an innovation exercise sponsored by the IEA Greenhouse Gas R&D Programme. This report was prepared by:

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NOVEL APPROACHES TO IMPROVING THE PERFORMANCE OF CARBON DIOXIDE CAPTURE

Background

Carbon dioxide capture processes have been studied extensively and a large body of literature is available on this subject. Despite all the research and development work which has been done to date, the costs of CO_2 capture remain high and the efficiency of the processes to which it is applied, particularly power generation, are reduced by 6-12 percentage points. The high capital cost of CO_2 capture remains a barrier to wide scale implementation of CO_2 capture and storage (CCS) but is perhaps less important than the extra costs of operation given the very long lifetimes of major capital facilities such as power plants. Extra operational costs are in part accounted for by extra fuel costs because of efficiency reductions and this particular extra cost is of concern not only because fuel costs might escalate in the long term but also because reliance on fossil fuels is increased at a time when directionally it would be preferable for reliance on fossil fuels to decrease.

The IEA Greenhouse Gas R&D Programme (IEA GHG) thus elected to undertake a study search for innovative new avenues for CO_2 capture which might lead to significant improvements in the cost of capture technology and reductions in the energy penalty. The brief was to search outside traditional fields of enquiry and break away from a classical Chemical Engineering process based approach.

Study approach

The approach adopted for this study was to identify some leading specialists in innovation and as a first step invite them to set up an innovation process. Key aims were: to develop contacts in other fields of research and development, and to identify some potentially interesting avenues for further investigation. A second step, beyond the scope of this study, would be to follow up on any really promising avenues which might be uncovered.

Three companies with experience in innovation were identified and were invited to tender on the basis of a very broad functional scope. A contract was awarded to a relatively small company, Innovaro, whose tender was cost competitive, and had good references from major industrial groups who use their services regularly. The process started with a small workshop between 3 Innovaro staff and 3 IEA GHG staff. This was used to identify a number of themes or "vectors" around which a 24 hour innovation event would be built. To this event a selection of external specialists drawn from diverse backgrounds would be invited along with Innovaro and IEA GHG staff. In addition, the outline of an invitation aimed at encouraging participants interest was drawn up. Also a list of potential participants extracted from Innovaro's list of contacts was prepared.

Prior to the Innovation event a further meeting was held to run through the programme for the event and a thought provoking introduction which would be presented to stimulate and direct the innovation process.

The event was held at The Belfry near Birmingham, UK with 12 external participants starting with presentations on the first evening, followed by intensive structured sessions the next day. The ideas and insights emerging from the sessions were captured in part one of the report. This material was reviewed by the three IEA GHG staff who attended the session and was used to draw up a set of insights into areas for further exploration. In total 8 such areas were identified and for each Innovaro suggested that outlines were documented as to:

- What technologies are involved with examples?
- With whom could IEA GHG collaborate to develop the area?
- With whom could IEA GHG consult to obtain more understanding of the area?
- Who could IEA GHG influence to promote development work to occur on the technologies involved?

The key output of this work is the details of these insights which are discussed below.

Results and Discussion

Participants and their backgrounds

The following people attended the workshop at The Belfry. All expressed great interest in the subject area and confirmed that they would welcome further contacts.

Name and company	Position/interests
Andy Winship – BOC/Linde	UK hydrogen solutions business activities.
Dave Wardle – Oxford Catalysts	Business Development Director
Semali Perera – Bath University	Senior Lecturer Department of Chemical Engineering. Research interests include nano- and novel materials
John Hancox – Rolls-Royce	Environmental Specialist – Company Strategic response to climate change
Jamie Turner – Lotus Engineering	Chief Engineer of Powertrain Research
Graham Hillier – CPI	New Energy Director - Centre for Process Innovation.
Andy Treen – QinetiQ	Business Group Manager - Materials Group
Mercedes Maroto Valer – CICCS	Professor in Energy Technologies Director Centre for Innovation in Carbon Capture and Storage (CICCS), Deputy Head of School of Chemical and Environmental Engineering.
George Morris – QinetiQ	Technical Director - Energy and Environment
Tony Booer – Schlumberger Carbon Services	Business Development Manager, Northern Europe
Karl Bindemann – Arup	Associate Director - Major Power Projects
William Megill – Bath University	Lecturer in Biomimetics - Mechanical Engineering department

Areas for further exploration
The following 8 areas were identified as of interest for further exploration in attempts to improve the overall value of carbon dioxide capture technology.

1. *Bundling of CCS as part of a low carbon energy offer to end users*

The challenge is to see CCS not as a way of delivering low carbon electricity to be bought in preference to conventional power from other sources but as part of an overall low carbon energy offering. The market is seen as divided into domestic, commercial and industrial sectors with quite different options.
For domestic consumers the offering might feature delivery of CCS electricity coupled with obligations to install high energy efficiency devices, intelligent remote load control and advantageous buy back price for electricity from domestic CHP or renewable power installations.
For commercial customers the offering could be similar with for example automated remote device control for certain fraction of the connected load, assistance with installation of high efficiency appliances and assistance with the installation of local area CHP and power export facilities.
For industrial consumers tailored "responsible CCS" which could include obligations to use CHP, possibly running on hydrogen supplied along with the carbon free electricity supply and some on-site CCS for some applications using high temperature absorbent regeneration specifically in situations where a lot of heat is generated or consumed during processing.

2. Better use of oxygen and nitrogen in oxy-combustion processes

Current designs for coal fired oxy-combustion capture plant typically require up to 20% excess oxygen to ensure full coal burn out. If operation could be close to stoichiometric there would be significant reductions in the size of the air separation unit (ASU) and the parasitic power required to run it. Two leading options are to recover oxygen from the CO_2 clean up vent stream and to burn out residual oxygen with natural gas or hydrogen after the coal burn out zone. This is a near term idea which has already been fed to the oxy-combustion network. Uses for the large amount of very dry nitrogen co-produced by the ASU could also improve the economics of capture. A diligent search for new applications for this nitrogen stream is proposed.

3. Siting of CCS capture plant

Power plants have been sited in the past based on considerations of access to fuel and electricity markets. It became apparent in the workshop that many more factors could be important in choosing a site for a CCS plant because of the need to consider access to CO_2 storage as well as opportunities for greater integration of such plants with next generation industrial, commercial and domestic consumers. Matters which might be considered were:
What else will be built as well as CCS plants? For example, new processes, new industrial sites and new towns and how this might influence site selection.
How the industrial scene will change in typical countries where CCS might be implemented leading to production of an integrated road map from which opportunities for improved CCS plant siting might be identified?
What new technologies that are likely to appear on the scene, such as more nuclear, more desalination , more waste processing and how these might integrate with CCS plants and affect their siting?

4. Partial mineralisation to lock-up some of the captured CO_2

Once CO_2 is readily available from the capture plant it will be relatively easy to react some of it with wastes or other materials to make new products or simply to lock up some CO_2. Total mineralization was considered to be unrealistic but there could well be niche applications for example alkaline wastes which could be carbonated thus fixing a small percentage of captured CO_2 and possibly forming a more valuable byproduct or at least reducing waste disposal costs.

5. *Bio-systems to create solid carbonates*

This was essentially a "blue sky" idea based on the observation that there are natural organisms able to convert a supply of CO_2 and Calcium ions into solid calcium carbonate structures. It is also related to the previous area. Unlike photosynthetic routes to fixing CO_2, the reaction is exothermic and hence represents an energy source amenable to exploitation by natural processes. Seawater itself does not contain significant amounts of calcium ions which would have to come from a geological source which may prove to be a practical limitation. The best examples of the process are formation of corals and the shells of shellfish. The biochemical pathways responsible are as yet not that well characterized and understood. A significant amount of work has been done on chemical routes but so far all tend to have very high energy demands and/or very low reaction rates as well as considerable logistical problems.

6. *Better use of bio-mass co-fired in CCS plant*

It is increasingly common for fossil fueled power plants to co-fire biomass from a variety of sources and this practice is likely to be considered also for fossil fueled power plants fitted with CCS . It may be possible to produce higher value products from such biomass and co-fire only the residue from the intermediate process. There is an issue with regard to how to monetize the negative emissions of CO_2 when biomass is used as a fuel in fossil fuel fired power plants with CCS. Possible technologies to integrate with CCS plants are pyrolysis of biomass to produce hydrocarbon fuels followed by co-firing of the pyrolysis residues and fermentation of biomass to produce bio-gas followed by co-firing of residues.

7. *Pre-combustion capture catalyst improvement*

Catalysts are essential in the pre-combustion capture process for the shift reactions and also for some of the natural gas gasification processes such as steam reforming and catalytic partial oxidation. Better lifetimes and cheaper catalysts would help overall economic performance. In particular, sour shift catalysts which have only recently been developed may benefit from further improvements. Useful aims could be to develop cheaper, longer lifetime shift catalysts able to operate with smaller steam to carbon ratios and improvements in Catalytic Partial Oxidation systems for application to natural gas.

8. Greater use of information flows to improve CO_2 capture processes

This insight arises from the observation that biological systems appear to achieve very high efficiencies through greater structural complexity which is under pinned by a considerable internal use of information feeding from one element to another. A profitable line of thinking could thus be to examine how information in the broadest sense could be harnessed to improve the performance of capture processes. The car industry is a prime and successful example of this;

in particular the advanced engine management systems which have been developed are known to have greatly improved overall efficiency and performance.

As mentioned for each of these development areas an analysis of which organizations to collaborate with, consult and influence was drawn up. The table below gives an overview of these but more detailed suggestions are included in the main report.

Insight	Technologies	Collaboration	Consultation	Influence
1. CCS Bundling	Remote distant control, Grid export CHP	UC+IND, UC+CHP, UC+CT or ADV	CT or ADV, CHP	UC
2. Better use of O_2/N_2 in Oxy-combustion	N_2 use, drying and EOR; O_2 separation; gas over-firing	IGC+UNI, OILCO+OXY-PC	INFRA, IGC, UNI, OILCO	OXY-NET, IGC
3. Siting of capture plants	Industry trends	CPP+IND	IEA, EU, US DOE, BERR	CPP
4. Partial mineralisation	Waste survey, CO_2 products	RI+IND	UNI, ALCAN, ECN	Researchers
5. Bio-systems to create carbonates	Enzymic systems	UNI Biotech Depts.	UNI	UNI Biotech Depts.
6. Better use of bio-mass in co-firing	Pyrolysis, Fermentation	UC+BCE	CPP, IEA, BCE	BCE
7. Pre-combustion catalysts improvement	Shift catalysts, CPO catalysts	UC+CAT	SGO, CAT	CAT
8. Greater use of information flows mimicking bio systems	Sensors and Controls	UC+ACS	UC	ACS, UC

UC = Utility company (Planning CCS) CT or ADV = Carbon trust or similar advisors CHP = CHP purveyors

IND = Wider Industry IGC= Industrial gas company RI = Research Institute OILCO = Oil company

OXYNET = Members of oxy-combustion OXY-PC = oxy fuel power company CPP = Central policy & planning

BCE = Biomass conversion experts SGO = Operators Syngas plants with shift ACS = Advanced control specialists

ECN = Energy Centre Netherlands BERR = UK department of Business Efficiency and Regulatory Reform

CAT = Catalyst Company UNI = University

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Expert reviewer comments

The output from the workshop was reviewed by the participants who considered the summary to be a fair and accurate record of the event. It was not deemed appropriate to extend the review beyond those who had taken part.

Conclusions

The wider community proved to have great interest in the topic of CO_2 capture but for those not directly involved it was clear that some of the implications of the technology are not fully appreciated. There was a recurring strong interest in photosynthetic processes to capture CO_2 which may be because this has been the most widely known example or because it is sensed as being sustainable and green. In furthering developments with the wider scientific and industrial community it will be important to keep focus on "Industrial CO_2 capture" and avoid straying into this field. Particularly in any interactions with the bioscience community for example in the field of bio mineralization it will be important to maintain focus away from photo-synthetic processes.

An overarching insight when considering the 8 areas which emerged from this work is that systems integration in its widest sense seems to offer the greatest potential for improving the CCS offering. In fact apart from area 7 all others involve an increase in the complexity of the CCS system. Integration is a difficult field in which to work and there is likely to be resistance to the complications which this inevitably brings since these often run counter to the conventional wisdom that simplicity is best. However the management of modern car engines illustrates the advantages which can accrue. These are dramatically more sophisticated than the original single carburettor and fixed ignition timing system and are adding even more "intelligence" as they start to include multi fuel capability. The gains in efficiency are impressive. Area 8 provides the insight that these gains are perhaps obtained not through complexity but rather through intelligence and use of information.

The report includes detailed recommendations as to which organisations to interact with in order to promote further development of the ideas. It is proposed that initially between one and three of the areas are selected for further work and that initial consultations are progressed in order to establish:

- How much merit the area has for further development
- How strong the interest of specialists and supporters is
- What the next steps to progress in the area should be

It is suggested that a short term, mid term and long term area are selected and that some form of structured selection process is adopted.

The easiest area on which to start is area 2, that for reducing the consumption of oxygen in oxy-combustion and finding new uses for the co-produced dry nitrogen. This could bring early success. A second area on which consultation could start is area 6 , better use of biomass in fossil fired power plants with CO_2 capture plant. This would be very helpful in forging synergies between CCS and renewables. This is likely to lead to tangible results in the mid term The third area where it might be worthwhile making a start is on biological methods for CO_2 mineralisation. Results would be very long term and the main task would be to bring influence to bear to direct some fundamental research in this direction.

Recommendations

Based on the results of this study IEA GHG should consider further actions initially in the form of groundwork which would lead to further studies in some of the following areas. These have been listed in order of priority. In all cases the pre-work should include a check of existing activities on the topic to ensure that the line of investigation is indeed novel.

Eventual study topic	Proposed pre-study groundwork
Reduction of surplus oxygen requirements for oxy-combustion Capture processes	Consultations with key experts from industrial gas and power companies, one to one and in small one day workshop. Introduction and debate on topic at next oxy-combustion network meeting.
Processes for optimal co-use of biomass in fossil fuel power plants with CCS.	Consultations with biomass process designers/operators to understand key features of processes which produce higher value products so that only part of the biomass is burnt directly.
Options for partial consumption of captured CO_2 into useful products	Consultations with universities and research institutes engaged in CO_2 reaction chemistry.
System integration and siting considerations in design of power plant CCS projects	Award and substantial completion of the approved studies on integration of post combustion capture processes and development of CO_2 transport infrastructure. These will enable better definition of needs and possibilities. Consultations with those planning major CCS plants on siting issues. Consultations with major energy intensive existing and emerging industries and urban planners on general topic of CCS integration opportunities.
Integrated product options for fossil fuel CCS plants	Consultations with power industry to identify and understand additional product aspects such as remote load shedding management, inclusion of consumer device related obligations. Internal "order of magnitude" assessment of potential advantages prior to scoping of study

Use of information systems to improve value of CCS	Initial workshop activity with mostly IEAGHG staff to formulate what this could mean in the CCS context. Consultations with specialists in other industries with a track record in this area to identify information technologies which are being successfully applied.
Uses for nitrogen from oxy-combustion co-produced processes	Consultation, possibly via a questionnaire to a selection of industries, in order to assess level of interest. Engagement of a market research consultant to follow up if sufficient potential is identified.
Performance and development of shift catalysts for use in CCS processes.	Consultations to assess performance of existing catalysts and scope for improvement.
Biologically enhanced routes to mineral carbonation	Such a study could only be undertaken some way in the future on the basis of significant findings from research. Activity at present is to engage in discussion with the appropriate part of the research community to encourage fundamental research in this area. Possibly could be added as a sub topic to the Bio-fixation network but would probably need to engage different members.

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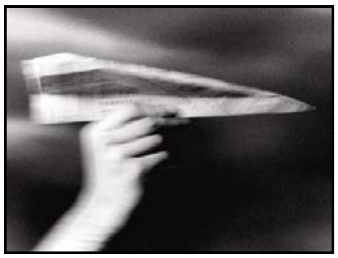


IEA GHG Programme

NOVEL APPROACHES TO IMPROVING THE PERFORMANCE OF CARBON DIOXIDE CAPTURE

Briefing Document for IEA GHG Programme Event

Date: 12th / 13th May 2008-03-28; Venue: The Belfry http://www.thebelfry.com/

Novel Approaches to Improving the Performance of Carbon Dioxide Capture

Introduction

Innovaro is running a project for the IEA GHG (International Energy Agency, Greenhouse Gas, R&D) Programme exploring novel approaches to CCS (Carbon Capture and Storage), with particularly emphasis on carbon dioxide separation and capture.

Specifically, we are exploring areas and sectors outside the normal scope of CCS in the power generation industry, with a remit to seek out technologies and practices that could change the current, conventional thinking and hunting ground; solutions that would be novel to the power generation industry.

We have identified a number of 'vectors' that we want to converge during the May event. We will facilitate this convergence through a number of discussions based on selected themes.

In this context, a vector is a topic area that hitherto may not have converged with CCS and power generation, but that could have related attributes that could / should be of interest if the scope is wide enough.

The vectors we have identified are:

- Industrial Gas management – where purification and separation technologies could be transferred to CCS

- Advanced Materials – that could contribute to the new challenging conditions of temperature, pressure and corrosion in power generation, hence raising efficiency to compensate for the losses when CCS is applied to the burner / turbine configurations

- Advanced Control Systems – learning from systems where control precision is paramount, thus enabling optimal control of the more complex systems when raising power generation efficiencies to compensate for the losses when CCS is applied to the burner / turbine configurations

- Biological Systems where natural separation and purification processes result in pure gases and potable water, hence leading to possible routes to be mimicked in power generation

- Active Materials – where surface or bulk materials are used to adsorb and absorb, to clean and capture gases and liquids. What are the capabilities of such materials and where might they be applied in the capture process?

- Process Intensification – where small size and high efficiency are the norm and low emission are mandatory, for example in distributed and domestic power, and CHP systems

To explore how these vectors can impact on CCS, we have identified and invited a number of key people who will be facilitated in discussion centred on a number of selected themes that cross these vectors, and in seeking synergies, have the potential to represent possible solutions in striving to improve the lacklustre performance of CCS.

Background

In 2004, carbon-based fossil fuel resources comprised some 80% of global primary energy. Electricity generation, transportation, and industry converted this fossil fuel into 23.6 Pg[1] of carbon dioxide (CO_2) and released it into the atmosphere. Through these emissions, CO_2 is accumulating in the atmosphere at an ever-increasing rate and as one of the main constituents of greenhouse gas, it is reported to be a significant contributor to climate change.

Concentrations have grown and are likely to continue to substantially rise unless significant changes to energy systems are made. It has been proposed that a pure stream of CO_2 can be safely and successfully stored in a variety of carbon sinks on time scales long enough to reduce or eliminate its contribution to the accumulation of CO_2 in the atmosphere. Since it is unlikely that this entire stream can be subject to diversion and storage, breaking down the emissions from fossil fuels into sectors gives a good indication of the CO_2 sources most readily addressed by technological advancements. Figure 1 illustrates the typical flow of carbon through the energy system from fossil fuels to its eventual emission into the atmosphere.

[1] 1 Pg = 10^{15} g = 1 Gt = 10^9 metric tones = 10^{12} kg

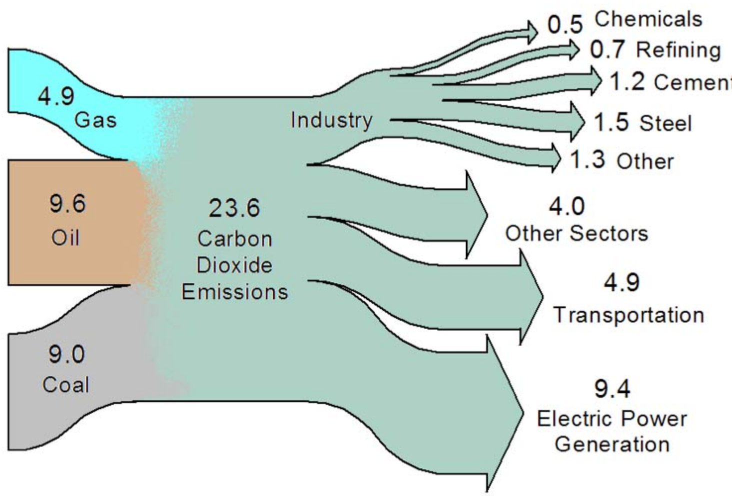


Figure 1 Global CO_2 Emissions from Fossil Fuels in Pg CO_2/yr (2004)

Emissions can be reduced by a variety of measures, such as improving energy generation efficiency and developing alternative energy sources, like wind and solar power. However, a rapid move away from fossil fuels is unlikely as energy supply infrastructure has a long lifetime, and such a move could destabilise economies.

Currently, resources are focused on a number of ways to reduce emissions based on capturing the CO_2 that is released from fossil fuel-fired power plants and potentially storing it underground. The capture mechanisms are classified as post-combustion, pre-combustion and oxy-combustion (See Appendix 1).

Post-combustion: Separation of CO_2 from combustion products (nitrogen, oxygen, water). Capture can occur anywhere along the product-processing stream from combustor to effluent exhaust. The concentration of CO_2 is rarely above 15% mole fraction. Post-combustion capture uses a solvent to capture CO_2 from the flue gas of power plants.

Pre-combustion: Separation of carbon in the form of CO_2 from a resource after the energy content of the resource is transferred to a carbon-free energy carrier. The most common configuration involves gasification with air or oxygen. The products undergo a water-gas shift to a high-concentration stream of CO_2 and H2. The CO_2 is then captured and the H_2 is reacted with air.

Oxy-fuel combustion: Separation of oxygen from nitrogen in the air to produce a nitrogen-free oxidizer stream. Reaction with fuel produces a stream composed primarily of CO_2, oxygen, and water. The water can then be removed through phase separation.

The Current State of Play

There are three main issues with current CCS technological pathways in terms of power generation:

1. The technologies reduce the efficiency of power plants and consume more fossil fuel

2. The technologies add significantly to the capital cost of power generation.

3. The scale-up and integration of the technologies is speculative and has not been demonstrated on a large industrial scale

As a result, it is acknowledged that CCS isn't currently commercially viable; there are no commercially operating power plants in the world capturing CO_2 for storage (there are a few plants capturing CO_2 for other purposes, such as feeding marine algae) and for all the industry's efforts, even the new E.ON high efficiency plant at Kingsnorth in Medway, Kent, UK will not be able to capture and store carbon; it will just be ready to incorporate CCS should the technology ever become viable in the future.

As to when CCS will become commercially viable and readily available is highly debatable. Many predict that CCS won't be able to play any significant role for decades, and the bulk of its deployment would take place in the second half of this century - and even then only if the appropriate subsidy mechanisms and policy drivers are put in place.

Even The UK Chancellor, Alistair Darling – a supporter of coal – admits that CCS "may never work". "Yes, carbon capture and storage, if it can be developed, would help," he said. "But at this stage we cannot be certain of that. There is no commercial scale operation of CCS on power generation anywhere in the world."

Our Brief for the May event

For the evening of the 12th May and for the full day of the 13th May we have convened several key people who represent various aspect of the vectors mentioned above, with the objective of sharing their respective experience. Using a number of themes, we will facilitate discuss and debate about how the represented technologies could converge to impact on CCS, initially in a general sense but eventually with a focus on the power generation industry.

This is highly speculative but with the long timeframes predicted for the introduction of the CCS technologies cited above, the belief is that all avenues must be explored. For the IEA GHG, R&D Programme, this is the start of this exploration.

The event will be run under Chatham House Rule and the results will be shared amongst all participants. We would like to stress this is not presentation-based but a chance to cross-fertilize with people from areas and sectors you wouldn't normally meet, with a view to exploring as yet unidentified spaces where new and novel solutions to the conundrum of carbon capture could emerge.

APPENDIX 1

The three different types of capture process for CO_2 are[2]:

Post-Combustion Capture Power Plants

Post-combustion capture normally uses a solvent to capture CO_2 from the flue gas of power plants. The solvent is then regenerated. The solvents for CO_2 capture can be physical, chemical or intermediate but chemical solvents, known as amines, are most likely to be used for post-combustion capture. This is because chemical solvents are less dependent on partial pressure than physical solvents are, and the partial pressure of CO_2 in the flue gas is low, typically 4-14% by volume, at one atmosphere. However, chemical solvents require more energy (as steam) to regenerate, that is, to break the relatively strong chemical link between CO_2 and the solvent. Sterically hindered amines need less steam for regeneration.

It is likely that amines will be used for the first generation of CO_2 post-combustion capture, because of the advanced state of development of amine absorption. However, the presence of oxygen can be a problem for flue gas amine scrubbing, as it can cause degradation of some solvents and corrosion of equipment. Inhibitors can be included in the solvent to counteract the activity of oxygen. At present the process of scrubbing CO_2 with amines does not operate on the scale of power plants, but increasing the technology to this size is not considered to be a major problem.

The flue gas must contain very low levels of oxides of nitrogen and sulphur (NO_2 and SO_x) before it is scrubbed of CO_2. This is because NO_2 and SO_x react with the amine to form stable, non-regenerable salts, and so cause a steady loss of the amine. The preferred SO_x specification is usually set at between 1 and 10 ppm (v). This means that post-combustion CO_2 capture on coal-fired power plants requires upstream de- NO_x and flue gas desulphurisation (FGD) facilities. The limits for NO_x can usually be met by the use of low NO_x burners with selective catalytic reduction (SCR), and the SO_x limit can be achieved by some FGD technologies.

Post-combustion CO_2 capture processes can be considered a current technology, although some demonstration of these technologies at large coal-fired power plants is necessary.

[2] Capturing CO_2 - IEA Greenhouse Gas R&D Programme - ISBN: 978-1-898373-41-4, Published May 2007

Pre-Combustion Capture Power Plants

Pre-combustion capture can be used in conjunction with gas turbine combined cycles. In this process, a fuel is reacted with air or oxygen to produce a fuel that contains CO and H_2. This is then reacted with steam in a shift reactor to produce a mixture of CO_2 and H_2. The CO_2 is separated and the H_2 is used as the fuel in a gas turbine combined cycle, which is the most efficient thermal cycle for power generation, currently. Pre-combustion capture can be used in natural gas or coal based plants. When the primary fuel is coal, and the key process is the gasification of the coal, it is known as an integrated gasification combined cycle (IGCC). Gasification is the partial oxidation of coal, or any fossil fuel to a gas, often known as syngas, which has H_2 and CO as its main components. Gasification can act as a bridge between coal and gas turbines, with the target of high-energy efficiency and minimum emissions to the environment. However, at present, none of the existing coal-fired IGCC plants includes shift conversion with CO_2 capture.

There are two types of gasifier:

- A slurry feed gasifier, in which the gas product is cooled by quenching with water

- A dry feed gasifier, in which the gas product is cooled in a heat recovery boiler.

In the slurry feed IGCC plant without CO_2 capture, the coal is ground and slurried with water and then pumped to the gasifier vessels where it reacts with oxygen. The products from gasification are quenched with water, the saturated gas is cooled, and condensed water and minor impurities are removed. The sulphur compounds are removed from the gas by passing it through a reactor and feeding it to a Selexol acid gas removal (AGR) plant. Selexol is a physical solvent. The clean fuel gas is fed to the gas turbine combined cycle plant.

However, in the case of the IGCC with CO_2 capture, the gas from the gasifier is fed to a CO_2-shift converter prior to cooling and the Selexol unit removes CO_2 as well as sulphur compounds. The Selexol is regenerated to produce separate CO_2 and sulphur compound streams. The CO_2 stream is compressed and dried for transport by pipeline. The removal rate of CO_2 is over 90%, which means that an overall CO_2 capture rate of 85% can be achieved.

In the dry feed gasifier plant without capture of CO_2, the coal is dried, ground and then fed to the gasifier vessels. The gasifier product gas is quenched, cooled and is then fed to a dry particulate removal unit. Some of the gas is recycled as quench gas and the remainder is scrubbed with water, reheated, the COS is removed and it is fed to an MDEA solvent acid removal plant. The clean fuel gas is fed to the gas turbine combined cycle plant. The configuration of the plant with CO_2 capture is the same except that the COS removal process is replaced by a two-stage shift converter and H_2S and CO_2 are separated in a Selexol AGR unit.

Note: For this to work, there is the need for a H_2 burning gas turbine. The H_2 has to be mixed with large amounts of N_2 from the ASU to control flame stability and NO_x formation.

Oxy-Combustion Capture Power Plants

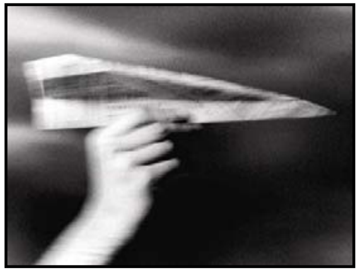
Oxy-combustion is the term for when a fossil fuel is combusted with nearly pure oxygen and recycled flue gas or CO_2 and water/steam to produce a flue gas consisting essentially of CO_2 and water. It may have potential as part of a system for capturing and storing CO_2 as the nitrogen concentration in the flue gas is much lower than when air is used for firing. So the CO_2 can be separated for storage with less downstream processing.

The pulverized fuel oxy-combustion plant uses the same steam conditions as the other post-combustion capture plant. A large and stoichoimetric excess amount of oxygen is required for combustion, which is obtained from an air separation unit. The flue gas from oxy-combustion is compressed and chilled to separate out nitrogen, oxygen and other impurities. The resulting CO_2 concentration is typically 95mol% or more.

The EU NO_x emission limits can be met due to an intrinsically low level of NO_x as a result of the absence of N_2 (although some fuel NO_x may occur). However, if present, the NO_x and SO_x can be converted to acid and removed from the CO_2 stream, so SCR and FGD units may not be needed.

Oxy-combustion is at a relatively early stage of development but integrated pilot plants are being built and plans to build commercial power plants are also at an advanced stage.

Note: For all the above processes currently being considered, there is the need for ‘deeper’ drying, compared with conventionally used glycol drying to prevent corrosion during transport by carbon steel pipelines.

IEA GHG Programme

IEA Event 12th and 13th May 2008

Output from Workshop

This document is a record of the IEA GHG workshop

In this document we present the raw output plus an initial review by the IEAGHG

Part 1 of this document is the record of the workshop, detailing the output from the various sessions and summarising the opportunities selected by the participants.

Part 2 is a review of the raw material carried out by the IEAGHG where ideas have been filtered. This section reflects the 8 key insights which the IEAGHG participants jointly select as being of greatest interest for further development

Part 1: Raw Output

Looking for extraordinary solutions to the issues associated with CCS…

The Objective of this study was to have a wider look at methods and technologies that might be successfully applied in the arena of CCS, as applied to power generation, to improve its intrinsic value

The approach has been to explore areas outside the known territory of CCS in power generation by bringing together experts from disciplines that have a vested interest in CCS but are not involved in addressing the main stream problems of efficacy of the technology and cost associated with power generation

We invited people from a wide diversity of backgrounds…

The following people were invited, and contributed greatly, to addressing the objective of identifying potential areas to explore outside the known territories associated with CCS:

Andy Winship – BOC/Linde
Semali Perera – Bath University
Jamie Turner – Lotus Engineering
Andy Treen – QinetiQ
George Morris – QinetiQ
Karl Bindemann – Arup
Dave Wardle – Oxford Catalysts
John Hancox – Rolls-Royce
Graham Hillier – CPI
Mercedes Maroto-Valer – CICCS
Tony Booer – Schlumberger
William Megill – Bath University

…covering a wide range of disciplines…hydrogen and catalysts…

Andrew Winship is the UK Hydrogen Solution Manager, The Linde Group. He graduated from Leeds University with a degree in Fuel and Energy Engineering in 1989 and the majority of his career has been in energy business. He worked for BP at their research and development centre at Sunbury-on-Thames looking at combustion processes before joining Total (formerly Elf Oil UK). At Elf he was responsible for providing technical support to the downstream refining and marketing operations. Andrew joined BOC in 1998 and has had varying roles in product development and technology sales and marketing in that time. In 2006, he took over responsibility for BOC/Linde's UK hydrogen solutions business activities. He is a chartered member of the Institute of Mechanical Engineers and has an MBA from Warwick University Business School

Dave Wardle is Business Development Director, Oxford Catalysts, responsible for developing the chemical steam and hydrogen generation business at Oxford Catalysts. Previously as Corporate Business Development Manager for The BOC Group he was part of a small team charged with corporate growth and was personally responsible for the Innovation Strategy. Prior to that he led the European Hydrogen Energy business and amongst his achievements he managed the delivery of the UK's first hydrogen refuelling station for BP. During that time David was involved in numerous sustainable energy initiatives. For three years he led BOC's Metals Treatment business globally; the single largest market for delivered hydrogen gas worldwide. Earlier, as Global Technology Manager for applied cryogenics, he managed laboratories in the USA and UK. While in the USA he started a service based information business serving the food industry.

…nanotechnology and aerospace engineering…

Semali Perera's research interests are centered on the design and development of hollow fibers and novel low pressure drop monolithic structures/devices from nano materials and biodegradable biocompatible polymers for biomedical and pharmaceutical applications, adsorptive separation and environmental protection. Her particular interest is in the technology development from novel molecular sieving adsorbent hollow fibers and membranes and pervaporation/separation using fine pore (<2nm, 10-20nm, 20-50nm, <100nm) ceramic mechanically strong fibers. She has extensive experience in development of membranes and hollow fibers from a range of materials. In addition to the development of fine pore ceramic hollow fibers, the fibers are constructed from biocompatible polymers of Polylactide (PLA) and Polyglycolide (PGA), Poly e-caprolactone (PCL), poly(lactide-co-glycolide) (PLGA), Poly (ethylene terephathalate) (PET). Dr Perera's group has extensive experience, expertise and know-how to tailor porosity, surface area and morphology of the fibers for various applications. She has a strong research interest in drug and protein encapsulation in smart bio-materials and development of slow release drug delivery devices

John Hancox holds a BSc in physics and a PhD in electrical engineering, both from the University of Sheffield. In a 20-year career with Rolls-Royce he has held a variety of roles including engineering and technology research, quality assurance and metrology. He is currently an Environmental Specialist concerned with formulating Rolls-Royce's strategic response to the threats and opportunities presented by climate change. He is a member of the Institute of Physics and registered as a Chartered Engineer.

…automotive engineering and process innovation…

James Turner is Chief Engineer of Powertrain Research at Lotus Engineering. He is a specialist in the field of spark ignition combustion and pressure charging systems. Jamie has 20 years experience in the field of internal combustion engines, primarily in performance development, having gained a Master of Engineering degree in Mechanical Engineering from City University, London in 1987. He has published over 20 papers in the field and has been co-author on many more. In addition to his areas of specialisation, his main areas of interest currently are renewable energy and its application to the transport sector. He has previously worked at both Norton Motorcycles and Cosworth Engineering.

Graham Hillier is the New Energy Director for the Centre for Process Innovation (CPI). He has a Degree in Metallurgy, PhD from the University of Cambridge and an MBA. He is a Chartered Engineer, a Fellow of the Institute of Materials, Minerals and Mining and a Fellow of the Royal Society of Arts, Manufactures and Commerce. He is also a visiting Professor in the Department of the Built Environment at the University of Salford.

He has a wide-ranging business background including recycling operations, new product development, business development and strategic planning and forecasting. Prior to joining CPI he was Director of Strategy and Planning for ICI's Petrochemicals, Plastics and Fertilizers Business before working for Corus where he was Construction Director. He was responsible for a global programme in sustainable urban design and construction.

As New Energy Director at CPI Graham works to get fuel cells and bioenergy systems applied to everyday applications.

…advanced materials and the environment & energy…

Andrew Treen graduated from the University of Bath in 1990 with a degree in Physics and Electronics. After a period working for British Aerospace, in the area of high frequency RF devices, Andrew returned to Bath to undertake a PhD in micro-machining technology. In 1994 Andrew joined the Defence Research Agency (DRA), one of the predecessor organisations of QinetiQ, to undertake research in the area of stealth materials. Andrew is now the Business Group Manager for the Materials Group within QinetiQ covering areas such as metallic, polymeric and composite materials as well as smart and stealth technologies. In this role Andrew is particularly involved in the area of commercialisation of the companies Defence related materials capabilities within both the Defence and non-military markets.

Mercedes Maroto-Valer's research interests are widespread and encompass several fields related to the multidisciplinary areas of the environment and energy, with particular emphasis on carbon management, including CO_2 capture and sequestration; recovery and utilization of combustion by-products; mercury control technologies; and coal carbonization. She is Professor in Energy Technologies, the Director of the EPSRC funded Centre for Innovation in Carbon Capture and Storage (CICCS) and Deputy Head of School of Chemical and Environmental Engineering. Her research programmes cover all the range from blue sky research to proof of concept and patent development leading to commercialisation. Prof Maroto-Valer has secured £2.6 million to date in research grants and awards, and she is currently principal investigator in projects worth over £1.7 million from EU, EPSRC, BCURA-DBERR and industries. Prof Maroto-Valer has over 180 publications, holds numerous prestigious international prizes and leading positions in professional societies, editorial boards and acts regularly as reviewer for journals and funding agencies.

…portable power and geoacoustics

George Morris – After working for some years in materials research in 1993 I joined the UK Ministry of Defence, working initially in support of the central management and direction of research programmes and, from 1998, working on a variety of practical projects within the MoD research establishments. These years saw many of these establishments change their nature fundamentally, eventually emerging as QinetiQ Plc. In anticipation of this I, and others, sought change to a ‘mixed economy’ based on new customers in new fields and increased involvement in work bringing a share of downstream revenue. From around 2000 I, and others, began to seek to develop commercial activities in energy and environment. In 2005 QinetiQ created an Energy and Materials Division (with myself as Technical Director). This unit has, for the past three years, prosecuted the development of some half dozen Focus Product Areas, including Portable Power; Industrial Power; Advanced Fuels and Lubricants; Smart Devices [supporting oil and gas exploration and production]; and others. In the immediate past QinetiQ has fundamentally re-organised, re-configuring to present a different face to the future. As a part of this the company has identified Energy and Environment as a major theme (one of only three) and I have been privileged to take up the pan-company role of Technical Director Energy and Environment where I hope to play a part in guiding this important development.

Tony Booer is a Technologist and Manager. He has 25 years experience at Schlumberger in various roles including Research Director for Geoacoustics and, separately, for Reservoir Imaging in their US- and UK-based research laboratories. He has also been Technology Centre Manager for both seismic processing development and well completion answer products. Tony holds and BSc in electronic engineering, a Ph.D. in geophysics and an MBA. He is currently Business Development Manager, Northern Europe, for Schlumberger Carbon Services, providing site selection, characterization, construction, operation and monitoring services for the geological storage of CO_2.

…power generation and biomimetics…

Karl Bindemann – I am currently an Associate Director with Arup Energy heading the company's Major Power Projects Team providing strategic engineering consultancy support to the power generation and energy distribution business sectors. Since graduating from Strathclyde University I have worked in the power generation industry in various capacities. My career commenced with Babcock Power (now Doosan Babcock) developing expertise in low emission combustion technology and was part of the award winning low NOx burner development team. After 10 years with Babcock I joined Powergen's Power Technology Centre as a Senior Combustion Consultant providing consultancy services on a national and international basis. I later took up the role of Business Account Manager managing the interface between Power Technology and its customer portfolio to ensure service provision met customer requirements across the technical disciplines. Having spent 6 years with Powergen and greatly expanded on my knowledge and experience base I joined ScottishPower's Asset Management Team initial in the role of Engineering Standards Manager and later promoted to the role of Generation Engineering Manager taking responsibility for good engineering practice and associated engineering governance across the company's generation portfolio. In October 2007 I joined Arup to help develop the company's energy business and associated engineering consultancy service offering.

William Megill is Lecturer in Biomimetics in the Mechanical Engineering department of the University of Bath, specialising in Biomimetics and Ocean Science. His background is interdisciplinary, a combination of Physics, Physiology, Ecology and Engineering. His current work is focused on the development of tools to study coastal biodiversity. This includes submersibles whose propulsion systems are based on our understanding of the swimming mechanics of aquatic animals such as fish & penguins, as well as sensor systems based on the acoustic behaviour of whales and dolphins. His research in ecology has focused on the coastal ecosystems of British Columbia and Baja California - the focus in Canada is on zooplankton swarms and the factors that influence their distribution, including predation by grey whales, while in Mexico, the focus is on soft-bottom benthic habitat and its importance in conservation plans for sea turtles.

The workshop was an intense 24hr experience…

8.30am	Plenary overview of process and introductions
9.00am	2 X Breakouts for theme 1 – small and distributed
10.00am	Present back
10.45am	2 X Breakouts for theme 2 natures solutions
11.30am	2 X Breakouts for theme 3 old dogs new tricks
12.15pm	Present back and top 3 plus Mapping of clusters
2.00pm	Breakout groups 3 X Deep Dives into opportunities
3.30pm	Top opportunities present back and feedback
4.30pm	Concluding Remarks

We selected three themes to be the focus for our discussions…

These themes were used to stimulate the participants to think outside the box with respect to CCS and future process associated with power generation. Initially, we allowed the themes to invoke approaches that could apply to CCS in general, which was followed by bringing the focus round to power generation.

Key criteria for selecting the themes were:

- They crossed the issues identified as being relevant to CCS
- They stimulated thinking about new ways of approaching CCS
- They were exciting, challenging and interesting
- They were engaging for all the participants

Where these themes cut across all the issues related to CCS…

Small and Distributed	**Everything is shrinking and becoming less centralised – power, devices and networks – how will this influence CCS?**
Natures' Solutions	**Nature has been mimicked in many fields to give simple but effective outcomes – can nature be applied to CCS to give us a new avenues to pursue?**
Old Dogs – New Tricks	**We must not forget solution of the past that could impact CCS – should we not revisit materials and processes to ensure we are not missing a trick?**

In the first breakout session we focused on Small & Distributed…

Breaking the rules:

- The problem of carbon capture and sequestration is devolved to the local community
- Individuals are responsible for their own energy supply, and carbon capture and sequestration
- Individual buildings, even a single room in a building, becomes the energy focus – both as a source and sink for energy

Today and the near future:

- In the US, Caterpillar are one of the largest distributed energy suppliers through mobile power generators
- By 2010, distributed generation would represent 20 percent of new electric capacity additions in the US
- The EU wishes to make power grids smart and independent by 2025 so that regions, cities and citizens can produce and share energy in accordance with the same open-access principles as apply to the Internet now.

Where the outcome of the facilitated group discussions were…

Application	Technology	Enabler / Enables	Constraint
Converting waste into useful energy and to produce CO_2 which is fed to greenhouses and algae farms	Small scale anaerobic digestion, small scale absorption	Cash poor communities such as in India are better at recycling	Interconnectivity for the collection of CO_2
Distributed manufacturing as an analogue	Distributed rapid manufacturing – SLA, etc.	Reduces CO_2 footprint and packaging	The need for distributed power. Raw material supply
Enhanced oil recovery	CO_2 used in the recovery of bound oil	Price of oil at $136/barrel	
Useful products from CO_2 (fly ash) to produce road-fill	Distributed home capture systems - anaerobic digesters	Revenue streams from products, government incentives, etc	Interconnectivity for the collection of CO_2
Closed loop CO_2 ecosystem – such as submarines and deep mining	CO_2 absorption / adsorption systems that can be 'milked'	The room as the smallest unit of energy – retrofit systems to collect and distribute CO_2	Incentives and market forces – development of private infrastructure

…and focused on the contribution of the community…

Application	Technology	Enabler / Enables	Constraint
CHP localized power plants – distributed power as in Caterpillar	Complex but accessible technologies for CHP	Integrated two-way power supply and generation Legislation as in Germany	CO_2 must become a tradable commodity at a community level
Bundle the supply of power with the ability to self-regulate the use in the home	Home power use monitors – improved insulation and more economic appliances	Educating people to monitor and control the use of energy in the home. Legislation as in California due to power outages	Power companies reluctant to balance revenue against reduced power consumption
Zero carbon communities (50% reduction is already possible)	Home power use monitors – improved insulation and more economic appliances	Individuals taking responsibility for carbon footprint	The need for a new business model for the supply of energy
Processing waste where it is produced and producing energy where it is most needed	Digesters, incinerators, multi-fuel CHP, etc	The community / home as a closed loop system	The need for a new business model for the supply of energy

… and the individual…

Application	Technology	Enabler / Enables	Constraint
Taking carbon out of methane – pre-combustion in the community / home. CO_2 from the atmosphere and H_2 from electrolysis / reforming natural gas	CO_2 combined with H_2 (co-locations) to form CH4. Solar/wind/waste to form H_2	Cement works to produce CO_2, government influence, need for scale more than technical efficiency, smart grid (avoids co-location of supply and H_2 production), large ‘ power’ farms	Getting CO_2 from the atmosphere, solar electricity not efficient (circa 20%), subsidies in Germany mask true economics, 20 year payback for solar with a life of five years
Manufacturing processes	Synthetic chemistry based on methanol	‘grow’ structures that can be re-used	
Considering the total, local systems – power generated in industrial and business areas CO_2 fed to greenhouses for crop growth	Sterling engines, small CHP systems	Acceptance of local (community) heating – move heat not gas, use energy rich feed-stocks,	Ability to motivate co-operation and co-ordination of all community players, running town scale plant. NIMBY attitude

…which will rely on considerable co-operation and co-ordination...

Application	Technology	Enabler / Enables	Constraint
Urban central heating based on hot-spots such as power stations and cement works, wood not burnt but kept for photosynthesis	Up-stream, centralised decabonization of fuel, CO_2 scrubbers (c.f. lithium based re-breath systems), fine fiber filtration systems,	Small devices tend to be more efficient than large systems,	Post-war industrial model made too small and fragmented

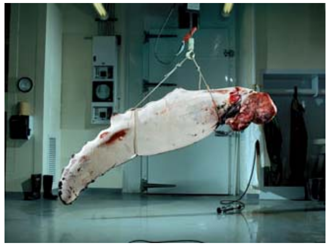
In the second session we looked at Nature's Solutions

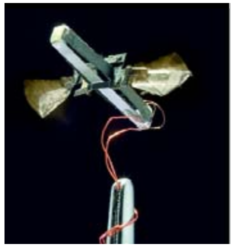
Breaking the rules:

- Gas separation effected in a similar fashion to nature's osmotic desalination of water in the human body
- Nano-scale biomimetic membrane and structures used in the separation and storage of CO_2
- Natural structures used to separate gases and liquids are developed to combat CCS

Today and the near future:

- The whale's scalloped edged flipper helps generate force in tightly banked turns – whale-inspired blades are currently being tested
- The wings of the blowfly flutter in a complex "U" shaped motion – mimicked by a device that is the nearly the weight of a paper clip
- The natural self-cleaning, water resistant lotus leaf – inspired a painted surface with micro-bumps



Studying nature has resulted is some remarkable outcomes

Application	Technology	Enabler / Enables	Constraint
Bio-systems to produce fuel – algae, elephant grass – photosynthetic adsorption of CO_2	GM to produce high-yield, oil baring algae and grasses that have high energy content. Needs to be seen as part of the bio-economy and the total eco-system, using augmented biological systems to grow 3-D algal beds hence using reduced light	The use of unproductive land; the need for fast, self-replicating crops,	Water consumption, area required to make volumes, available land / water / sea for growing and cropping; technology for harvesting large areas of crop, continuously
Products produced from the locking of CO_2 in solid bodies – tied to oxy-combustion processes	Zeolites as an absorber using PSA and TSA (pressure swing absorption and temperature swing absorption)	Technology exists but needs to be integrated with the CO_2 capture processes	Linking processes to give required efficiencies.

…artificial spider's silk can be effectively synthesised in reactors…

Application	Technology	Enabler / Enables	Constraint
Using 'bricks' produced by systems combining chemical mineral and biological ionic processes to lock in CO_2, - synthetic coral	Producing calcium carbonate through the natural (membrane) processes used by limpets in sea water, conversion of light into hydrocarbons, natural photosynthesis,	The manufacture of saleable products to encourage the capture and processing of CO_2, natural systems are low energy and work at the ionic level but need a cocktail of solutions for success.	Biological (ionic) systems not understood, supply of rock as a raw material in sufficient quantities, enzymes to speed up the kinetics, scaling the process
Artificial photosynthesized leaves to produce 'products'	Onions creating ethylene,		No waste production

Other biological systems worth looking at: fungi / fermentation, reed beds for absorption, bacteria for anaerobic systems, composting using worms colonies and mammalian digestion

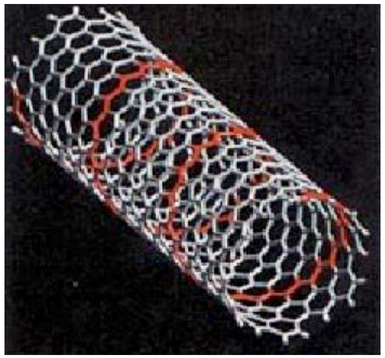
Revisiting processes and products could reveal pathways forward…

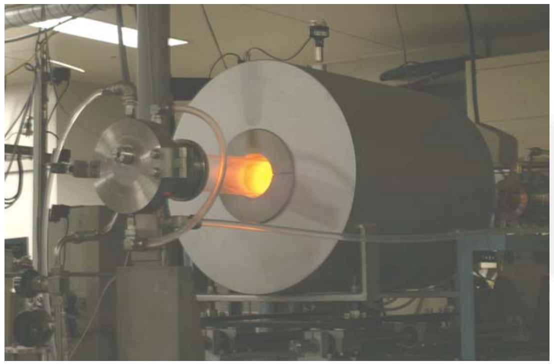
Breaking the rules:

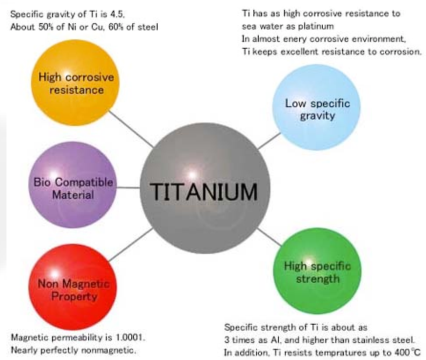
- Consider the production of carbon as an integrated whole whereby it is only part of the man-made energy cycle and can be used as a raw material
- Other forms of traditional material contributing to the reduction of carbon or the capture of CO_2 – such as carbon nanotubes?
- Smaller systems are much more efficient at converting fuel to energy?

Today and the near future:

- Power generation efficiencies need to be raised to counter losses due to CCS systems using advanced high temperature materials and processes
- New fuels and fuel systems used to generate power to reduce the carbon output
- Lessons to be learnt from other energy conversion processes and systems







Existing processes need to be developed to be more efficient…

Application	Technology	Enabler / Enables	Constraint
Carbon neutrality as a national goal – tier 1 – carbon negative, tier 2 – carbon producing	Systems for measuring personal energy use against quota – smart metering publically displayed	Ranking nationals according to CCS achievement	Government reluctance / willingness to tackle the problem / aspire to tier 1 level.
Closed loop systems – Exhaust Gas recirculation	Need cooling systems to increase efficiency.	Highly efficient heat exchange	
Running engines on the right fuels – methanol / ethanol	Technology already exists	Incentives to adapt engines for optimized running – measure automotive performance in mega Jules per Km	Natural apathy to change
Effective / efficient Fischer Tropes – GTL – tech. – small scale reactors	Replace platinum with rhenium as catalyst	Cheap catalysts	Availability of rhenium

Scaling systems appropriately could be a way forward…

Application	Technology	Enabler / Enables	Constraint
Small scale, mobile capture devices	Capturing and recovering hydrocarbons in gas stations	Absorbing / porous materials	High pressure needed for absorption
Location of power plant, co-locating power plants and CHP, home working / centralized operating – get the balance right	Nuclear and renewable sources in tandem. Use waste heat for domestic use	Inclusive approach to power generation, economies of scale no longer a barrier	Value of CO_2, local, national and international regulations, trading mechanisms drive inefficiencies,
Use of auxiliary power systems – power plant in urban areas, staff / company housing – urban design	Efficient insulation for domestic use,	Capital cost Vs efficiency, legislation Vs market, subsidies for insulation and heating control,	Irrational behaviour,
Public transport to reduce miles per passenger	Guided transport, etc	Cost of fuel, down-town urban development, CSR	

Following the sessions, we selected areas for further analysis…

The following areas were selected:

- **Biological / natural solutions:**
  - **Cherry picking biological processes**
  - **Biologically derived processes scaled up for industrial use**
  - **Carbon black to sequester CO_2 from plants**
- **Political Solutions – legislation and planning:**
- **Improve carbon tax / trading arrangements**
- **Balance policy - centralised / decentralised power generation**
- **Achieve the CO_2 goals**
- **Mandate CCS position for each country – developed / non-developed state**

Many reflected a high degree of frustration with progress

The following areas were selected:

General approaches:

- **Systemic "chemical engineering approach to planning and strategy**
- **Systems approach to vertical integration – appropriate technology, skills, scale to address the problem**
- **CCS as a manufacturing process – products that people want and that can be sold at a profit**
- **Bundling of CCS as part of the services offered by power / utility companies to consumers reduce GHG**

Three areas were selected for deep diving…

The following areas were selected for a deep dive:

Enhanced Mineralisation:

- **Natural zeolites for CO_2 absorption**
- **Packaging carbon into consumer desirable products for large scale deployment - brick from calcium carbonate**
- **Biologically enhanced mineralisation**

Algae as an absorber of CO_2:

- **(GM) Algae for sustainable CO_2 capture to produce food, bio-diesel and chemical precursors**
- **Algae / Calcium carbonate to produce useful molecules and salts**

Three areas were selected for deep diving…

Strategic location of power generation:

- Compromise between centralised and decentralised power generation
- Extracting work from waste heat using secondary cycles – sterling or organic rankine cycle
- Strategic location of power plant with and without CCS
- Locate plants (CHP) in cities for energy integration and recovery of CO_2

Questions:

1. What is the area of greatest impact – where and when?
2. What are the key drivers and constraints
3. What is the primary (business) opportunity?

Encourage the capture and use of CO_2 by developing products…

Output from Group 1

Opportunity:

- **To combine mineral and biological processing to give acceptable rates of reaction and to create high value product**

What is the area of greatest impact – where and when?

- **Countries with limited ability to store CO_2 in holes in the ground**
- **Using solid materials to 'fix' CO_2 when it cheaper than dumping underground**
- **To carbonate industrial waste with high ph (such as fly ash)**

Many are investing in algae as a source of bio-oil…

Output from Group 1

What are the key drivers and constraints?

- An opportunity to extend the life of underground stores
- More permanent, acceptable storage system for CO_2
- A way of reducing the fines and penalties for not attending to CCS
- A way of enhancing the value of CO_2 by making products for sale
- Technology for synthetically replicating biological systems does not exist
- The volume of earth needed to complete process – balancing the volume of rock with the loading of CO_2
- Messing with the sea may be an issue

Investment is global and users are already involved

Output from Group 1

What is the primary (business) opportunity?

An estimated costing model:

- Revenue from capturing and storing CO_2 underground: $5 to 10/tonne
- Cost of digging rock, processing and transport: $3/tonne
- If 1 tonne CO_2 : 10 tonnes rock, then 11 tonnes of product: $20 – 25 plus processing
- Therefore, 1 tonne upgraded rock costs $2.5 plus processing, c.f. cost of extracting rock at $3/tonne - $0.5/tonne margin
- Premium price can be achieved?

Algae as a way of capturing CO_2 and making useful products

Output from Group 2

What is the area of greatest impact – where and when?

- Production of bio-fuel by the displacement of CO_2
- Fertilizer for organic farming as a way of storing CO_2
- Growing fibrous product as a way of storing CO_2
- Can be grown in cold, high nutrition water – Norway, Northern Canada, plus desert areas where the land is non-productive. Locate next to power stations to mop up CO_2
- Algal farms (in Hawaii) are already in existence and some report high yields but there are still problems with harvestings and making economically viable product

Many are investing in algae as a source of bio-oil…

Output from Group 2

What are the key drivers and constraints?

- Identifying the best algal strains for oil production
- Optimising automotive engines to take non-esterified oil
- Issues to do with growth and separation need resolving
- Temperature band for growth is narrow and needs ‘stretching’
- Product needs tuning to existing (potential) applications: fuel and paper
- Capital investment is still very high
- The use of water in a water scarce world will need considerable justification

Investment is global and users are already involved

Output from group 2

What is the primary (business) opportunity?

- **Growing Algae for bio-fuel to stimulate investment and complement existing bio-fuel programmes**
- **Longer-term shift to fibres and fertilizer to facilitate CO_2 storage**
- **Could be up and running in 10 years**
- **We need a 'dream team' of experts working on this to achieve success, e.g. chemistry, engineering, biotech, biologists etc.**

Strategic location power generation could impact CO_2 production

Output from group 3

What is the area of greatest impact – where and when?

- CHP plant to be located in coastal cities – most mega cities sited on coastal plain
- Emerging, developing countries (China & India) have the potential / opportunity to take a technical and strategic lead
- No doubt about the (negative) effect of climate change over the next 20 years
- Land use policy must be clear – low opportunity in developed world
- Sited near ports for fuel delivery and product removal by sea
- No technical barriers – CCS will be designed into the power generation system

CHP will be matched to urban requirements…

Output from Group 3

What are the key drivers and constraints?

- **Society is a big driver in many geographies**
- **The price of carbon and Kyoto 2**
- **There are no fundamental technical barriers**
- **Precedents have been set – Battersea, Copenhagen and new York**
- **The location of appropriate CO_2 storage facility**
- **Electricity will be of high value and losses must be minimised**
- **Co-location of energy source near the end user**
- **Location of underground storage facility**

The opportunity is to combine plant location with storage of CO_2…

Output from Group 3

What is the primary (business) opportunity?

- **Build power plants next to commercial and business parks**
- **Buy land that could be used for storage**
- **Develop business based on secondary heat engines – sterling and rankine cycles – balance extra cost verses opportunity**
- **Use waste heat for desalination**
- **Use waste to create power – gasification and anaerobic digestion**

The conclusion indicates that there are possible avenues to follow…

The result of this programme has been the identification of a number of areas where technology and strategy may have a role to play in addressing the issues that currently surround this highly contentious subject of CCS in power generation. As an outcome of the discussions held, the key sentiment to prevail is that if CCS is to be resolved, then the issue must be brought to the attention of, and down to the level where, individuals can contribute. It has been suggested that this can be achieved by developing mechanisms where the responsibility and cost of CCS can be bundled and included in the delivery of power to the home, and where 'products' produced using CO_2 can be seen to contribute to the alleviation of carbon emissions.

The three deep-dive areas of Enhanced Mineralisation, Algae and Strategic Location of Power Plant are not new and in part are already being considered, either as part of research programmes or as part of national and regional policy.

…and some have already been embarked upon…

For example, Carl Mester, Shell Chief Scientist, Chemistry and Catalysis, has been exploring a reaction between CO_2 from power plants and refineries and a commonly-found mineral, iron-magnesium silicate, to form a carbonate based building products.

Another example, is the work done by the Newcastle University[1] team, led by Michael North, Professor of Organic Chemistry, where a highly energy-efficient method of converting waste CO_2 into chemical compounds known as cyclic carbonates has been developed. Cyclic carbonates are widely used in the manufacture of products including solvents, paint-strippers, biodegradable packaging, as well as having applications in the chemical industry. Cyclic carbonates also have potential for use in the manufacture of a new class of efficient anti-knocking agents in petrol. In the case of the use of algae to absorb CO_2, many processes[2] are being proposed and organisations such as Shell[3] are investing in algal plant for bio-fuel production

1. http://www.ncl.ac.uk/press.office/press.release/content.phtml?ref=1209034169
2. http://www.environmental-finance.com/onlinews/0403alg.html
3. http://www.shell.com/home/content/aboutshell/swol/jan_mar_2008/algae_13022008.html

From what we have heard, there may be threads for IEA GHG to follow…

It is suggested that IEA GHG follow up on a number of the ideas to emerge from the workshop:

- To explore the work being done on the role and use of CO_2 in making (building) products – to combine mineral and biological processing to result in calcium carbonate base products
- To explore the world of biological systems to see where intelligent feedback systems can be mimicked to enhance practical CCS, when seen as a totally integrated closed-loop process
- To develop an understanding of the role that biomass and algae can play in power plant CCS and the resulting product opportunities – as part of the bio-economy[1]
- To explore the concept of bundling 'products' supplied by power generators - for example, by providing the means for consumers to self-monitor consumption
- To consider the infrastructure needed to efficiently integrate CCS power plants within both industrial and social communities

1. http://www.oecd.org/department/0,3355,en_2649_36831301_1_1_1_1_1,00.html

Part 2: IEA GHG Review

The Following SummarisesThe IEAGHG Review

In reviewing the output from the workshop, the IEAGHG team have identified a number of areas that are worth exploring further.

In the following pages, these areas are summarised. As part of this initial assessment, a list of top-level discrete technology that might be involved has been drawn up and under the heading "Collaboration", a tentative list of groups that the IEAGHG could collaborated with has been generated. Two other categories show those who could be consulted with, and those who should be influenced

The Workshop Was Effective In Identifying New Areas For Exploration…

Insight	Technologies	Collaboration	Consultation	Influence
1. CCS Bundling	Remote distant control, Grid export CHP	UC+IND, UC+CHP, UC+CT or ADV	CT or ADV, CHP	UC
2. Better use of O_2/N_2 in Oxy-combustion	N_2 use, drying and EOR; O_2 separation; gas over-firing	IGC+UNI, OILCO+OXY-PC	INFRA, IGC, UNI, OILCO	OXY-NET, IGC
3. Sitingof capture plants	Industry trends	CPP+IND	IEA, EU, US DOE, BERR	CPP
4. Partialmineralisation	Waste survey, CO_2 products	RI+IND	UNI, ALCAN, ECN	Researchers

UC = Utility company (Planning CCS) CT or ADV = Carbon trust or similar advisors CHP = CHP purveyors

IND = Wider Industry IGC= Industrial gas company RI = Research Institutes UNI = University OILCO = Oil company

OXYNET = Members of oxy-combustion network OXY-PC = oxy fuel power company CPP = Central policy & planning groups

BCE = Biomass conversion experts SGO = Operators of Syngas plants with shift ACS = Advanced control specialists

It Was Noted That There Was AStrong Interest In Photosynthetic Technologies For Capturing And Fixing CO_2 …

Insight	Technologies	Collaboration	Consultation	Influence
5. Bio-systems to create carbonates	Enzymic systems	UNI Biotech Depts.	UNI	UNI Biotech Depts.
6. Betteruse of bio-mass in co-firing	Pyrolysis, Fermentation	UC+BCE	CPP, IEA, BCE	BCE
7. Pre-combustion catalysts improvement	Shift catalysts, CPO catalysts	UC+CAT	SGO, CAT	CAT
8. Greater use of information flows mimicking bio systems	Sensors and Controls	UC+ACS	UC	ACS, UC

UC = Utility company (Planning CCS)   CT or ADV = Carbon trust or similar advisors   CHP = CHP purveyors

IND = Wider Industry   IGC= Industrial gas company   RI = Research Institutes   UNI = University   OILCO = Oil company

OXYNET = Members of oxy-combustion network   OXY-PC = oxy fuel power company   CPP = Central policy & planning groups

BCE = Biomass conversion experts   SGO = Operators of Syngas plants with shift   ACS = Advanced control specialists

1. Bundling Of CCS As Part Of The Low Carbon Energy Offer To End Users – Domestic, Commercial and Industrial

The challenge is to see CCS not as a way of delivering low carbon electricity to be bought in preference to power from other sources but as part of an overall carbon energy offering.

The offer could be developed for three distinctly different segments:

Domestic Consumers - The 'bundled' offer could include:

- Supplier / consumer contracts that include the obligation to use high efficiency devices and appliances (LED lights and class 'A' appliances)
- Provision of a reverse power to grid export control facility coupled with the installation of advanced power generation via solar, CHP, etc., plus ground source heat pump systems
- Inclusion of automatic remote device control for a certain fraction of the connected load

Issuing of improved energy rating certification for domestic properties

Commercial Users - including premises such as hospitals, offices, shopping complexes which would have similar consuming devices as domestic but in different proportions and could also include additional systems such as air-conditioning and local area CHP systems. The 'bundled' offer might include:

- Automated remote device control for certain fraction of the connected load
- Assistance with installation of high efficiency appliances
- Assistance with the installation of local areas CHP and power export facilities

Note: Concentrating on new-builds and major rebuilds where upgrade and retro-fits would be comparatively easy

1. Bundling Of CCS As Part Of The Low Carbon Energy Offer To End Users – Collaboration, Consultation and Influence

Industrial Users– is much more diverse and will have very specific opportunities in the different sectors such as iron & steel, chemicals, refining, automotive, etc. The offer could be framed as "embracing responsible CCS". It is likely that the 'bundled' offers might include:

- CHP, possibly running on hydrogen supplied along with the electricity supply
- On-site CCS for some applications possibly using high temperature absorbent regeneration specifically in situations where heat is generated during processing

Collaboration– the following collaborations would most likely to support such offers:

- Utility companies with customers in the refining, chemicals, steel sectors, on a company to company basis
- Utility companies that supply CHP systems
- Utility companies with low carbon technology advisors such as the Carbon Trust, or equivalent

Consultation– the following organisations should be consulted:

- Suppliers of CHP systems
- Carbon Trust

Influencers– the following should be influenced to encourage development:

- Power companies – through existing or new networks

2. Better Use Of Oxygen And Nitrogen In Oxy-combustion Processes – To Improve Stoichiometry

Up to 20% excess oxygen is used in current oxy-combustion capture processes which parallels the requirements for low CO and good coal burnout in conventional power plants. However when the excess has to be supplied as pure O_2 rather than as additional air, the cost implications are significant. Furthermore for every mole of oxygen generated there will be about 4 of completely dry nitrogen for which there is currently no identified use. The new insight is that reducing the O_2 production requirement as close to the stoichiometric requirement as possible and finding new uses for large quantities of dry nitrogen could deliver significant improvements in the overall value of CCS using oxy-combustion. The following technologies are amongst those that could be considered:

- Capture oxygen from the vent stream of the CO_2 purification process using membranes or chemical absorbants
- Greater burnout of oxygen using gas or hydrogen introduction after the coal burnout zone
- Seek uses of low cost by-product nitrogen as a dessicant in other industrial or agricultural processes
- Determine whether nitrogen has any positive effects on crop growth.
- Seek new applications for nitrogen as an inerting agent in other processes
- Nitrogen for EOR either pure or admixed with CO_2

Other considerations arising during the discussion were the need to ensure that reducing conditions are avoided as this can cause degradation of steel materials. There is a preference for capturing oxygen from the vent stream as air in leakage may prevent full burn-up of the oxygen. However, some air maybe a good substitute for pure oxygen to ensure reducing conditions do not occur. Too low oxygen may result in increased CO levels in vent gas to atmosphere although this too might be captured.

2. Better Use Of Oxygen And Nitrogen In Oxy-combustion Processes – Collaboration, Consultation and Influence

Collaboration– the following collaborations would most likely to support such technology:

- Industrial gas companies with research institutions and Universities to develop schemes and processes for lowering oxygen consumption of oxy-combustion processes.
- Oil companies with oxy- combustion power companies to explore EOR opportunities involving nitrogen

Consultation– the following organisations should be consulted:

- Infrastructure development groups
- Industrial gas companies
- Universities specialized in drying
- Oil companies with regard to Nitrogen or N_2/CO_2 mixtures for EOR

Influencers– the following should be influenced to encourage development:

- Members of the oxy-combustion network to raise the profile of this opportunity
- Industrial gas companies to seek out customers for dry nitrogen

3. Siting of CCS Capture Plant - Based on CO_2 Storage…

Power plants have been sited in the past based on considerations of access to fuel and electricity markets. It became apparent in the workshop that many more factors could be important in choosing a site for a CCS plant because of the need to consider access to CO_2 storage as well as opportunities for greater integration of such plants with next generation industrial, commercial and domestic consumers.

Technologies and examples

The following ideas were put forward during the in-house discussion on this insight:

- The need to assess what else will be built as well as CCS plants. For example, new processes, new industrial sites and new towns and how this might influence site selection.
- The need to assess how the industrial scene will change in typical countries where CCS might be implemented and produce an integrated road map from which opportunities for improved CCS plant siting might be identified.
- Consider new technologies that are likely to appear on the scene, such as more nuclear, more desalination , more waste processing.

3. Siting of CO_2 Capture Plant – Collaboration, Consultation and Influence

Collaboration– the following collaborations would most likely to support this insight:

- Central policy and planning organisations and researchers, Central Government institutions should collaborate with wider Industry on the siting issue

Consultation– the following organisations should be consulted:

- IEA policy /statistics groups
- EU commission
- US DOE
- BERR

Influencers– the following should be influenced to encourage development:

- Make policy makers aware of the issue

4. Partial Mineralisation – To Lock-up CO_2

The insight here is that once CO_2 is readily available from capture plant it will be relatively easy to react some of it with wastes or other materials to make new products or simply to lock up some CO_2. During the workshop the idea of complete mineralization of captured CO_2 was visited but it was soon clear that this is not an attractive option. However that said there could well be niche applications where alkaline wastes could be carbonated thus fixing a small percentage of captured CO_2 and possibly forming a more valuable byproduct or at least reducing waste disposal costs.

Technologies and examples

The following ideas were put forward during the in-house discussion on this insight:

- A survey of wastes could be made to identify what might be available for partial carbonation. Alkaline ashes and slags from furnaces or other industrial processes are prime candidates.
- New products containing CO_2 such as artificial bricks

4. Partial Mineralisation – Collaboration, Consultation and Influence

Collaboration– the following collaborations would most likely to support this technology:

- Research institutes should collaborate with specific industries

Consultation– the following organisations should be consulted:

- Nottingham university – CO_2 innovation group
- Alcan (Aluminium processing wastes)
- ECN – has group working on this subject
- University of Louisiana (Doug Harrison) working on solid carbonates reactions

Influencers– the following should be influenced to encourage development:

- The mineralization community – should be an open door

5. Bio-systems To Create Solid Carbonates – Mimicking Shellfish…

This was essentially a “blue sky” idea based on the observation that there are natural organisms able to convert a supply of CO_2 and Calcium ions into solid calcium carbonate structures. Also, unlike photosynthetic routes to fixing CO_2, the reaction is exothermic and hence represents an energy source amenable to exploitation by natural processes. The best examples of the process are formation of corals and the shells of shellfish. The biochemical pathways responsible are as yet not that well characterized and understood.

A significant amount of work has been done on chemical routes but so far all tend to have very high energy demands and/or very low reaction rates as well as considerable logistical problems.

Technologies and examples

- Enzyme systems to facilitate reaction of CO_2 with calcium ions in very dilute solutions
- Enzyme systems to facilitate the reaction of CO_2 with solid calcium compounds

5. Bio-systems To Create Solid Carbonates – Collaboration, Consultation and Influence

Collaboration– the following collaborations would most likely to support this technology:

- University biotechnology departments

Consultation– the following organisations should be consulted:

- Bath University
- Nottingham university –CO_2 innovation group
- One or two leading overseas Universities working in the bio-chemistry/technology area.

Influencers– the following should be influenced to encourage development:

- Selected Universities to consider fundamental research on the biological mechanisms

6. Better Use Of Bio-mass And Other Waste Co-fired In CCS Plant – Coupled With High Value Products

It is increasingly common for power plants to co-fire biomass and other wastes and this practice is likely to be considered also for CCS plants. It may be possible to produce higher value products from such waste and biomass and co-fire only the residue from the intermediate process. There is an issue with regard to how to monetize the negative emissions of CO_2 when biomass is used as a fuel in CCS.

Technologies and examples

- Pyrolysis of biomass to produce hydrocarbon fuels followed by co-firing of the pyrolysis residues
- Fermentation of biomass to produce bio-gas followed by co-firing of residues.

6. Better Use Of Bio-mass And Other Waste Co-fired In CCSPlant – Collaboration, Consultation and Influence

Collaboration– the following collaborations would most likely to support this technology:

- Power industry with biomass conversion specialists

Consultation– the following organisations should be consulted:

- Regulators on the subject of income from negative emissions when CO_2 from biomass is captured and stored
- Bio-mass conversion experts
- IEA to understand trends in bio-mass and waste co-firing.

Influencers– the following should be influenced to encourage development:

- Bio-mass conversion experts.

7. Pre-combustion Capture Catalyst Improvement – Cheaper and Longer Life

Catalysts are essential in the pre-combustion capture process for the shift reactions and also for some of the natural gas gasification processes such as steam reforming and catalytic partial oxidation. Better lifetimes and cheaper catalysts would help overall economic performance. In particular sour shift catalysts which have only recently been developed may benefit from further improvements.

Technologies and examples

- Cheaper, longer lifetime shift catalysts able to operate with smaller steam to carbon ratios.
- Improvements in CPO systems and catalysts for application to gas

7. Pre-combustion Capture Catalyst Improvement – Collaboration, Consultation and Influence

Collaboration– the following collaborations would most likely to support this technology:

- Power industry with catalysts suppliers and developers

Consultation– the following organisations should be consulted:

- Catalyst suppliers and developers
- Operators of syn-gas sour shift and shift reactors

Influencers– the following should be influenced to encourage development:

- Catalyst suppliers and developers

8. Greater Use Of Information Flows To Improve CO_2 Capture Process – Using Information to Raise Efficiencies

This insight arises from the observation that biological systems appear to achieve very high efficiencies through greater structural complexity which is under pinned by a considerable internal use of information feeding from one element to another. A profitable line of thinking could thus be to examine how information in the broadest sense could be harnessed to improve the performance of capture processes. The car industry is a prime and successful example of this, in particular the advanced engine management systems which have been developed are known to have greatly improved overall efficiency and performance.

Technologies and examples

- Greater use of sensors and control algorithms to control operation of capture processes..
- Use of information rich control systems to enable reliable integration of capture plant with other processes
- Use of information rich control systems to successfully add performance enhancing additions and peripheral processes.

8. Greater Use Of Information Flows To Improve CO_2 Capture Process – Collaboration, Consultation and Influence

Collaboration– the following collaborations would most likely to support this technology:

- Implementers of CCS systems with advanced control specialists.

Consultation– the following organisations should be consulted:

- Implementers of CCS systems
- Advanced control specialists

Influencers– the following should be influenced to encourage development:

- Implementers of CCS systems.